Availability Evaluation and Optimisation of Grid Connection Concepts for Wind Farms

Diploma Thesis

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Abstract

Over the past years, the wind power market has changed from a sellers to a buyers market, thus the customer requirements regarding performance capabilities of wind farms and their technical availability became tougher. The subject of this thesis is the availability evaluation of grid connection concepts for large wind farms, with approaches to determine the level of availability of wind farms and approaches for improvement measures. Reliability calculation methods and their applicability to wind power systems will be discussed as well as certain cost-benefit methods in order to quantify the impact of different levels of reliability. Where is the optimal point between technological possibilities and economic design of electrical grid connection systems. What are the best network configurations and the most efficient maintenance strategies for wind farms according to their installed capacity. These questions together with questions concerning insurance possibilities and contractual aspects will be elaborated. Although whole wind farms will be taken into account the main focus will be on the electrical grid connection system.

Keywords: Reliability, Availability, Maintenance, Wind Farm, Grid Connection, Risk Assessment, Insurance, Layout Optimisation

Kurzfassung

Die Windkraft Branche hat sich innerhalb der letzten Jahre von einem Verkäufermarkt zu einem Käufermarkt entwickelt. Die Anforderungen der Kunden an die Leistungsfähigkeit von Windparks und deren technische Verfügbarkeit sind dadurch zusehends gestiegen. Diese Arbeit beschäftigt sich mit der Verfügbarkeit von Netzanbindungssystemen großer Windparks. Wie hoch ist die technische Verfügbarkeit bestimmter elektrischer Komponenten und Systeme und wo sind Verbesserungsmöglichkeiten. Welches ist die effektivste Netzstruktur sowie die effizienteste Wartungsstrategie von Windparks und welchen Einfluss darauf hat die installierte Leistung. Eine Risikobewertung von Netzanbindungssystemen sowie Versicherungs- und vertragliche Möglichkeiten werden diskutiert, um das Risiko zu minimieren. Der Schwerpunkt dieser Diplomarbeit liegt in der Bewertung von Windpark-Netzanbindungssystemen und nicht einzelner Windkraftanlagen.

Schlüsselwörter: Zuverlässigkeit, Verfügbarkeit, Wartung, Windpark, Netzanbindung, Risikomanagement, Versicherung, Optimierung

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Symbols and Abbreviations

Acronyms and Abbreviations

AP ………. Actual Production
BIP ……… Burn-In Period (Teething Period)
CB ……… Circuit Breaker
CCF ………. Common cause failure
CDF ……… Cumulated distribution function
CEA ……… Canadian Electricity Association
CMF ………. Common mode failure
COI ……… Continuous operating Item
DC ……… Disconnector
EENS ………. Expected Energy not supplied
ETS ……… External Transformer Station
HV ……… High Voltage (72,5kV<U_N<125kV)
IEC ……… International Electrotechnical Comission
IEEE ……… Institute of Electrical and Electronics Engineers
IOI ……… Intermittent operating Item
IRR ……… Internal Rate of Return
ISP ……… Integrated Service Package (incl. availability guarantee)
ITS ……… Internal Transformer Station
LBS ……… Load Break Switch
LCC ……… Life-cycle Costs
LCLR ……… Life Cycle Lost Revenue
LCMC ……… Life Cycle Maintenance Cost
LD ………. Liquid Damage
LP ………. Lost Production
LV ……… Low Voltage (U_N<1kV)
MAD ……… Mean Administrative Delay
MFT ……… Mean Time of a Fault
MLD ……… Mean Logistic Delay
MRT ……… Mean Restoration Time
MTBF ……… Mean Time between Failure
MTBM ……… Mean Time between Maintenance
MTD ……… Mean Technical Delay
MTTF ……… Mean Time to Failure
MTTM ……… Mean Time to Maintain

MTTR ……… Mean Time to Repair

MV ……… Medium Voltage (1kV$<U_N<$72,5kV)

NPV ……… Net Present Value

O&M ……… Operations and Maintenance

PDF ……… Probability density function

RBD ……… Reliability Block Diagram

REAG ……… REpower Systems AG

TP ……… Theoretical Production

ULP ……… Useful life period

VDN ……… Verband deutscher Netzbetreiber (neu BDEW)

WEC ……… Wind Energy Converter

WP ……… Wear out period

WSV ……… Wartungs- und Servicevertrag

Symbols

A	………	Availability	[p.u.]
C_0	………	Investment cost	[€]
m	………	MTTM	[h]
P_L	………	Power Loss	[kW]
P_r	………	Rated Power	[kW]
Q	………	Unreliability	[p.u.]
r	………	MTTR	[h]
R	………	Reliability	[p.u.]
scl	………	System Cable Length	[km per 3~]
T_D	………	Down Time	[h]
T_U	………	Up Time	[h]
U	………	Unavailability	[p.u.]
x	………	Mean Value (Expected Value)	
α	………	Weibull-Distribution Shape Parameter	
γ	………	Confidence Level	
η	………	Efficiency	[%]
λ_F	………	Failure Rate (frequency)	[1/yr]
λ_M	………	Maintenance Rate	[1/yr]
σ	………	Standard Deviation	
σ^2	………	Variance	
μ	………	Repair Rate	[1/yr]

Executive Summary

Goal

In order to ensure a certain level of availability of whole wind farms, a thorough understanding of how the system can fail is needed. Thus the objective of this investigation is the evaluation of wind farms regarding their failure mechanisms and their level of availability; furthermore an optimisation of grid connection concepts with respect to their configuration, their maintenance strategy and their support structure will be carried out. In addition specific insurance possibilities and contractual settings will be elaborated as well, in order to mitigate the inherent risk of certain layouts.

Methods

The first part of this investigation deals with quantitative and qualitative methods to evaluate the reliability of electrical components and whole systems. Mathematical models are derived using reliability block diagrams and fault tree methods. The second part basically consists of the application of these mathematical models to wind farm layout alternatives. Cost-benefit analysis methods are used to optimise the layout with respect to its level of availability and maintainability.

Results

The wind energy converter itself is the major cause of reduced power output at the point of common coupling. The level of availability of the grid connection is beyond the target value of 97% and can be assumed to be not less than 99%. The bottleneck of the grid connection is still the high voltage part, not because of the high failure rate but because of the high impact of failure and maintenance related energy not supplied. Thus a thorough design and maintenance strategy is essential for this part of the wind farm in order to mitigate the corporate risk. The investigation shows, that a redundant layout of the HV connection is reasonable for wind farms with an installed capacity larger than 100MW and a capacity factor above 40%.

Conclusion and Outlook

Over the next years the market requirements will certainly get even tougher for availability and performance guarantees for wind farms. Therefore it is necessary for companies to pay more attention to disturbance mechanisms. Furthermore a specific quality management process to improve the long term performance is recommended with the special focus on failure data acquisition and evaluation as well as maintenance strategies and support. The results of this investigation are based on analytical evaluation methods, for further calculations simulation approaches should be considered. (E.g. Monte Carlo Method)

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1 Introduction

1.1 Investigation of the Problem

Over the last decades the wind energy market developed from a research field to an important factor in electrical power generation. Due to the increasing amount of installed wind power generation, network companies established some rules for connections to the grid, also known as grid codes. The goal of these grid codes is to ensure system stability and reliability and therefore treating wind turbines as distributed active generators, which remain connected to the grid during disturbances and are able to contribute to the restoration of the system. However, a large wind farm may have hundreds of generators, which are distributed in the range of several kilometres, so that, at a certain level of reliability, there are various solutions for the electric connection system of wind farms. (Figure 1.1) The engineer has to search for an optimal solution, usually with the criterion of lowest cost. Such an optimization is of much significance [25].

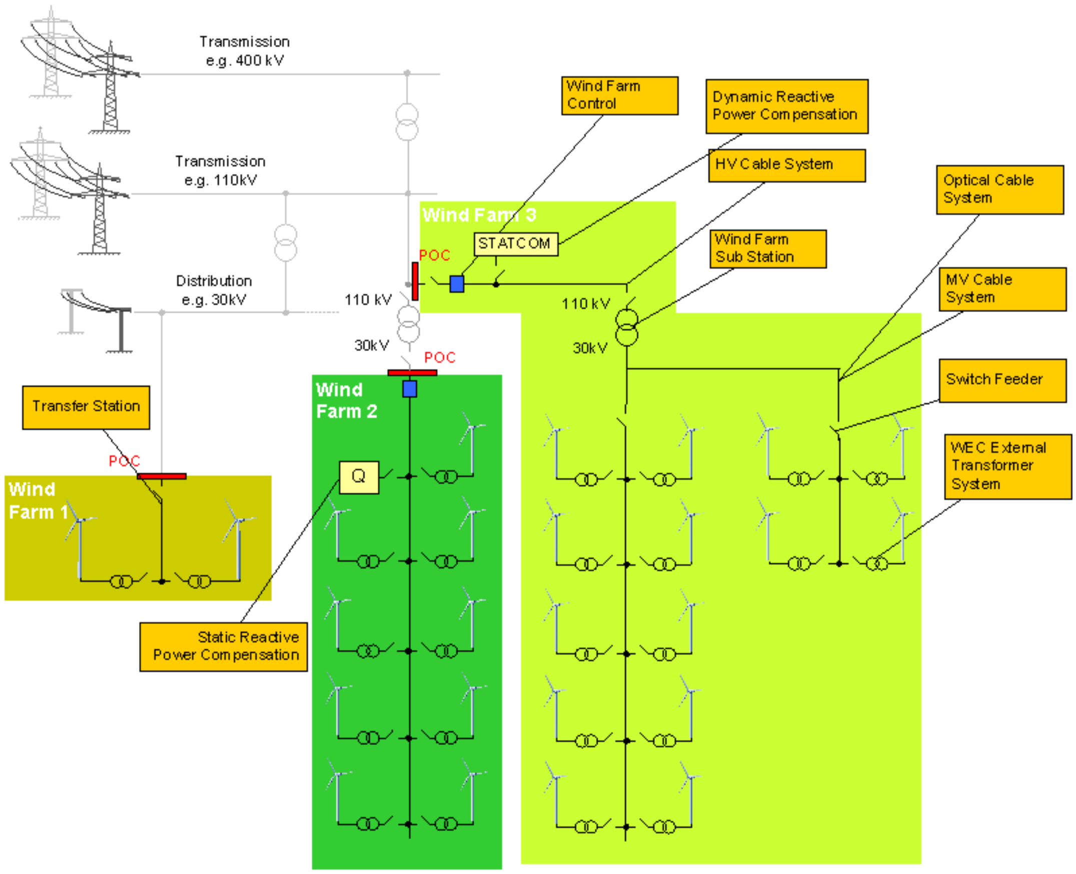


Figure 1.1 Single line diagram of an internal connection system

In fact, the internal electric connection system, which comprises numerous devices, also has a major influence on the availability of wind farms, thus economy and reliability has to be considered as one problem [62]. There are many requirements concerning the design and operation of electrical power systems. These requirements may be grouped into five classifications as shown in Figure 1.2.

The safety requirements include prefentive of damage to equipment and humans. The availability requirements include increasing the amount of time the system can operate. The performance requirements include the intended function of an item or a system. Finally the usability requirements include the applicability and the system's handling. Therefore the main objective is to optimise the design and operation of complex systems within these five evaluation criteria.

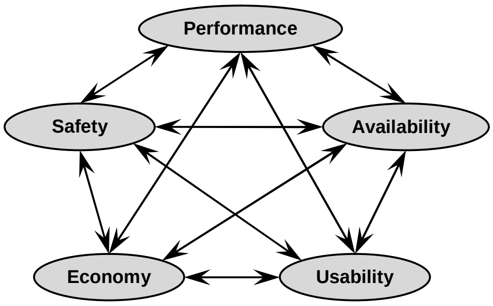


Figure 1.2 Evaluation criteria for technical equipment

The focus of this thesis is the definition of availability measures and the design of reliability models considering economical aspects.

According to IEC 60300 (Dependability Management) the term availability is subdivided into reliability, maintainability and support. (Figure 1.3) The particular subdivisions and their interaction will be explained and discussed in detail in subchapter 2.3 (*Reliability Theory*)

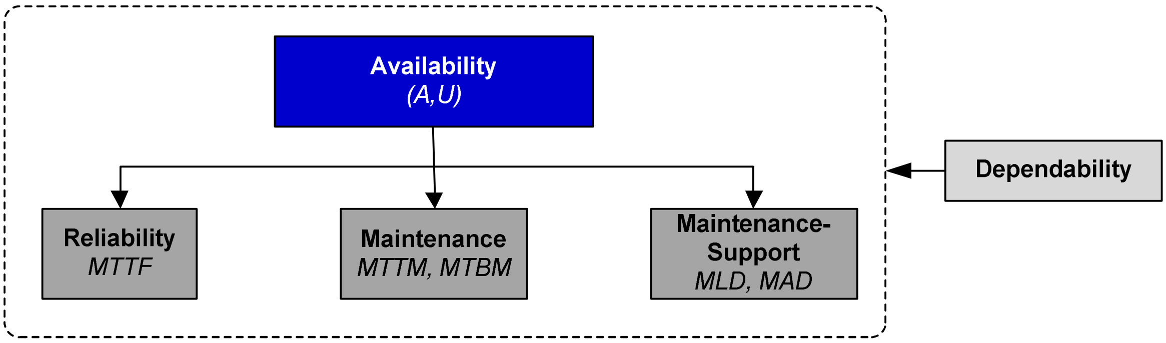


Figure 1.3 Dependability management [25]

To improve the availability of an item or system the four basic parameters are: quality (manufacturing, testing, human factors), redundancy (active, standby), diversity (software, hardware) and maintenance (stocking spares etc.). Quality and redundancy solutions are always related to additional investments.When it comes to maintainabillity and support the reliability centered maintenance (RCM) is the state-of-the-art strategy. This is a method for developing and selecting maintenance design alternatives, based on safety, operational and economic criteria. RCM analysis system functions, failures of functions, and prevention of these failures.

The scope of reliability engineering can be described by the following tasks [16]:

- The collection and evaluation of component failure data
- The definition of reliability measures and the determination of reliability requirements or standards for the various applications
- The development of mathematical models for system reliability, and the solution of these models
- The verification of the results
- The evaluation of results, conclusions and recommendations

During tendering phase future wind farm operators are most concerned about the performance curve of the wind energy converter and the time-dependent availability of the whole system. That means; wind farm operators are most interested in the energy yield of the farm and thus maximising the revenue. It is common practise to guarantee a certain level of availability of the wind farm (at the point of common coupling) which is contractually stated. It is obvious that if the availability doesn't meet the guaranteed value, a contractual penalty has to be paid in order to compensate for the customer's damage. For this reason, a good understanding and thorough consideration of the systems behaviour and its reliability is needed.

In this case the point of interest is the point of common coupling and the improvement of the wind farms ability to stay connected.

1.2 Investigation Questions and Goals

As penetration levels of wind power increase, the contribution of wind generators to the system adequacy is becoming an important reliability issue. Therefore large wind farms are requested to stay in operation and connected to the grid, during disturbances, in order to ensure power system stability and reliability. In other words, to ensure system adequacy, large wind farms have to be available at a very high level. Out of these considerations the following questions arise: Where is the optimal point between technological possibilities and economic design of power systems? What is the best network configuration and the most efficient maintenance strategy for wind farms according to their installed capacity.

These questions together with questions concerning insurance possibilities and contract standards will be elaborated in the described work.

1. What is the level of availability of grid connection systems used by REpower Systems AG?
2. Are there any significant influences to the systems availability? How can these parameters be optimised to achieve a higher availability and what is the optimum - relationship between technological and economical design?

3. What recommendations for contractual aspects can be derived from case studies by the use of reliability models?

The scope of this master's thesis is to determine the availability of different grid connection concepts for onshore wind farms as well as their optimisation. By use of analytical and simulative approaches single components as well as whole grid connection systems will be evaluated and improved. The availability of the wind energy converter system shall not be taken into account. Hence the main focus lies on the grid connection system that connects each wind turbine to the transmission system, including all significant components.

A special challenge is the goal of contract causes and insurance possibilities. Therefore, the impact of the availability evaluation on contract settings and insurance possibilities and how they have to be adopted to meet the specified requirements shall be investigated.

1.3 Structure of the Thesis

In ***chapter 2*** *(General)* probability theory, reliability theory and cost-benefit analysis will be presented and different evaluation methods and there applicability will be discussed.

In ***chapter 3*** *(Reliability Data)* the necessary basis for reliability evaluations i.e. reliability figures will be presented. Furthermore different data preparation methods as well as the concept of confidence limits for failure rates will be explained.

In ***chapter 4*** *(Reliability Modelling)* reliability models of primary grid connection components as well as for entire subsystems will be established, based on reliability figures presented in chapter 3. In addition a wind farm example will be evaluated regarding its availability, active power losses and its expected energy not supplied, the results of this chapter serve as reference for chapter 5.

In ***chapter 5*** *(Availability Optimisation)* referring to the results of chapter 4, concepts are proposed to optimise the availability of whole wind farms. According to the classification made in the previous chapter, each subsystem will be optimised regarding its availability, maintainability, active power losses and investment costs. The Life cycle costs will be elaborated and serve as basis for the optimisation and the decision process.

Chapter 6 *(Contract and Insurance Policies)* is intended to give an overview about current contractual settings, risk assessment concepts and different insurance possibilities. The first section of this chapter deals with contractual settings (e.g. guarantee, warranty...etc.) and the risk assessment of the wind farms grid connection. The second part of this chapter focuses on risk mitigation possibilities in general and on insurance policies in particular.

In ***chapter 7*** *(Results and Increase of Knowledge)* the final results from the availability and investment analysis, which was carried out in chapter 5, are presented.

In ***chapter 9*** *(Conclusion and Outlook)* further investigation problems shall be discussed, as well as a short outlook on market requirements and their influences on availability guarantees are provided.

The ***appendix*** serves as reference for reliability figures, statistical tables and theoretical background of different fault types.

2 General

This chapter is intended to provide a short overview of significant terms and definitions which will be used in this investigation. A basic understanding of different reliability evaluation methods and their applicability in electrical power system design shall be provided. Furthermore the life cycle cost management according to IEC 60300-3-3 as well as basic cost benefit analysis methods will be introduced to estimate the economic output of different levels of reliability.

2.1 Terms and Definitions

To evaluate the reliability and availability of engineering systems, many terms and definitions have to be taken into account. The international electrotechnical vocabulary (*Electropedia*[1]) published by the *International Electrotechnical Commission* (IEC) contains all electrical engineering definitions and shall serve as a basis for this work. Especially the publication IEC 60050-191 ‘Dependability and quality of service’ is used for reliability and availability definitions in this thesis. Some basic terms and definitions are listed below.

Item: Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered

Dependability: The collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance.

Availability: The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the external resources are provided

Reliability: The ability of an item to perform a required function under given conditions for a given time interval (t_1-t_2)

Maintenance: The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.

Failure: The termination of the ability of an item to perform a required function

Common Mode Failures: Failures if items characterized by the same fault mode

Fault: The state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources

[1] Electropedia contains all the terms and definitions in the International Electrotechnical Vocabulary or IEV which is published also as a set of publications in the IEC 60050 series that can be ordered separately from the IEC. http://www.electropedia.org/

(Instantaneous) Failure Rate: the limit, if it exists, of the quotient of the conditional probability that the instant of a failure of a non-repaired item falls within a given time interval (t, t + Δt) and the duration of this time interval, Δt, when Δt tends to zero, given that the item has not failed up to the beginning of the time interval

(Instantaneous) Failure Intensity: the limit, if this exists, of the ratio of the mean number of failures of a repaired item in a time interval (t, t + Δt), and the length of this interval, Δt, when the length of the time interval tends to zero

Error: a discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition

Force Majeure Event: means an exceptional event or circumstance which is beyond the reasonable control of the seller or the client and which could not reasonably have been provided against and which makes it impossible or unlawful for a Party to perform its obligations under this Contract.

Most of the terms and definitions above will be explained in more detail in the relevant subchapters. In particular, the equations used for calculating the different reliability parameters will be derived in subchapter 2.3.2.

In order to develop reliability models of single electrical components and furthermore of entire electrical systems a thorough understanding of basic probability theory and its application to electrical power systems is needed. Therefore, the basic theoretical background of reliability engineering will be introduced within the next few subchapters. For further information regarding probabilistic methods for electrical power systems see [5],[8],[9],[10] and [44].

2.2 Stochastics

Stochastics is a mathematical sub discipline and combines probability theory and statistics. Mathematical stochastics focus on random processes, also known as stochastic processes which are the counterpart of deterministic processes. Instead of dealing with only one way of how the process might evolve under time, in a random process there is some statistical indeterminacy in its future evolution described by probability distributions. (See random processes p.11) [44] Since the *mean time to failure* (MTTF) of electrical components is of stochastic nature only random processes will be taken into account.

2.2.1 Probability Theory

Set Theory (Sample Space and Events)

The sample space of an experiment is the set of all possible outcomes of that experiment. Mathematically the sample space is denoted by the symbol *S*. An event is any collection (subset) of outcomes contained in the sample space *S*. To illustrate this concept Venn diagrams can be used, which are a useful way to graphically illustrate sets and their relationships.

Venn Diagrams

A Venn diagram is a representation of a Boolean operation using shaded overlapping regions. There is one region for each variable, all circular in the examples below (figure 2.1 – 2.3). The interior and exterior of region *x* corresponds respectively to the values 1 (true) and 0 (false) for variable *x*. The shading indicates the value of the operation for each combination of regions; with dark denoting 1 and light 0 (some authors use the opposite convention).

The Venn diagrams in Figure 2.1,Figure 2.2 and Figure 2.3 represent respectively conjunction $x \vee y$, disjunction $x \wedge y$, and complement $\overline{x}$

Boolean Algebra

Boolean algebra provides a mean for evaluating sets. The rules are fairly simple and the basic axioms can be seen in Table 2.1 .

Operator	Logic theory		Set theory	
OR	Disjunction	$\wedge$	Union	$\cup$
AND	Conjunction	$\vee$	Intersection	$\cap$
NOT	Complement	$\overline{X}$	Complement	$\overline{X}$

Table 2.1 Boolean Operators

In this thesis the set theoretical interpretation and notation will be used.

Axioms [5]

$A \cup B = B \cup A$	Commutative Law	(2.1)
$A \cup (B \cup C) = (A \cup B) \cup C$	Associative Law	(2.2)
$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$	Distributive Law	(2.3)
$A \cap (A \cup B) = A$	Absorption Law	(2.4)
$A \cup \overline{A} = 1$	Complementation Law	(2.5)
$\overline{(A \cup B)} = \overline{A} \cap \overline{B}$	deMorgans's Theorem	(2.6)

Basic Laws of Probability

Probability theory has a long history in science, but yet there is no consistent definition for the word probability itself. The three major conceptual interpretations of probability are the classical interpretation also known as the equally likely concept, the frequency interpretation (empirical Concept) and the subjective interpretation of probability [38]. The classical interpretation supposes that all possible outcomes of an event are different and equally likely. The subjective interpretation assumes that the probability is a measure of degree of belief one holds in a specified event. Both concepts are rather inadequate for engineering applications.

The most widely used definition in engineering applications today is the frequency interpretation. It defines the probability of an event as the limit of its relative frequency in a large number of trials. This concept is based on the *central limit theorem* equation (2.8)

Frequentists talk about probabilities only when dealing with well-defined random experiments, also known as stochastic processes. The set of all possible outcomes of a random experiment is called the sample space of the experiment. An event is defined as a particular subset of the sample space that you want to consider. For any event only one of two possibilities can happen; it occurs or it does not occur. The relative frequency of occurrence of an event, in a number of repetitions of the experiment, is a measure of the probability of that event.

The relative frequency of an event (E) can be obtained from the following equation:

$$f(E) = \frac{n(E)}{n} \tag{2.7}$$

If an experiment with *n* trials the event *E* (outcome *E*) occurs *n(E)* times the relative frequency of *E* can be calculated with the above equation. Where *E* is a special event, *n(E)* is the number of elements in the set *E* or in other words how often the event occurs during the experiment and n denotes the number of trials, hence the possible outcomes.

With the increasing number of trials the ratio *n(E)/n,* called the relative frequency of the event *E,* would tend to a finite limit. This value is called the probability of the event.

$$P(E) = \lim_{n \to \infty} \left(\frac{n(E)}{n} \right) \tag{2.8}$$

The limit cannot be calculated exactly from a sample, because of the lack of knowledge, but one can estimate the limit in an accurate way for *n>>1.*

$$P(E) \approx f(E) \qquad n \gg 1 \tag{2.9}$$

A problem associated with the relative frequency concept is that some events occur only once or rarely, yet the uncertainty associated with these rare events has to be measurable. In cases like this another probability interpretation such as the subjective probability that would measure a degree of belief that the event will occur may be used. Furthermore *f(E)* of a random experiment, if repeated, would change, because the event itself occurs at random. Despite this, the relative frequency concept is still the tool that engineers apply the most to estimate the probability of repeated events.

The first one who described the probability concept in an axiomatic way and therefore can be seen as the founder of the modern probability concept was *Andrei Kolmogorow* in 1933. According to *Kolmogorow* a probability quantity has to fulfil the following three axioms [60].

The probability (P) of some event (E) of a sample space (S) must satisfy the following axioms:

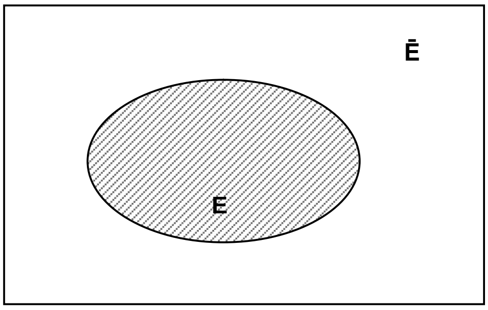
$$0 \le P(E) \le 1, \quad \forall E \in S \tag{2.10}$$

$$P(S) = 1 \tag{2.11}$$

$$P(E_1 \cup E_2) = P(E_1) + P(E_2) \qquad \textit{if } E_1 \textit{ and } E_2 \textit{ are mutual exclusive events} \tag{2.12}$$

Two consequences of the axioms of probability theory: [61]

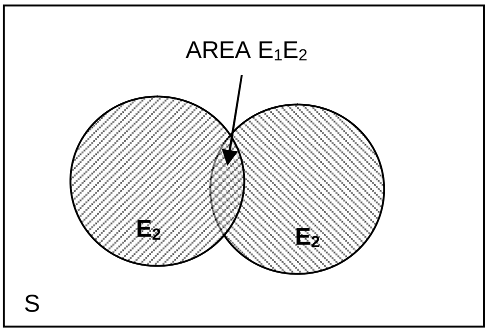
- Complementation



$$P(E) + P(\bar{E}) = P(S) = 1 \tag{2.13}$$

Figure 2.1 Venn diagram for complementation

- Joint Probability (Union of Sets)

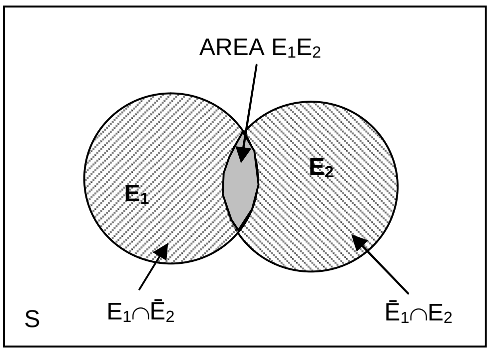


$$P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1, E_2) \tag{2.14}$$

for any two events E_1 and E_2

Figure 2.2 Venn diagram for joint probability

- Intersection



$$P(E_1 \cap E_2) = P(E_1) \cdot P(E_2) \tag{2.15}$$

Figure 2.3 Venn diagram for intersection

Properties of Events

Independency: Events E_1 and E_2 are independent if:

$$P(E_1 \mid E_2) = P(E_1)\,, \qquad \textit{or equivalent if:} \tag{2.16}$$

$$P(E_2 \mid E_1) = P(E_2)\,, \qquad \textit{or more general if} \tag{2.17}$$

$$P(E_1 \cap E_2) = P(E_1) \cdot P(E_2) \tag{2.18}$$

Real-life events are independent if the occurrence of one has no effect on the occurrence of another.

Mutual Exclusiveness: In probability theory events are mutual exclusive if they cannot occur at the same time, e.g. tossing a coin. In other words the intersection of events is the null set.

$$P(E_1 \cap E_2) = 0 \tag{2.19}$$

Conditional Probability

When calculating probabilities sometimes the likelihood of an event E_1 occurring whether another event E_2 has occurred (or not) is of interest. The conditional probability of E_1, given E_2 *(*$P(E_1|E_2)$*)* can be obtained by the following equation.

$$P(E_1 \mid E_2) = \frac{P(E_1 \cap E_2)}{P(E_2)} \tag{2.20}$$

Therefore,

$P(E_1 \cap E_2)$ can also be obtained by $P(E_1 \cap E_2) = P(E_2) \cdot P(E_1 \mid E_2) = P(E_1) \cdot P(E_2 \mid E_1)$

Bayes'Theorem

An important law known as Bayes'theorem follows directly from the concept of conditional probability and it shows the relation between conditional probability and its inverse.

$$P(E_1 \mid E_2) = \frac{P(E_1) \cdot P(E_2 \mid E_1)}{P(E_1) \cdot P(E_2 \mid E_1) + P(\overline{E_1}) \cdot P(E_2 \mid \overline{E_1})} \tag{2.21}$$

Equation 2.21 can easily be simplified to the following equation:

$$P(E_1 \mid E_2) = P(E_1) \cdot \frac{P(E_2 \mid E_1)}{P(E_2)} \tag{2.22}$$

The Bayes'theorem enables calculations with conditional probabilities and particularly the calculations with their reverse. Furthermore it provides a mean of changing the knowledge about an event because of new evidence related to the event. Because of the updating capability, Bayes'theorem is useful for failure data analysis [38].

2.2.2 Probability Functions

Random Variables

A random event can be represented by a random variable. A random variable *(X)* is a function that defines a real number *(X(s))* to each element *(s)* of a sample space *(S).* The function has to be one to one and mutually exclusive events are mapped into disjoint intervals on the real line, see Figure 2.4 *P(X≥x)* is then the probability that the random variable *X* is not smaller than a real number (*x*) [5]. In other words, a random variable transforms an outcome of an event into a real number.

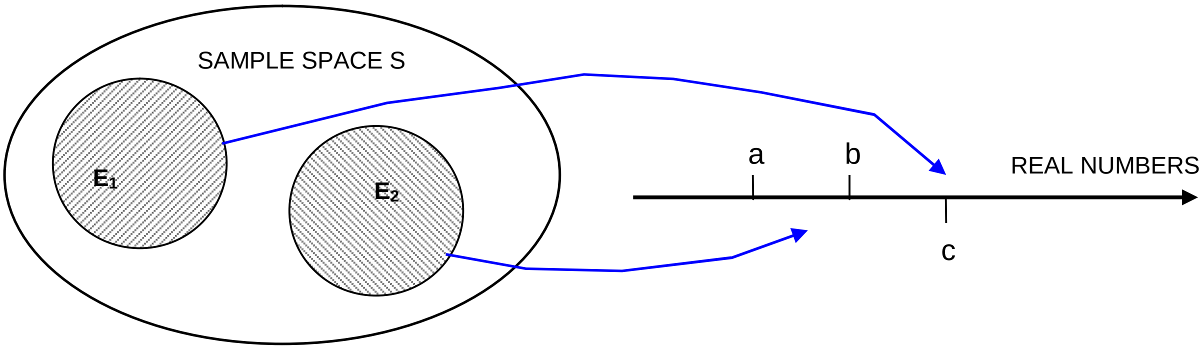


Figure 2.4 The concept of random variables

The parameter of the measured event (e.g. the failure rate of a component) is a variable that randomly varies in time and/or space. It may be defined as discrete or continuous random variable [8].

Probability Distribution- and Density-Function

Given a continuous random variable *X*, the probability of *X* being not larger than a real number *x* is a function of *x*. This function is defined as the cumulative distribution function *F(x)* of random variable *X*

$$F(x) = P(X \geq x) \qquad (-\infty < x < \infty) \tag{2.23}$$

The cumulative distribution function (CDF) contains the probabilities of all possible values of *X*. Where *f(x)* is the probability density function (PDF).

$$F(x) = \int_{-\infty}^{x} f(x)\,dx \tag{2.24}$$

$$f(x) = \frac{dF(x)}{dx} \tag{2.25}$$

According to equation 2.24, the probability of a continuous random variable at a single point is zero. If the random variable takes values in the set of real numbers, the probability distribution is completely described by the cumulative distribution function, whose value at each real x is the probability that the random variable is smaller than or equal to x.

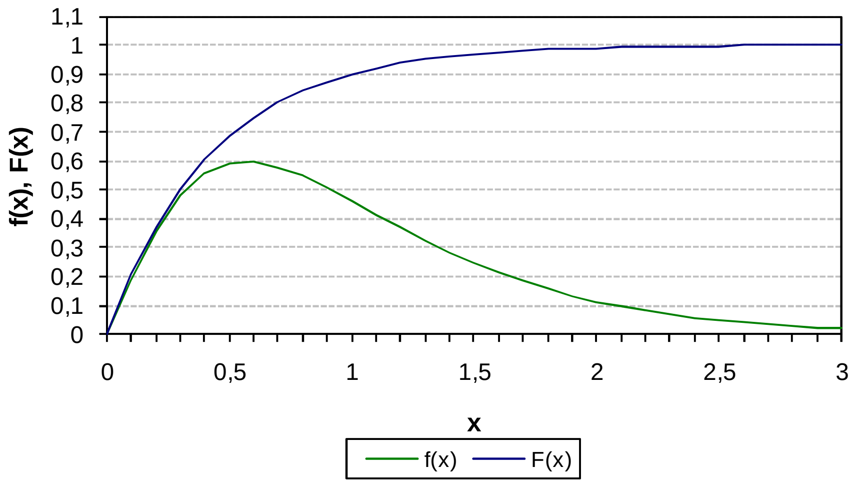


Figure 2.5 Probability density function (PDF) and cumulative distribution function (CDF)

Properties of the CDF and PDF:

$$\lim_{x \to -\infty} F(x) = 0 \qquad (2.26)$$
$$\lim_{x \to +\infty} F(x) = 1$$

$$f(x) < 0 \qquad (2.27)$$

The CDF is a monotone increasing function, according to equation 2.26. Furthermore the CDF of a continuous random variable cannot be calculated at a single point; as shown in equation 2.24.Unlike the CDF of a discrete random variable which is exactly defined for each x, the CDF of a continuous random variable can only be evaluated for a defined interval.

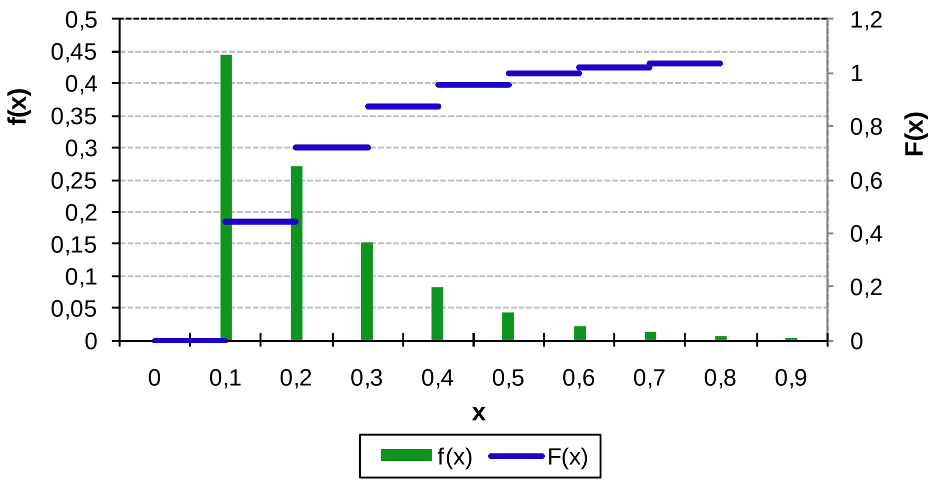


Figure 2.6 CDF and PDF of a discrete random variable

Figure 2.6 shows the CDF and the PDF of a discrete random variable, it is obvious that the integral in equation 2.24 can be replaced by a simple summation. Please note, that F(x) has actually a quadratic shape for small values of x, according to equation 2.24.

Random Processes

A stochastic process (*X(t),t E Q*) is a collection of random variables, also known as random process. *Q* is called the index set of the process and for each index *t* in *Q*, *X(t)* is a random variable. The index *t* is often interpreted as time, and *X(t)* is called the state of the process as time *t*. Discrete and Continuous processes according to the properties of the index set *Q*.

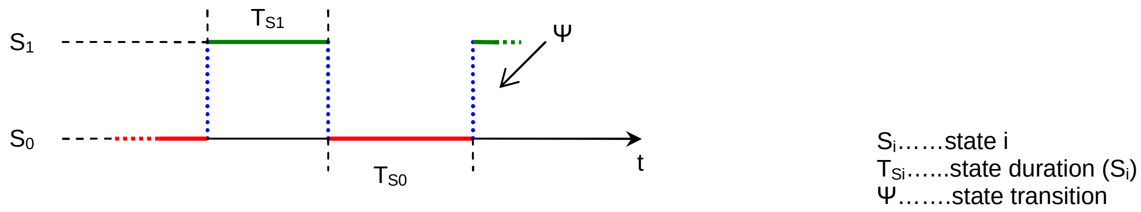


Figure 2.7 State, state duration and state transition of a two-stage process

State transition rates will be neglected - t_ψ=0.

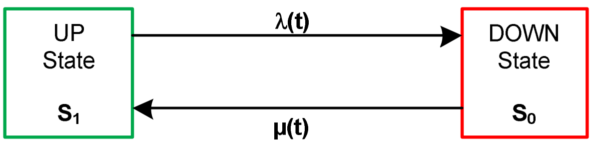


Figure 2.8 A two state Markov model

The probability that the component is in state *i* is equal to the transition rate (μ,λ) times the state duration (T_{Si}). Hence the proportion of time the component is in state *i* is:

$$P_i = \begin{pmatrix} \lambda \\ \mu \end{pmatrix} \cdot \mathrm{T}_i \tag{2.28}$$

The frequency of encountering the up state (equation 2.28) is therefore the probability of being in the up state times the rate of departure from the up state.

$$f = P_1 \cdot \lambda = P_o \cdot \mu \qquad \textit{frequency of encountering the up state} \tag{2.29}$$

Continuous Markov Process

Counting Process, particular stochastic process [N(t), t>0], where N(t) denote the number of events (failures). The state of the system at time t is denoted X(t), a special class of stochastic processes which are following the property [*X(t), t>0*] are called a Markov process [44]. One of the major properties of Markov models are their lack of memory, or in other words the system’s ability to work accurately at an arbitrary time in the future does not depend on previous states and conditions of the system. Hence Markov chains do not take the systems history into account, the future function only depends on the current state.

By use of Markov models entire complex systems can be modelled and evaluated in a very accurate way. Nevertheless the high calculation effort of this particular method has to be taken into account.

Electrical Components and their Operation Modes

Electrical components can be categorised according to their repairability and their operation mode. Figure 2.9 displays the two operation modes of electrical components and the related states.

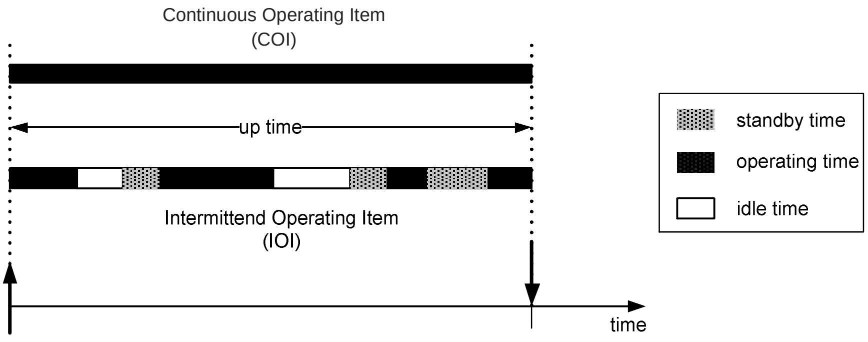
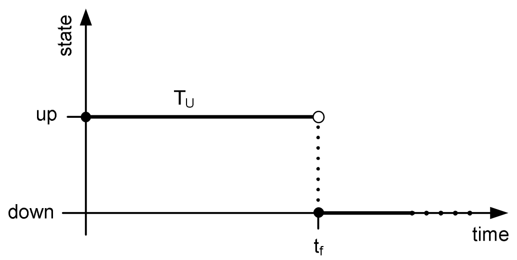


Figure 2.9 Operation modes of items and their states

It can be distinguished between continuous operating item and intermittent operating item. Most of the grid connection components are continuously operating; therefore the main focus will be on this type.

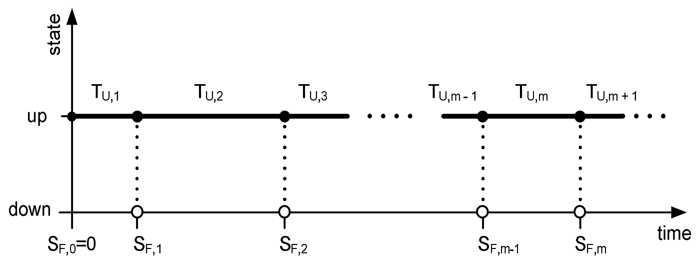
Concerning the repairability of electrical components it can be distinguished between not repairable items and repairable items with zero or non-zero time to restoration. The figure above shows the particular state diagram for a not repairable item. It is obvious that in case a failure occurs the component stays out of service.



This concept is applicable for most of the electronic components where the repair of the component is technically possible but economically not reasonable.

Figure 2.10 Not Repairable item

The state space diagram of repairable items with zero time to restoration is shown in the following figure.



Software and most of the redundant systems can be assigned to this particular type of components.

Figure 2.11 Repairable item, T_R=0

Almost all primary components of electrical power systems are repairable items with non zero time to restoration (*MTTR>0*). Since most of the grid connection components are assumed to be repair- or replaceable, the following state space diagrams are valid.

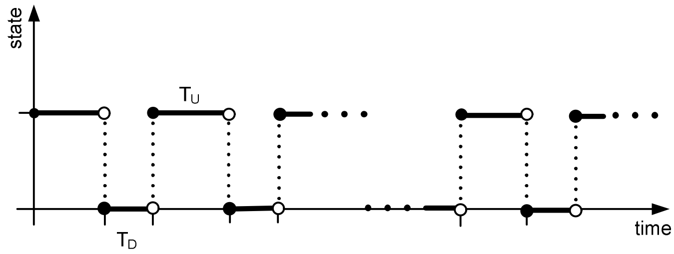


Figure 2.12 Alternating renewal process (Stochastic point process), T_R>0

The component is in operation until it fails, then it is repaired and put into operation again. This process continues over the life cycle of the component and is called an alternating renewal process. This process is defined by its time to failure and time to repair ($\lambda(t),\mu(t)$) which are the random variables of the process and may be interpreted as the average length of uptime and average length of down time.

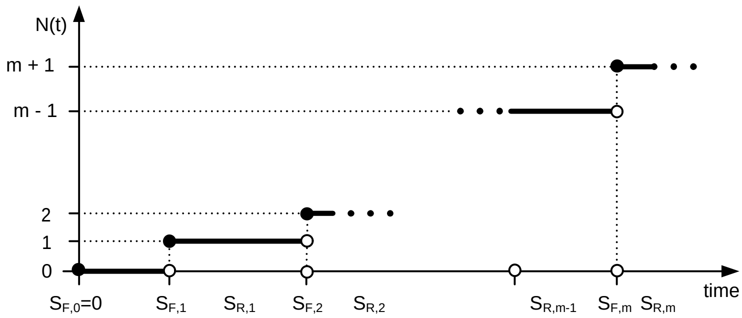


Figure 2.13 Frequency of failures in the time interval (0, t)

A system's renewal process is determined by the renewal processes of its components. For example, considering the grid connection of wind farms, which is basically a series system. In case one component fails (e.g. MV cable) the whole system fails.

It should be noted, that the components are assumed to be independent from each other, in other words: if a component experiences a failure it doesn't' affect other components. Furthermore, perfect repair is assumed. Hence if a component has been repaired it can be regarded as good as new.

2.3 Reliability Theory

2.3.1 Reliability and Availability

From the previous reliability and availability definition in subchapter 1.1, there are some important differences between these two concepts. The term reliability refers to the notion that the system performs its specified task correctly for certain time duration (t_1,t_2). Hence the reliability of an item is time dependent that means the longer the time the lower the reliability, regardless of the system design. The term availability refers to the readiness of a system to immediately perform its task, at a particular time. When calculating the availability of a system its maintainability and repairability is taken into account. In Figure 2.14 the concept of reliability and availability and their influences are graphically illustrated.

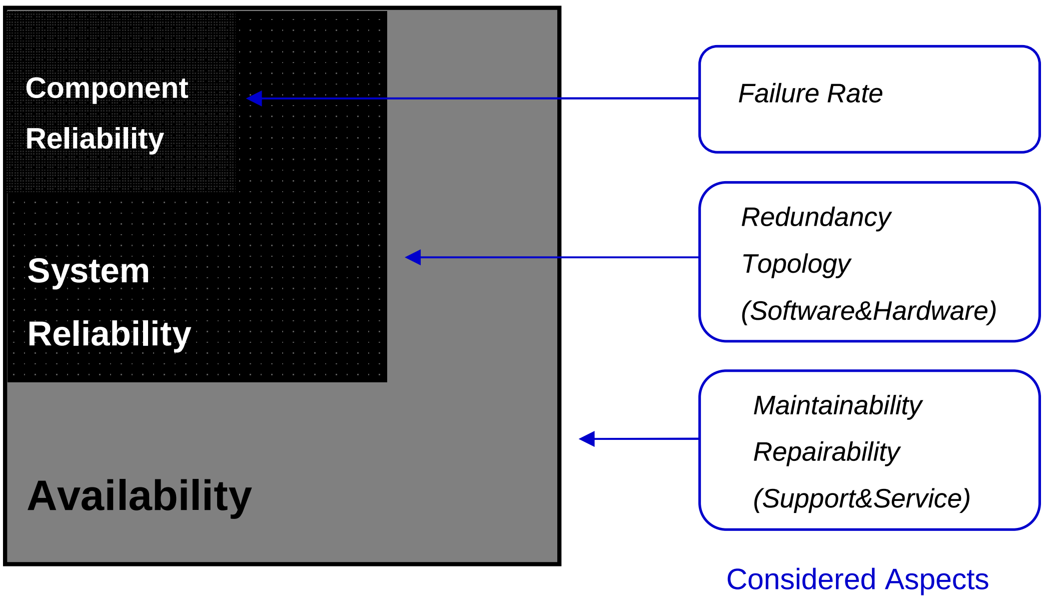


Figure 2.14 Concept of availability and reliability

Note, that the availability of a non-repairable item or an item with zero time to restoration is equal to the reliability of that particular item.

First of all it can be distinguished between non-repairable items, repaired items with zero time to restoration and repairable items with non-zero time to restoration. This concept was discussed in more detail in the previous chapter. The transition between a repairable and a not repairable item is continuous [8]. Since almost all primary electrical components are repairable items with non-zero time to restoration (*mean time to repair MTTR* > *0*) only this type shall be taken into account. However, for more information see [5] and [65].

Within the next few subchapters each subsection of Figure 2.14 will be described in detail and furthermore different evaluation methods of significant reliability parameters will be introduced.

2.3.2 Reliability of Components

2.3.2.1 Reliability

Reliability is the ability of an item to perform a required function under given conditions during a given time interval (t_1,t_2) with $t_1<t_2$.

$$R(t_1,t_2) = R(t_2) + \int_0^{t_1} R(t_2 - t_1)\cdot \mu(t)dt \tag{2.30}$$

R(t_2) is the reliability of the item until t_2, the second term of this equation is the probability of the restoration of the item in the interval ($t<t_1$) and the item survives until t_2. This definition and mathematical reliability expression is especially applicable for repairable electrical systems with non-zero time to restoration. In a more general sense the reliability function of an item is defined by equation 2.31 and 2.32

$$R(t) = P(T > t) = 1 - F(t) = \overline{F(t)} \quad \text{for} \quad t>0 \tag{2.31}$$

$$R(t) = 1 - \int_0^t f(t)dt = \int_t^\infty f(t)dt \tag{2.32}$$

R(t) is therefore the probability that the item doesn't fail in the time interval (*0,t*). The strength of a technical component is modelled as a random variable (*T*, time to failure). The reliability of the component is defined as the probability that the strength is greater than the load. Now since both, strength and load are time dependent the reliability of a component can be calculated using equation 2.31. Where the time to failure (*T*) of the component is the shortest time interval until the load of the component exceeds its strength. (*T=min[t;strength<load]*) It should be also noted, that the time to failure must not always be measured in calendar time, but may also be measured in switching cycles, for example.

At this point it is important to point out, that reliability is the probability that a component or system survives a given period of time. Influences like reparability, maintenance support...etc. are not taken into account when calculating reliability. Thus, reliability is commonly used to quantify mission oriented systems. (E.g. rockets)

<u>Asymptotic Reliability:</u>

The following equations can be derived from equation 2.30 by means of Markov-process or Laplace-transformation, but only if the times to failure and the times to restoration are exponentially distributed.

$$R(t_1,t_2) = \left(\frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\cdot e^{[-(\lambda+\mu)\cdot t_1]}\right)\cdot e^{[-\lambda\cdot(t_2-t_2)]} \tag{2.33}$$

$$\lim_{t\to\infty} R(t,t+\Delta t) = \frac{\lambda}{\lambda+\mu}\cdot e^{-\lambda\cdot\Delta t} \qquad \textit{asymptotic reliability} \tag{2.34}$$

The reliability of electric systems can be classified into to functional aspects. *Adequacy*, which is the ability of the electric system to supply the energy requirements of customers at all times, taking into account scheduled and unscheduled disturbances. And *Security*, which can be described as the ability of the electric system to withstand sudden disturbances, like short circuits etc.

2.3.2.2 Failure Rate

The probability that an item will fail in the time interval ($t,t+\Delta t$) is given by equation 2.35, assuming that the item is functioning at time t.

$$P(t < T \le t+\Delta t \mid T > t) = \frac{P(t < T \le t+\Delta t)}{P(T > t)} = \frac{F(t+\Delta t)-F(t)}{R(t)} \tag{2.35}$$

Now the failure rate function can be obtained by dividing the probability by the time interval (Δt) and calculate the right-hand limit for $\Delta t \to 0$. The received equation (2.36) is also known as the instantaneous failure rate function ($\lambda(t)$).

(Instantaneous) Failure Rate: the limit, if it exists, of the quotient of the conditional probability that the instant of a failure of a non-repaired item falls within a given time interval (t, $t + \Delta t$) and the duration of this time interval, Δt, when Δt tends to zero, given that the item has not failed up to the beginning of the time interval

$$\lambda(t) = \lim_{\Delta t\to 0}\left(\frac{1}{\Delta t}\cdot\frac{F(t+\Delta t)-F(t)}{R(t)}\right) = \frac{f(t)}{R(t)} \tag{2.36}$$

(Instantaneous) Failure Intensity: the limit, if this exists, of the ratio of the mean number of failures of a repaired item in a time interval (t, $t + \Delta t$), and the length of this interval, Δt, when the length of the time interval tends to zero.

$$z(t) = \lim_{\Delta t\to 0}\left(\frac{E[N(t+\Delta t)-N(t)]}{\Delta t}\right) = \frac{dZ(t)}{dt} \tag{2.37}$$

$$Z(t) = E[N(t)]$$

Where $N(t)$ is the number of failures that occur in the time interval (0, t) and E denotes the expectation. If the item is continuously operating and its up-time is exponentially distributed the following simplifications are valid (A(t) denotes the availability of the item).

$$z(t) = A(t)\cdot\lambda(t) \tag{2.38}$$

$$z(\infty) = \lim z(t) = \frac{1}{MTTF} = \lambda \qquad \textit{asymptotic failure intensity} \tag{2.39}$$

Equation 2.40 can be obtained by means of Markov-process or Laplace-transformation, but only if the times to failure and the times to restoration are exponentially distributed.

$$z(t) = A(t) \cdot \lambda = \frac{\lambda \cdot \mu}{\lambda + \mu} + \frac{\lambda^2}{\lambda + \mu} \cdot e^{[-(\lambda+\mu)\cdot t]} \tag{2.40}$$

$$z(\infty) = \lim_{t \to \infty} z(t) = \frac{\lambda \cdot \mu}{\lambda + \mu} = \frac{1}{\frac{1}{\lambda} + \frac{1}{\mu}} \tag{2.41}$$

It should be stated, that the difference between the failure rate of components and the failure intensity lies only in the operation mode. The instantaneous failure rate function is normally restricted to not-repairable items, or repairable items with zero time to restoration (*MTTR=0*). On the other hand the instantaneous failure intensity function is also valid for repairable, intermittent operating items with non-zero time to restoration (*MTTR>0*). However, since both terms (*z(t), λ(t)*) become identical for long observation times (equations 2.38-2.40), in this thesis only the term failure rate (*λ(t)*) will be used for further calculations.

2.3.2.3 Lifetime Indices (*MTTF, MTBF, MTTR*)

There are different possibilities to determine the lifetime of components or a systems. The mean lifetime of an item, (mean time to failure *MTTF)*, is the expected value *E(T)* of the lifetime *T* that can be calculated by using equation (2.42).

Mean Time To Failure (*MTTF*): The expectation of the time to failure.

$$MTTF = E(T) = \int_0^\infty t \cdot f(t)\,dt = \int_0^\infty R(t)\,dt \tag{2.42}$$

$$MTTF = \frac{\sum_{i=1}^{n} (time\ of\ operation)_i}{n} \tag{2.43}$$

n…number of failures in the time interval

If the time to repair or replace a failed item is very short, compared to the MTTF, or in other words if the repair rate (*μ*) is significantly less than the failure rate (*λ*), the MTTF also represents the MTBF (mean time between failure). On the other hand, if the time to repair cannot be neglected, the MTBF also includes the MTTR. This concept is mathematical described by equation 2.44 and 2.45.

Mean Time Between Failures (*MTBF*): The Mean operation time between failures.

$$MTBF = MUT + MTTR \quad \rightarrow \quad \text{for intermittent operating items (IOI)} \tag{2.44}$$

$$MTBF = MTTF + MTTR \quad \rightarrow \quad \text{for continuously operating items (COI)} \tag{2.45}$$

MUT….mean up time
MDT….mean down time } *for IOI*

$$MTBF = \frac{\sum_{i=1}^{n} (total\ time)_i}{n} \tag{2.46}$$

Since the restriction λ<<µ is applicable for electrical components, the term MTBF will be used throughout the ongoing chapters. (Assumed MTTF=MTBF)

Mean Time to Repair or Restoration (*MTTR*): The expectation of the time to restoration. The mean time to repair of a failed item can be described as the sum of the expected times of the included actions.

$$MTTR = MUFT + MAD + MLD + MTD + MRT \tag{2.47}$$

MUFT	*meantime of a fault*
MAD	*mean administrative delay*
MLD	*mean logistic delay*
MTD	*mean technical delay*
MRT	*mean restoration time*

If repair figures of different items are available (e.g. from experience) the following equation provides a good estimate for the MTTR.

$$MTTR = \frac{\sum_{i=1}^{n} (time\ to\ restoration)_i}{k_R} \tag{2.48}$$

k_R….*cumulated time to restoration*

Assuming that the repair times follow an exponential distribution, with a constant repair rate (*µ*), the equation for MTTR can be written as follows

$$MTTR = \frac{1}{\mu} \tag{2.49}$$

Mean Residual or Remaining Life (*MRL*)

The probability that an item in operation at time *t,* survives an additional time interval (*x*) is called the mean residual life (*MRL*)

$$MRL(t) = g(t) = \frac{1}{R(t)} \cdot \int_t^{\infty} R(x)dx \tag{2.50}$$

At time *t=0* the item is new and therefore *g(0)* is equal to the MTTF.

The relationship between stress level and mean residual lifetime is displayed in Figure 2.15 Mean residual life of an item

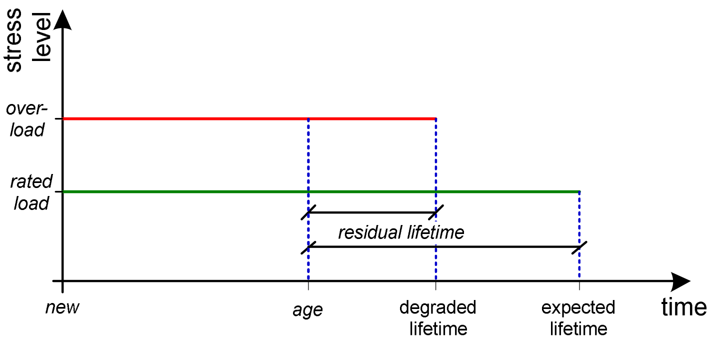


Figure 2.15 Mean residual life of an item

2.3.2.4 Reliability Indices and their Interaction

The relationships between *f(t), F(t), R(t)* and *λ(t)* are presented in Table 2.2 below.

given	$f(t)$	$F(t)$	$R(t)$	$\lambda(t)$
$f(t)=$		$\frac{dF(t)}{dt}$	$-\frac{dR(t)}{dt}$	$\lambda(t)\cdot e^{\left[-\int_0^t \lambda(t)\,dt\right]}$
$F(t)=$	$\int_0^t f(t)\,dt$		$1-R(t)$	$1-e^{\left[-\int_0^t \lambda(t)\,dt\right]}$
$R(t)=$	$\int_t^\infty f(t)\,dt$	$1-F(t)$		$e^{\left[-\int_0^t \lambda(t)\,dt\right]}$
$\lambda(t)=$	$\frac{f(t)}{\int_t^\infty f(t)\,dt}$	$\frac{1}{1-F(t)}\cdot\frac{dF(t)}{dt}$	$-\frac{1}{R(t)}\cdot\frac{dR(t)}{dt}$	

Table 2.2 Relationships between reliability indices

The mathematical concepts in Table 2.2 are graphically illustrated in Figure 2.16 in order to provide a thorough understanding of the different equations, their relations and interactions among themselves.

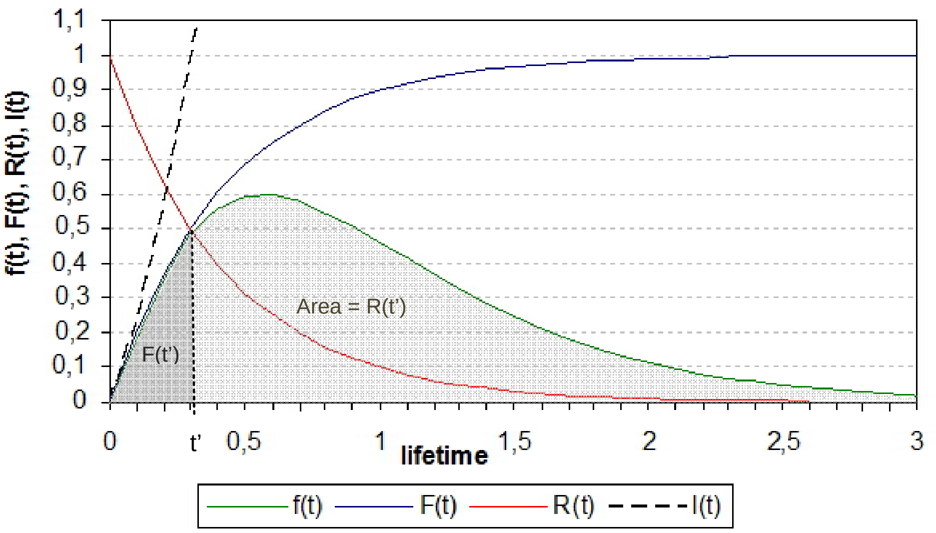


Figure 2.16 Relation between failure probability F(t), failure density f(t), failure rate λ(t) and reliability R(t) (survivor function)

It is important to understand the difference between reliability, also known as the survivor function (*R(t)*) and the probability of failure (*F(t)*).

2.3.2.5 Lifetime Distributions

There are numerous distribution functions to model the lifetime of items and systems from different scientific areas. Since this investigation focuses mainly on electric power system components but also considers some human and environmental aspects; the most relevant distribution functions and their application will be introduced. As pointed out in subchapter 4.1, only the useful-life period and the wear-out period of the failure rate function are taken into account, because of warranty and guarantee periods given by the company (REpower). Hence the exponential distribution as well as the Weibull distribution will be explained in more detail.

For further information regarding life-distribution functions and their application see [8],[16] and [44].

The Exponential Distribution

The distribution function:

$$F(t) = P(T \leq t) = 1 - e^{-\lambda \cdot t} \qquad (t > 0) \tag{2.51}$$

The density function:

$$f(t) = \frac{d}{dt}F(t) = \lambda \cdot e^{-\lambda \cdot t} \qquad (t > 0) \tag{2.52}$$

The mean and variance of the exponential distribution are *1/λ* and *1/λ²*, respectively.

$$R(t) = e^{-\lambda \cdot t} \quad \rightarrow \quad \lambda = \frac{1}{MTBF} \tag{2.53}$$

<u>Properties:</u> Failure rate (λ) is constant (independent of time, failures occur at random)
Requires only the MTBF
MRL is equal to MTBF
Fits to most electrical power system components

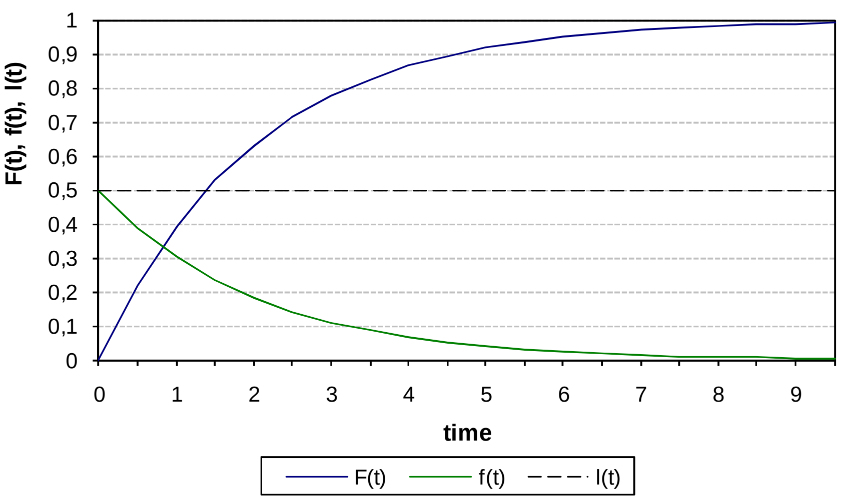


Figure 2.17 Exponential distribution (λ=0,5)

The Weibull Distribution

The distribution function:

$$F(t) = P(T \le t) = 1 - e^{-(\lambda \cdot t)^{\alpha}} \qquad (t > 0) \tag{2.54}$$

The density function:

$$f(t) = \frac{d}{dt}F(t) = \alpha \cdot \lambda^{\alpha} \cdot t^{\alpha-1} \cdot e^{-(\lambda \cdot t)^{\alpha}} \qquad (\infty > t \ge 0,\ \alpha > 0) \tag{2.55}$$

Where λ and α are denoted as the shape and scale parameters of the Weibull distribution. Their influence on the shape of the distribution and density function is shown in more detail in Figure 2.19. For α=1, the Weibull distribution is equal to the exponential distribution.

The mean and variance:

$$MTBF = \frac{1}{\lambda}\Gamma\left(\frac{1}{\alpha} + 1\right) \tag{2.56}$$

The survivor function (*R(t)*) and the failure rate function (*λ(t)*) can be calculated using following equations

$$R(t) = e^{-(\lambda \cdot t)^{\alpha}} \quad \rightarrow \quad \lambda(t) = \alpha \cdot \lambda^{\alpha} \cdot t^{\alpha-1} \qquad (t > 0) \tag{2.57}$$

<u>Properties:</u> Very flexible distribution (has no specific characteristic shape)
Used to model life distributions with decreasing, increasing or const. λ(t)
Two-parameter model (*α* and *λ* shape and scale parameters)

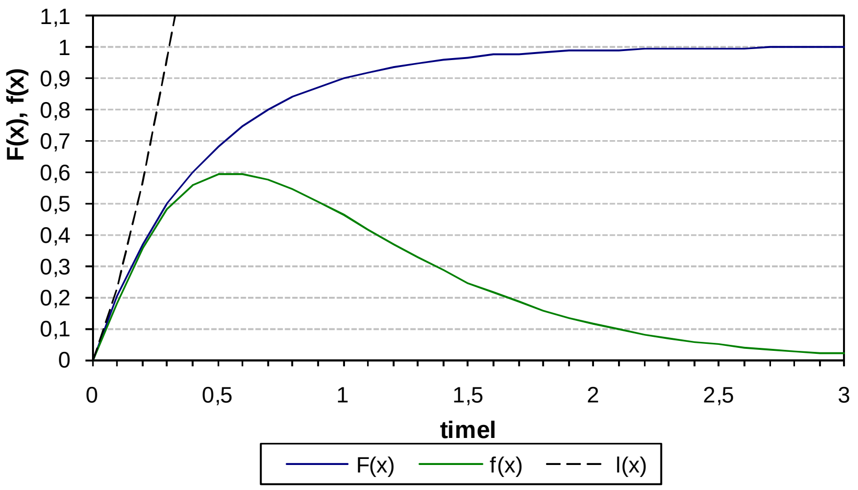


Figure 2.18 Weibull distribution (λ=1, a=3)

Figure 2.18 displays the PDF (*f(t)*) and the CDF (*F(t)*)of a Weibull distribution, for an increasing failure rate function. Because of its flexibility, the Weibull distribution is commonly used to model the wind speed of wind energy systems at different areas and altitudes.

The following three graphs describe the shape and scale parameters in more detail and thus provide a better understanding of their influence and their applicability.

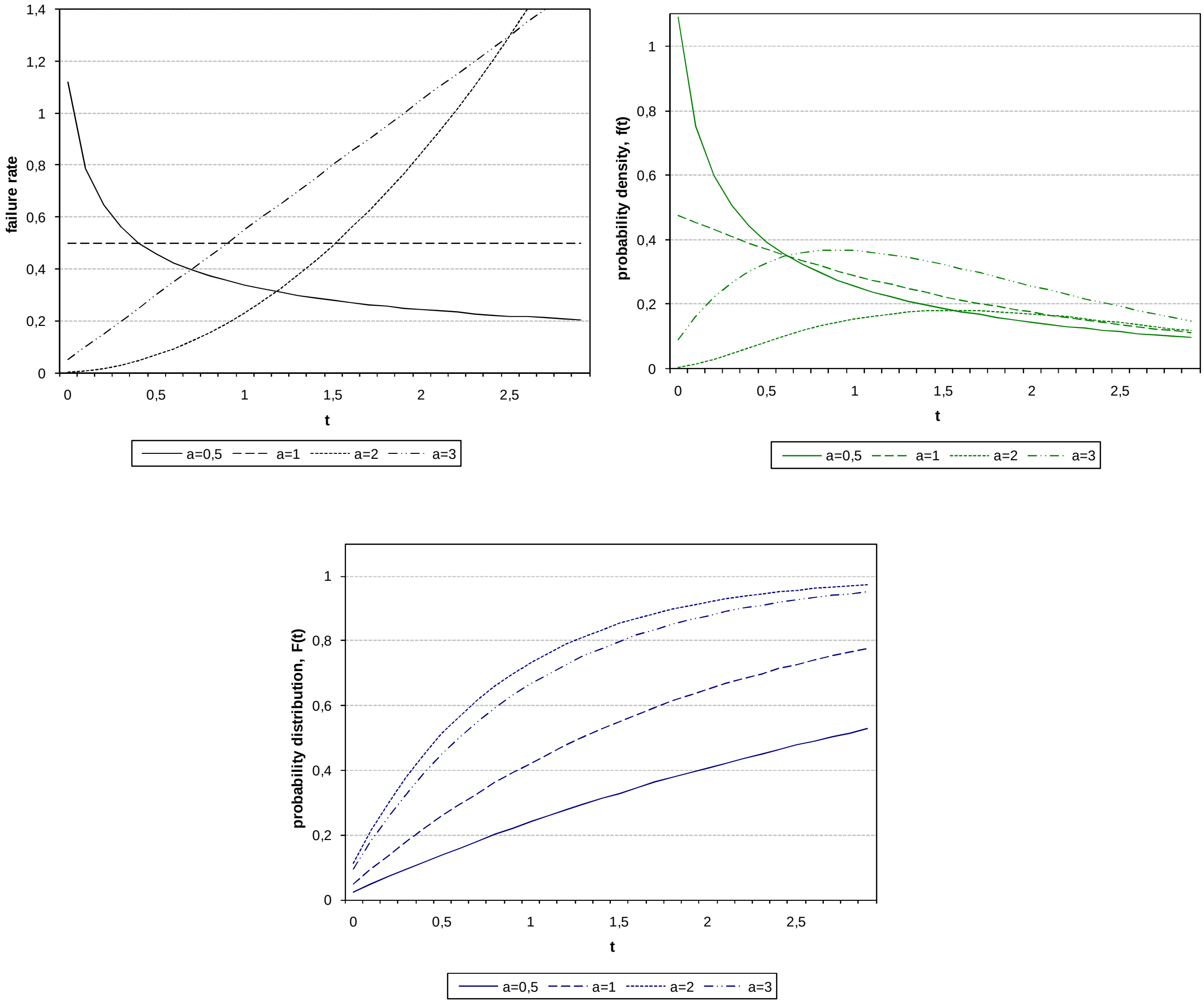


Figure 2.19 Behaviour of the Weibull distribution at different shape parameter settings (λ and α)

It is important to point out, that the failure rate function is a function of the shape parameter α and therefore discontinuous. This can be seen in Figure 2.19 and by looking at equation 2.55. The discontinuity of the failure rate function is important to be aware of, since for example α=0,9999, α=1 and α=1,0001 will provide significantly different failure rate functions. (see the first graph in Figure 2.19) The related PDF (*f(t) green*) and CDF (*F(t) blue*) are also shown in Figure 2.20. Due to the discontinuity of the failure rate function the Weibull distribution is one of the most important distributions in engineering. Regarding electrical components and their various life time distributions, the Weibull distribution is commonly used to model the burn-in period and more significantly the wear-out period, were failure occur because of ageing mechanisms. This concept will be discussed in more detail in subchapter 4.1 (Lifetime of Electrical Components, page 59ff)

2.3.2.6 Availability

Availability is one of the most important measures in reliability theory. There are various kinds of availabilities. (Pointwise, interval, limiting interval, multiple cycle...etc.) [38][44][25] A general valid definition of availability is given as follows:

The ability of an item, to perform its required function at a stated instant of time, or over a stated period of time.(under aspects of its reliability, maintainability and maintenance support) (See Figure 1.3, page 2.)

The mathematical concept of availability is defined by:

$$A(t) = P(S(t) = 1) \tag{2.58}$$

The above equation provides the probability that the item is functioning at time *t*, where *S(t)* denotes the state variable. Furthermore it can be distinguished between availability at time t (*instantaneous availability A(t)*) and the average availability (*mean and asymptotic availability A*).

<u>Instantaneous Availability:</u>

$$A(t) = R(t) + \int_0^t R(t-x)\,\mu(x)\,dx \tag{2.59}$$

The following equation can be obtained by means of Markov-process or Laplace-transformation but only if the times to failure and the times to restoration are exponentially distributed.

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} \cdot e^{[-(\lambda + \mu)\cdot t]} \tag{2.60}$$

<u>Mean Availability and Asymptotic Availability:</u>

In general, availability is immediate readiness for use. The mean availability denotes the mean proportion of time the item is functioning. Only the mean availability is considered and calculated as shown below [29]

$$\overline{A}(t) = \frac{\sum_{i=1}^{n}(uptime)}{(t_2 - t_1)\cdot n} \qquad 0 \le t_1 \le t_2 \qquad n\ldots\text{number of items} \tag{2.61}$$

In this context $\overline{A}(t)$ denotes the mean availability and not its complement (unavailability).If the item is repairable and it can be assumed as ‘as good as new’ after each repair or restoration every time it fails, the average availability becomes the asymptotic availability (for long observation times). See equation 2.61 and 2.63.

$$A = \lim_{t \to \infty} A(t) = \frac{MUT}{MUT + MTTR} \qquad \textit{for IOI} \tag{2.62}$$

$$A = \frac{MTTF}{MTTF + MTTR} \qquad \textit{for COI} \tag{2.63}$$

The asymptotic availability of items with different operation modes can be obtained by equation (2.62) for intermittent operating items (*IOI*) and with equation (2.63) for continuous operating items (*COI*). The concept of IOI and COI and their different operation modes was discussed in more detail in subchapter 2.2.1 p.12ff

It should be pointed out here, that the above equations only evaluate the probability of availability and not the exact down time. This common misunderstanding should become clear by looking at previously state, mathematical definition *P(S(t)=1)* (equation 2.58)

If the time to failure and the time to restoration (*MTTF, MTTR for COI*) follow an exponential distribution, equation 2.59 can be used to calculate the mean availability.

$$A = \frac{\mu_R}{\lambda + \mu_R} \tag{2.64}$$

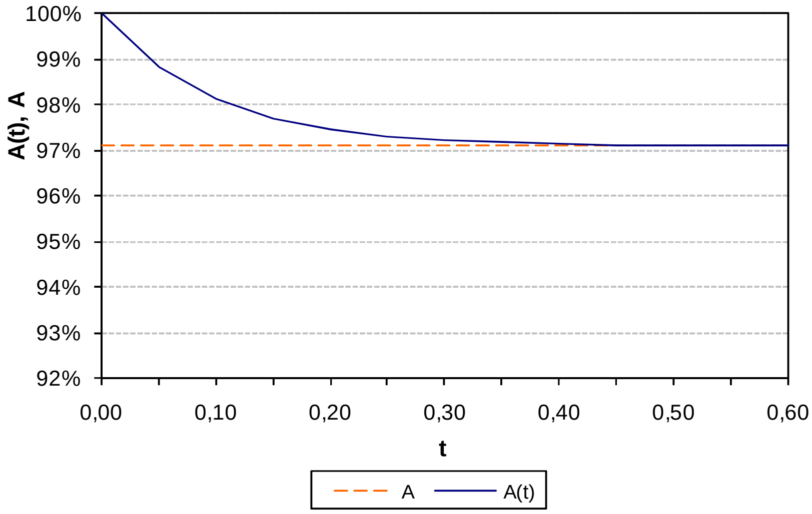


Figure 2.20 Availability of an item with exponential life and repair time (λ=0,3, μ=10)

Figure 2.20 shows the mean availability (*A*) (2.64) and the instantaneous availability (*A(t)*) (2.60) of a component with exponentially distributed repair and failure rates. It can be seen that the instantaneous availability becomes the mean or asymptotic availability for large values of *t*. Hence for long periods of observation the availability can be calculated using equation (2.64). However, because of the time dependent failure rate of electrical components a more accurate calculation method should be considered. (See 4.1 Lifetime of Electrical Components, p.59) Since the availability is the proportion of time in a given period during which the item is able to fulfil its required function, its complement (the unavailability), denoted as *U(t),* is defined by:

$$U(t) = 1 - A(t) \tag{2.65}$$

The unavailability is also known as the *forced outage rate* (*FOR*) of an item or system.

2.3.3 Reliability of Systems

The previous section 2.3.2 focused on single items and how to evaluate their availability in a quantitative way, on a single stochastic process basis. How to combine multiple stochastic processes and therefore, how to evaluate whole systems (set of items) will be explained in the following subchapter. Several methods are used to evaluate the reliability and availability of more than just one item [38]. The most common ones are the *failure mode and effect analysis* (*FMEA*), *fault tree analysis* (*FTA*) and *reliability block diagrams* (*RBD*). A short introduction on how to apply the different methods is carried out over the next few pages.

Reliability Block Diagrams

Reliability block diagrams (*RBD*) are success-oriented networks describing the logic connection of components according to their physical function and not according to their structural layout. Each component of the system that should be evaluated is illustrated as a block, see Figure 2.21. It is important to note, if the system has more than just one function, each function must be modelled and evaluated individually. RBDs are must suitable for reliability evaluations of non repairable items, or repairable items with very low MTTR and where the order in which the failures occur is not important. When the systems are repairable (MTTR cannot be neglected) and the order in which failures occur is important, Markov methods (Markov-chains) are usually more suitable [44].

- <u>Series Systems</u>

$$R_S(t) = R_1(t) \cdot R_2(t) .....R_n(t) = \prod_{i=1}^{n} R_i(t) \tag{2.66}$$

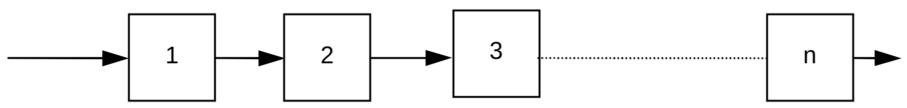


Figure 2.21 RBD series system

For a system with a certain number of serial components (i), the average failure rate, average outage time and average annual outage time are defined by the following equations.

$$\lambda_S = \sum_{i=1}^{n} \lambda_i \tag{2.67}$$

$$r_S = \frac{\sum_{i=1}^{n} \lambda_i \cdot r_i}{\lambda_S} \tag{2.68}$$

r = MTTR

$$A_S = 1 - \sum_{i=1}^{n} \lambda_i \cdot r_i \tag{2.69}$$

The index S denotes a serial system.

- Parallel Systems

Within a parallel system all components must fail in order to cause an outage of the whole system. Also in case more components fail, an intermediate level of availability is attained. For a system with parallel, independent components, the following equations define the average failure rate, the average outage time and the average annual unavailability.

$$R_S(t) = 1 - Q_S(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \qquad \textit{Q.... unreliability} \tag{2.70}$$

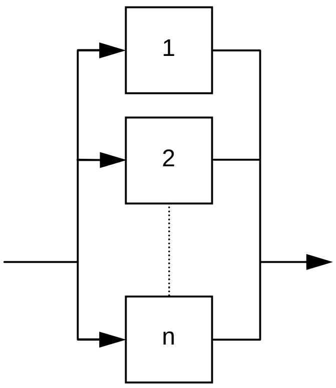


Figure 2.22 RBD parallel system

$$\lambda_P = U_P \sum_{i=1}^{n} \mu_i \tag{2.71}$$

$$U_P = 1 - A_P = \prod_{i=1}^{n} \frac{\lambda_i}{\lambda_i + \mu_i} \tag{2.72}$$

$$r_P = \frac{U_P}{\lambda_P} \tag{2.73}$$

Index P denotes the parallel system.

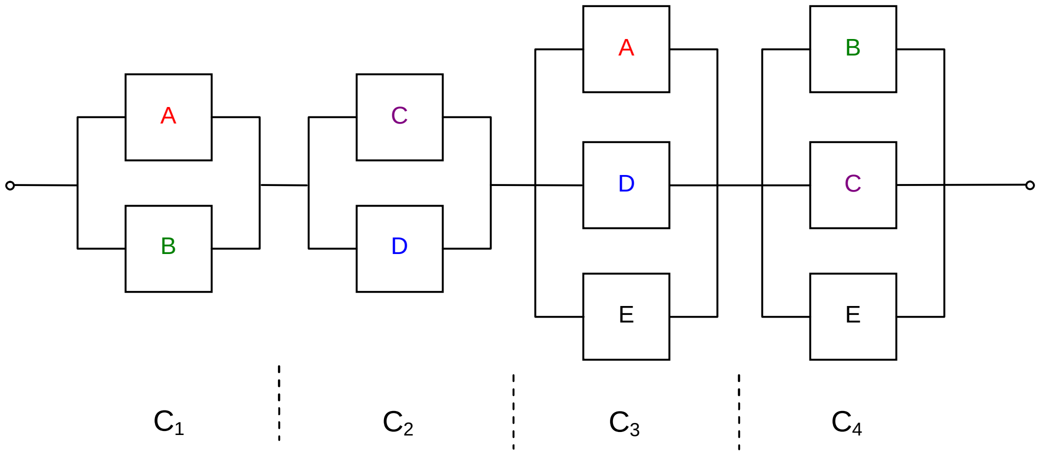
It is obvious that in reality an electrical power system does not only consist of series or parallel connected components. In order to calculate the reliability parameters of combined systems either the S*ystem Reduction Method* or more accurate the M*inimal Cut Set Method* can be applied. The Minimal cut set method can be implemented very easily to any electrical power system layout and benefits from the minor calculation effort.

A short introduction of how to apply the minimal cut set method is given below.

Minimal Tie and Minimal Cut-Set Method

A cut set is a set of system components which, when failed, causes failure of the system. That means that this set of components must fail in order to get the whole system to failure. The minimal cut set is therefore the minimum subset which can cause system failure, but only if every component of the subset is in the failure mode [5]. The tie set method is the complement of the cut set method. Both methods, when implemented with reliability block diagrams are equally to a parallel and series structure.

Example:



C_x…cut set number x

Figure 2.23 Minimal cut sets

The minimal cut sets from the reliability block diagram in Figure 2.23 are listed in the table below. Since the minimal cut sets are always represented by a parallel structure, the unreliability (Q) is used to evaluate the whole system in order to simplify the calculation effort.

Number of minimal cut set	Components of the cut set	Cut Set #
1	A B	C_1
2	C D	C_2
3	A D E	C_3
4	B C E	C_4

Table 2.3 Minimal cut sets of figure 4.4-3

$$Q_S = P(C_1 \cup C_2 \cup C_3 \cup C_4) \ldots\ldots \tag{2.74}$$

$$Q_S = \sum_{i=1}^{n} P(C_i) \ldots\ldots\ldots\ldots\ldots\ldots P_S = 1 - Q_S \tag{2.75}$$

Relationship between Reliability Block Diagrams and Fault Trees [5]

The Top-Event of the fault tree denotes the system failure condition. The events E_x that lead to the top event are connected to the top event through a logic gate. The construction of a fault tree always starts with the top event followed by the first level event which expresses for example the prime fault causes of the system. Figure 2.26 - Figure 2.27 show some basic fault trees which were established only by AND and OR gates. For further information see [44] and [5].

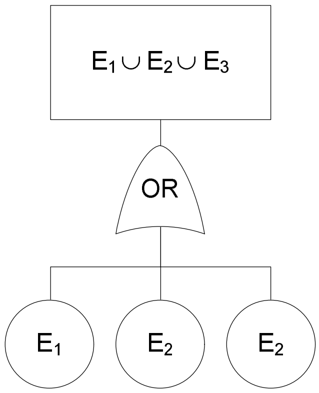


Figure 2.24 Fault tree for a series structure

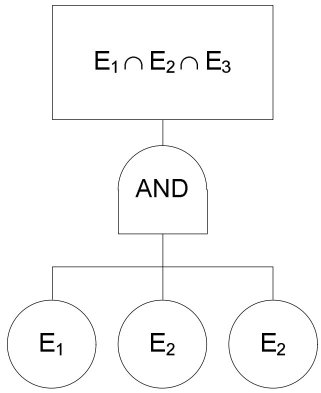


Figure 2.25 Fault tree for a parallel structure

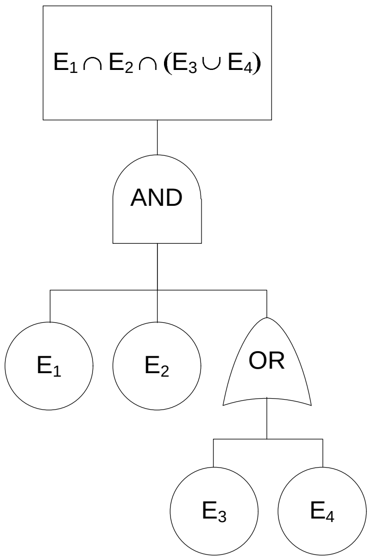


Figure 2.26 Fault tree for a combined structure

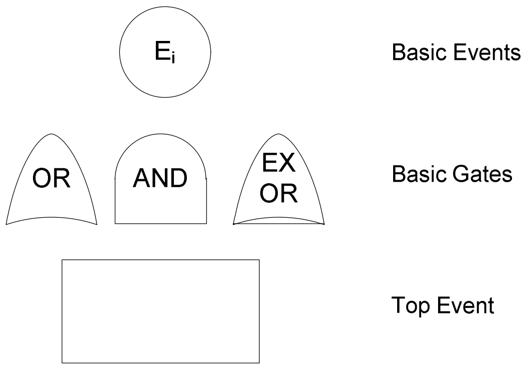


Figure 2.27 Basic fault tree (metric) shapes

<u>Simple rules when constructing fault trees:</u>

- An OR gate expresses system failure if any of the lower level failures occur (Series Structure) The unavailability of the subsystem is the sum of the device unavailability's.
- An AND gate is used if all of the lower levels failure have to occur in order to obtain a system failure. The unavailability of the subsystem is the product of the items

unavailability. Used for redundancy.

- If Top event is in the form of 'System fails to operate' event data in terms of unavailability should be used.

For further information on qualitative evaluation methods see [44],[38],[33],[9],[8] and [5].

2.3.4 Summary of Definitions and Equations

This summary is intended to give an overview of the most important availability and reliability parameters and how to calculate them. The equations in Table 2.4 Summary of definitions' are used in the subsequent chapters to evaluate significant electrical components regarding their availability. It should be noted, that the following equations are based on exponentially distributed reliability data.

Calculated Data	Equation
A , availability	$A = \frac{MTTF}{MTTF + MTTR}$
λ, failure rate [1/yr]	$\lambda = \frac{N}{T} = \frac{1}{MTTF}$
MUT , mean up time [h]	*see Figure 2.28 Calculation example*
MDT , mean down time [h]	*see Figure 2.28 Calculation example*
$MTTF$, mean time to failure [h]	$MTTF = \frac{T}{n} \approx \frac{1}{\lambda}$
$MTBF$, mean time between failures [h]	$MTBF = MTTF$ [2]
$MTTR$, mean time to restoration [h]	$MTTR = \frac{R\,dt}{n} \approx \mu$
$MTTM$, mean time to maintain [h]	*see appendix D*
$R(t)$, reliability	$R(t) = e^{-(\lambda \cdot t)}$

Table 2.4 Summary of definitions

Interpretation

In subchapter 2.2 the concept of stochastic processes was introduced. It was shown, that the probability of the component being in a particular state is equal to the proportion of time the component remains in the required state (*MTBF, MTTR*) times the state transition rates (μ λ) [44]. The relationships between the different lifetime indices are graphically illustrated in Figure 2.28.

[2] This can be assumed due to the fact that $\lambda << \mu$, as stated in chapter 2.3.2 (Reliability of Components).

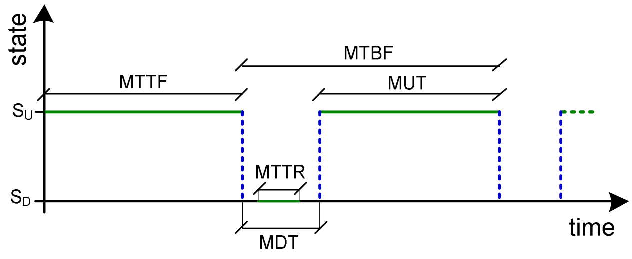


Figure 2.28 Calculation example

$$A = \frac{T_U}{T_U + T_D} = \frac{MTBF}{MTBF + MTTR} \quad \rightarrow \quad A = \frac{T_C - \lambda \cdot r}{T_C} \tag{2.76}$$

T_C…calculation period (e.g. 1 yr)

Equation 2.77 will be used to calculate the availability of components and systems within this investigation. The particular restrictions that were made to ensure the accuracy of this equation its application to electrical power systems are summarized in subchapter 2.6.

2.4 Cost-Benefit Analysis

There are four basic methods to determine whether an investment is profitable or not. The *net-present value method* (*NPV*), the *annuity method*, the *internal rate of return* (*IRR*) method and the *payback period* (*cash recovery, amortisation*...etc.) These methods are part of dynamic investment calculation methods, dynamic because the compound interest factor (2.77) is taken into account. Within the next subchapter, these methods and their application to electrical power systems in general and wind energy systems in particular, will be introduced very briefly.

2.4.1 Net Present Value and Internal Rate of Return

In order to ensure the profitability of a specific project investment the interest rate of an investment should be at least as high as its expected rate of return (yield) of. The corporate costs of capital are equivalent to the rate of return and may be classified into equity capital and dept capital. In order to estimate if a certain investment should be undertaken, the weighted average cost of capital (WACC) will be calculated.. The *WACC* are thereby equal to the least rate of return of the investment. For further information on how to calculate the *WACC,* see [49]. At the beginning of 2010 the Energiekontor AG[3] issued corporate bonds at an interest rate of 6%. The *WACC* can be obtained by weighting the equity and debt costs and amount to 6.78% [66]. This seems to be a realistic value for the interest rate. However, for large investments the *WACC* should be evaluated individually because of their high risk

[3] **Energiekontor AG** is one of Europe's first company developing, realising and operating wind power projects. http://www.energiekontor.de/

relation. Generally, in order to take the inflation into account the real interest rate should be used. Current Inflation in Germany: e=1,3% (10-2010)[4]

$$i = r - e \quad \text{in [\%]} \tag{2.77}$$

$$CIF = (1+i)^n = q^n \tag{2.78}$$

i real interest rate in %
e inflation in %
r nominal interest rate in %

In general, the *compound interest factor* (*CIF*) in equation 2.78 can be used to evaluate the *present value* (*PV*) of time dependent cash flows. For example, the following equation shows the PV of a future payment (S_n) at a certain discount rate (q^{-n}).

$$PV = S_n \cdot \frac{1}{(1+i)^n} = S_n \cdot q^{-n} \tag{2.79}$$

At equal annual costs, the above equation simplifies to:

$$PV = S_n \cdot \frac{(1+i)^n - 1}{(1+i)^n \cdot i} \quad \rightarrow \quad S_n = X_0 \cdot \beta \tag{2.80}$$

Where the character β denotes the *present value factor* (*PVF*).

The concept of present value of time dependent payments is graphically illustrated in Figure 2.29, where the PVF is shown at different interest rates and over a period of 40 years.

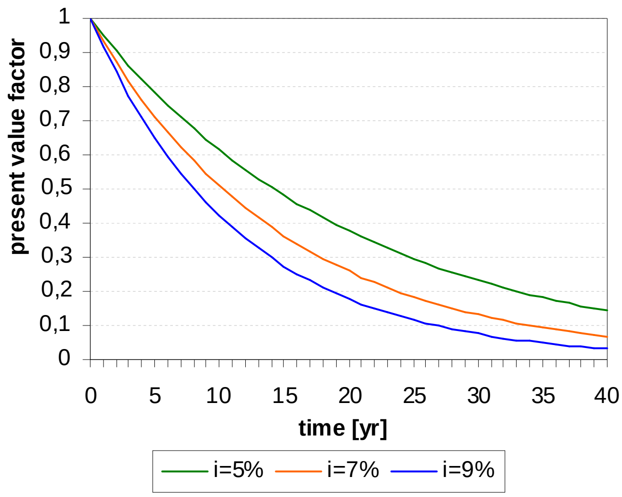


Figure 2.29 PVF at different interest rates

It is obvious that the if the interest rate is high future payments or costs result in an low present value. Therefore in case of high interest rates the life cycle costs of components are lower and investments in general should be taken at a later date

[4] Reference: Federal statistical office Germany. http://www.destatis.de/

With the present value factor future payments can be discounted to a reference date and furthermore the calculated present values will be summarised in order to obtain the *net present value* (*NPV*). The net present value is the value of a payment at the beginning of a project, which is stated at the reference time *t=0*.

Net Present Value

The *net present value (NPV)* is the difference between the sum of all present values of outgoing payments and the sum of all present values of incoming payments over a certain time interval. It can be calculated by the following equation:

$$NPV = -I_0 + \sum_{n=1}^{N} \frac{S_n}{(1+i)^n} \tag{2.81}$$

I_0	*investment*
S_n	*incoming payments*

If the net present value of an investment is beyond or equal to zero, the outgoing payments (investment) are less than the incoming payments (revenue) within the time interval, hence the investment is profitable. Therefore if the NPV is less than zero, the investment will not be profitable.

Capital Recovery Factor

The *capital recovery factor* (*CRF*) a certain amount of money (e.g. investment) into equal, annual parts by taking the compound interest factor *CIF* and the time interval (*n*) into account.

$$CRF = \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \tag{2.82}$$

$$I_A = I_0 \cdot CRF = I_0 \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \qquad \textit{equal annual costs} \tag{2.83}$$

The *CRF* can be interpreted as the amount of equal incoming payments to be received for *n* years such that the total *NPV* of all payments is equal to are greater than zero. The *CRF* is equal to the sinking fund debt plus the interest rate, or in other words it is the inverse of the present value factor *PVF.*

Internal Rate of Return

The *internal rate of return* (*IRR*) of an investment is defined as the discount rate that results in a zero NPV.

$$NPV = \sum_{n=1}^{N} \frac{S_n}{(1+R)^n} - I_0 = 0 \quad \rightarrow \quad NPV = S \cdot \sum_{n=1}^{N} \frac{1}{(1+R)^n} - I_0 = 0 \quad \rightarrow \tag{2.84}$$

$$S \cdot Q(n,R) = I_0 \tag{2.85}$$

The IRR can be obtained by solving equation (2.84) with respect to R. This calculation can be difficult, therefore a simplification is made by setting S_n (annual revenue) constant. Since wind farm projects have almost constant annuities this simplification is valid. If the values of Q and n are given the *IRR* can be found in economic tables.

From the previous explanations regarding basic investment analysis methods the following simplifications weather an investment is profitable or not, can be derived:

- If the NPV is greater or equal to zero the undertaken investment is profitable and visa versa.
- By looking at equation 2.84, the NPV is equal to zero if $i=R$. The *IRR* is always constant and the *NPV* will be negative for all $i>R$ and positive for all $i<R$. Hence R must be greater than i in order to obtain a profitable investment. If more investment alternatives have a *NPV* greater than zero, the investment with the highest *IRR* should be undertaken [49].

Calculation Period of an Investment

Every technical product has its useful lifetime and therefore every investment has its useful lifetime as well. Electrical power system components have different lifetimes according to their required physical function, their purpose and their aging characteristic. The physical life of a component is equal to the calculation period of an investment. The German federal ministry of finance provide specific AfA-tables[5] for most industrial branches. The physical life of significant components from the electricity supply sector is listed in Table 2.5.

Component	Useful lifetime
Transformer	20 years
MV cable	40-45 years
MV Overhead lines	30-40 years
Substations	25-35 years

Table 2.5 Useful lifetime according to BMF-AfA

To evaluate a wind farm project regarding its profitability, the physical life of the project is expected between 20 and 25 years.

[5] Abschreibungstabelle für allgemein verwendbare Anlagegüter
http://www.bundesfinanzministerium.de/nn_96040/DE/Wirtschaft__und__Verwaltung/Steuern/Veroeffentlichungen__zu__Steuerarten/Betriebspruefung/AfA-Tabellen/005.html

2.4.2 Application to Reliability Engineering

The degree of reliability and the size of the investment for an electric network are closely related. However, the relation between the investment costs and the degree of reliability of the system is not linear. The first measures taken to increase the reliability within a system can be made with a relatively small investment. For each additional quantity of reliability a larger investment must be made. This is illustrated in Figure 2.30.

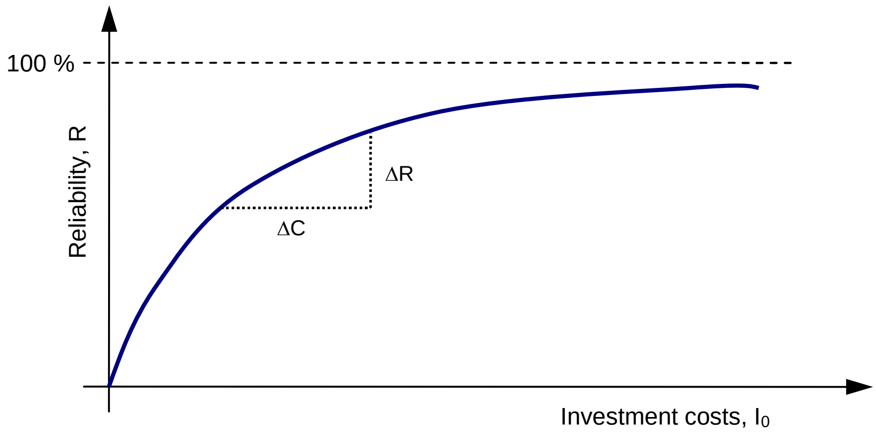


Figure 2.30 Incremental reliability (ΔR) with respect to investment costs (C_0)

A level of 100% reliability is from a technical point of view possible but not profitable because of the large logistic and financial effort that has to be made. The reliability of a technical system should be as high as possible with a limited amount of investment. Figure 2.31 shows the relation between investment and interruption costs at different levels of reliability.

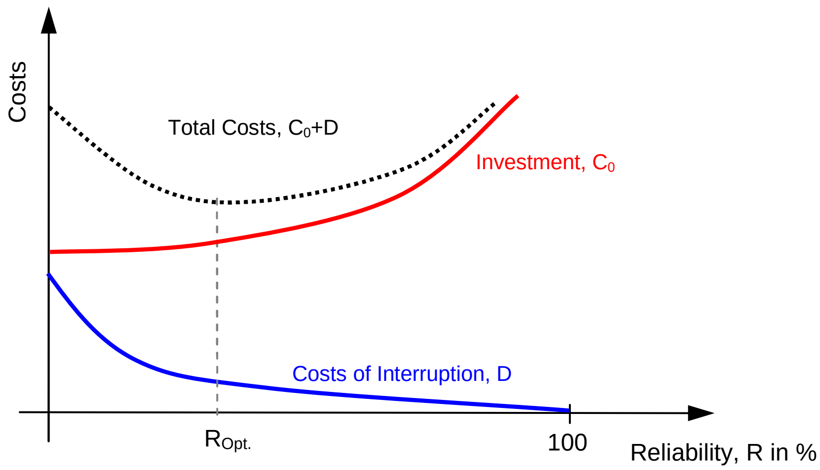


Figure 2.31. Relation of investment and interruption costs

This concept is a typical optimisation problem regarding reliability with a budget restriction. Although the reliability of a certain layout is of most interest, the down time and more accurate the repair time (MTTR) of components is also an essential parameter. The interruption costs are subdivided into costs that increase with time, like lost revenue, material or penalties, and costs that decrease with respect to time. These considerations together with general aspects about direct and indirect costs of interruptions are discussed in detail in [25], [29], [32] and [34]. The typical relationship between availability and *life cycle costs* (*LCC*) for the operation and maintenance phase is shown in Figure 2.32. Whereas the related costs are classified into preventive and corrective maintenance costs, as well as consequential costs.

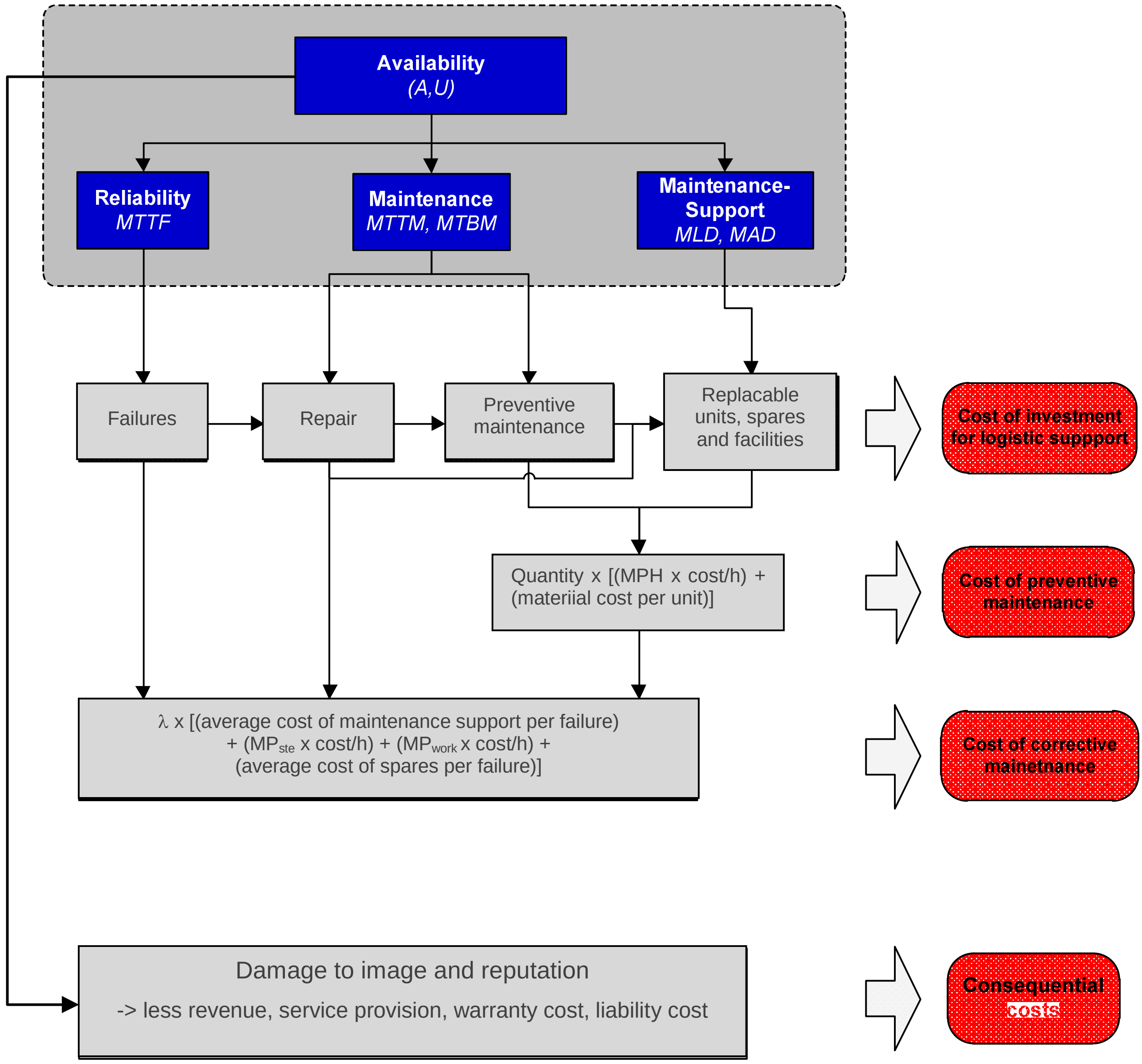


Figure 2.32 Life cycle costs in terms of availability [25]

Investment for Logistics and Support

In case of a failure of the component or system it is a vast interest of the company to repair the failure as soon as possible in order to keep the interruption costs as low as possible. Since most failures occur on parts of components that can be repaired or replaced very quickly at low costs, it is important that a certain amount of spare parts and replaceable units (e.g. bushings, cable joints, switches....etc) should be in stock. According to [67] the cost of investment for logistic support (mainly spare parts) of a company producing wind energy converters should be round about three million Euros in order to meet the requirements.

Maintenance Costs

For preventive maintenance:

$$C_M = Q \cdot (MP \cdot C_{MP} + K) \tag{2.86}$$

C_M Maintenance costs
C_{MP} Costs of manpower per hour
Q Quantity
MP Manpower
K Material costs per unit

For corrective maintenance:

$$C_M = \lambda \cdot [C_{MS} + (MP_S \cdot C_{MP} + MP_W \cdot C_{MP}) + C_{AF}] \tag{2.87}$$

C_{AMS} average costs of maintenance support per failure
C_{AF} average costs per failure
MP_S Manpower site
MP_W Manpower work

The average costs of manpower and electrical components (quantity) are available at 9. Appendix-E.

Consequential Disturbance Costs (Damage Costs)

When a product or service becomes unavailable, a series of consequential costs may be incurred. These costs normally include warranty costs, liability costs, loss of revenue and costs for providing an alternative service.

- Lost revenue

As previously mentioned (subchapter 2.4.3.1, p.41), the expected energy not supplied is equal to the lost energy revenue due to component or system failure. For the lost financial revenue influences like different countries and their subsidies (feed-in tariffs), direct marketing, avoid grid charges....etc. have to be taken into account.

- Warranty costs

The reliability, maintainability and maintenance support characteristic of a component or system is of great influence to the warranty costs of that particular item. Suppliers are able to affect these characteristics during the projects development and production phase, thus affecting the warranty costs. Warranty claims usually contain a limited number of conditions and apply only for a limited period of time. The difference between guarantee and warranty will be discussed in more detail in subchapter 6.2. Warranty claims normally don’t include protection against consequential costs due to component unavailability. Warranties or guarantees should always go hand in hand with a specific service contract, where the supplier or a stated subcontractor performs the required preventive and corrective maintenance actions. In this case, the supplier is also motivated to optimise his system in order to keep the additional costs low. This concept is already common practice at REAG.

Availability or performance guarantees are only valid if an additional service contract is included

- Liability costs

A liability will arise where, for example, a supplier fails to comply with his legal obligations [25]. Liability costs are also important for new products for which risks involved may not be fully apparent and/or well understood. Where required, a risk analysis, together with past experience and expert judgement, may be used to provide an estimate of these costs.

In addition, further consequential costs should be identified by applying risk analysis techniques to determine costs of impacts on the company's image, reputation or prestige. In a worst case scenario these impacts can lead to loss of clients.

Equation for calculating damage costs (DC) based on the actual availability of the system

$$DC = \left[\frac{(A_G \cdot E)}{A_{WF}} - E \right] \cdot p \tag{2.88}$$

E	*energy production (seasonal weighted)*
A_{wF}	*wind farm availability (measured, calculated)*
A_G	*guaranteed availability*
p	*electricity price (feed-in tariff, subsidies)*

General equation to calculate the damage costs regarding supply interruptions caused by component induced failures.

$$DC = P_O \cdot [k_P(T_D) + T_D \cdot k_E(T_D)] \tag{2.89}$$

P_0	*Capacity out of service [kW]*
T_D	*Down Time (~MTTR [h])*
k_P	*specific power based outage costs [€/kW]*
k_E	*specific energy based outage costs €/kWh]*

<u>Bonus-Penalty Solution</u>

During the time where the integrated service package (ISP) contract is valid, a bonus-penalty solution for the wind farms actual availability is offered. The mathematical evaluation methods for the liquid damage (LD) and the bonus payments (BP) are given below.

$$LD = (A_G - A_{WF}) \cdot \frac{E}{A_{WF}} \cdot p \tag{2.90}$$

$$BP = \left[(A_{WF} - A_G) \cdot \frac{E}{A_{WF}} \cdot p \right] \cdot 0{,}3 \tag{2.91}$$

LD	*liquid damages*
BP	*bonus payments*

Life-Cycle Costs

The *life cycle costs (LCC)* of electrical components are defined by the following equation.

$$LCC = C_0 + C_E + C_I + \sum_{0}^{n}(C_{PM} + C_{CM} + C_{OP} + C_O + C_R) + C_D \tag{2.92}$$

C_0	*investment costs*	C_E	*cost of erection*
C_I	*cost of infrastructure*	C_{PM}	*preventive maintenance costs*
C_O	*outage costs*	C_R	*costs of refurbishment*
C_D	*costs of disposal*	C_{CM}	*corrective maintenance costs*
C_{OP}	*operational costs (load/no load losses)*		

This equation presents the overhead costs and the variable costs of a component over its lifetime. The costs for infrastructure as well as the costs for refurbishment and disposal will not be taken into account within this investigation. The equations for the corrective and preventive maintenance costs were previously introduced and the operational costs which mainly consist of lost revenue caused by active power losses are discussed in more detail within the reliability modelling subsection. A brief introduction of life cycle costs of relevant grid connection components is given in chapter 4, with a special focus on their variable costs.

2.4.3 Application to Wind Energy Systems

2.4.3.1 Generation Duration Curve

In order to calculate the *expected energy not supplied* (*EENS*) the generation duration curve as well as the *capacity factor* (*cf*) of WECs will be introduced in this subchapter. The generation duration curve displays the time share the WECs operates at a certain level of rated power over a stated period of time. Normally over one year of observation. Figure 2.33 shows the generation duration curve for different wind farm locations.

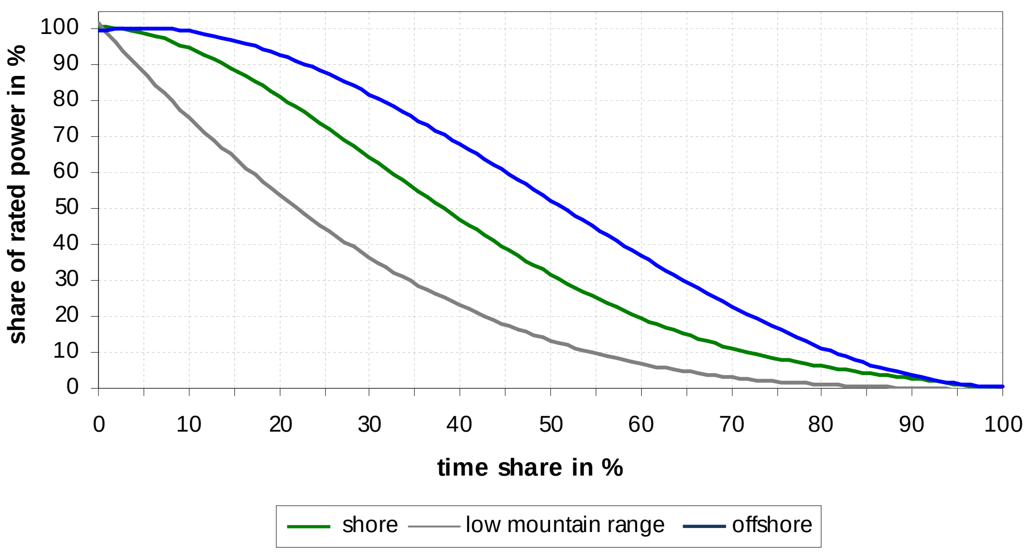


Figure 2.33 Generation duration curve

Two parameters can be used to describe the generation duration curve adequately, the capacity factor and the full-load-hours.

$$TP = P_r \cdot t_c \quad [kWh] \tag{2.93}$$

$$E = \int_{t_1}^{t_2} P(t)dt \quad [kWh] \tag{2.94}$$

Both parameters show the ratio between the energy yield (E) and the theoretical production (TP) during the calculation period (t_c). Thus the capacity factor represents the time share at which the wind farm operates at rated power (P_r). Equation (2.93) to (2.96) are used to estimate the capacity factor.

$$T_{cf} = \frac{E}{P_r} \quad [h] \tag{2.95}$$

$$cf = \frac{T_{cf}}{T_c} = \frac{\int_{t_1}^{t_2} P(t)dt}{P_r \cdot T_c} \qquad [x100 \; in \; \%] \tag{2.96}$$

The capacity factors of different wind farm locations are presented in Table 2.6. These figures present a best case scenario and were calculated by means of the REguard online portal. Whereas influencing factors as different countries, annual variations, down times, power curve…etc. were taken into account.

Location		cf *
A	low mountain range	30%
B	shore	40-50%
C	offshore	50-60%
D	high mountain range	25%

*) Best case scenario

Table 2.6 Capacity factors

In order to calculate the *EENS* in an easy way the above introduced generation duration cure is split up into 4 generation modes. This concept is illustrated in Figure 2.34.

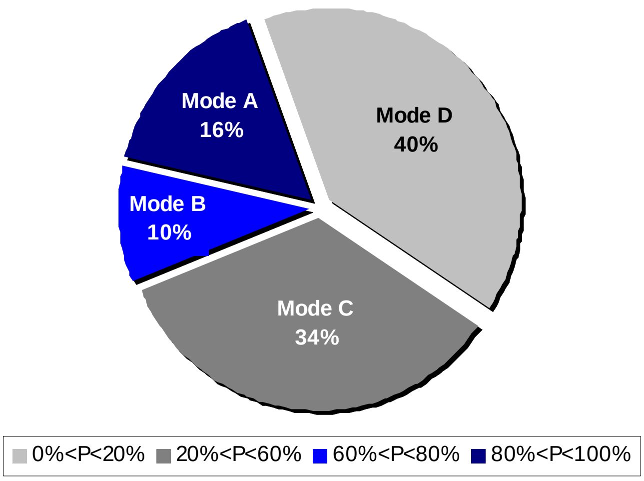


Figure 2.34 Generation modes, shore side

Approximately 70% of the time the wind farm is operating at less than 60% of rated power.The concept of generation modes shall serve as basis for the estimation of active power losses which will be discussed in detail in subchapter 5.3.

As mentioned above the generation duration curve depends on several influencing factors. In order to estimate the different generation modes in an accurate way the project specific wind assessment data should be used. How to calculate the required data from the measured wind data is very briefly introduced below.

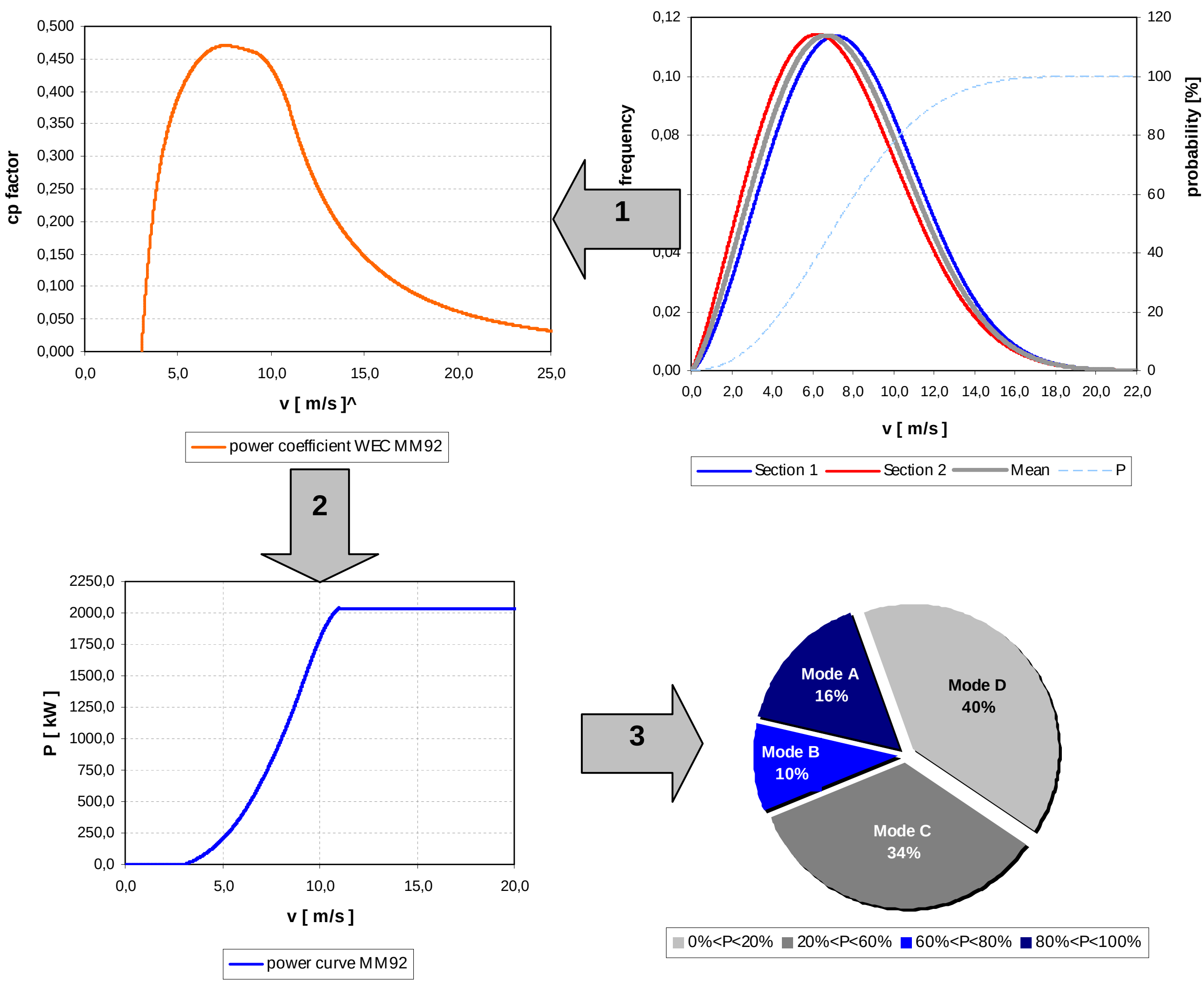


Figure 2.35 Approach for generation modes of different locations

Based on the Weibull distribution of the wind speed the cp factor of the relevant turbine can be calculated. In a next step the power curve is determined. After a convolution between the Weibull distribution and the power curve the relevant generation modes of the WEC can be obtained. It is obvious that the whole process depends on the accuracy of the evaluated wind data of the particular location. However, the wind speed is still the best estimator for wind power project.

2.4.3.2 Seasonal Energy Output Variations

In order to estimate the damage costs in an accurate way the seasonal variations regarding the energy output (yield) has to be taken into account. These variations are not only a function of time, but also a function of location, country…etc. Figure 2.36 below shall give an impression on how strong the energy output of a wind farm with can vary over a period of four years (2006-2010). The mean energy outputs of one month are represented in these figures, whereas the black curve in Figure 2.36 as well as the red curve in Figure 2.37 represent the trend line of the energy output.

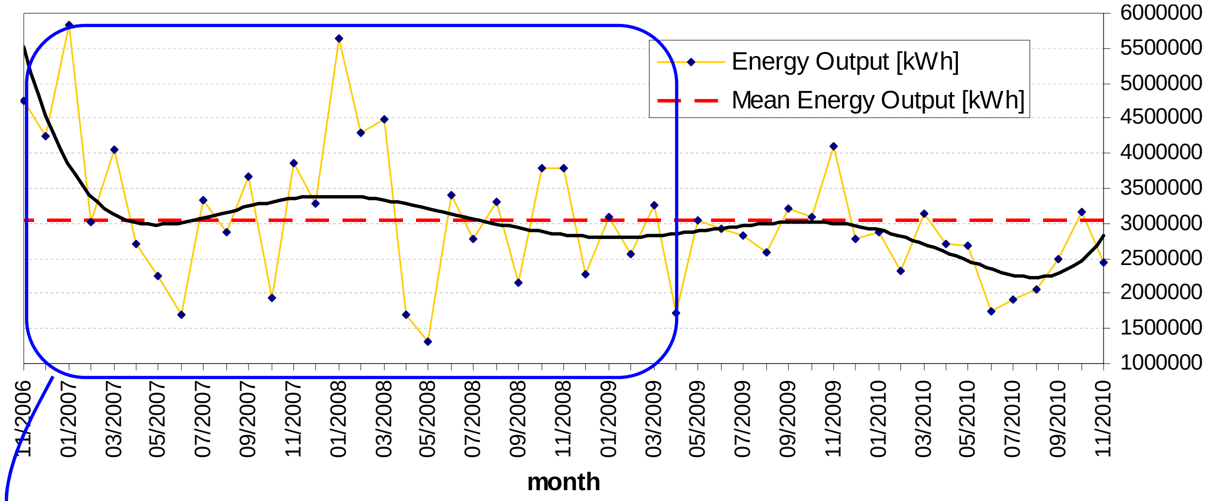


Figure 2.36 Seasonal energy output variation of WF Lübke Koog[6] 06-10

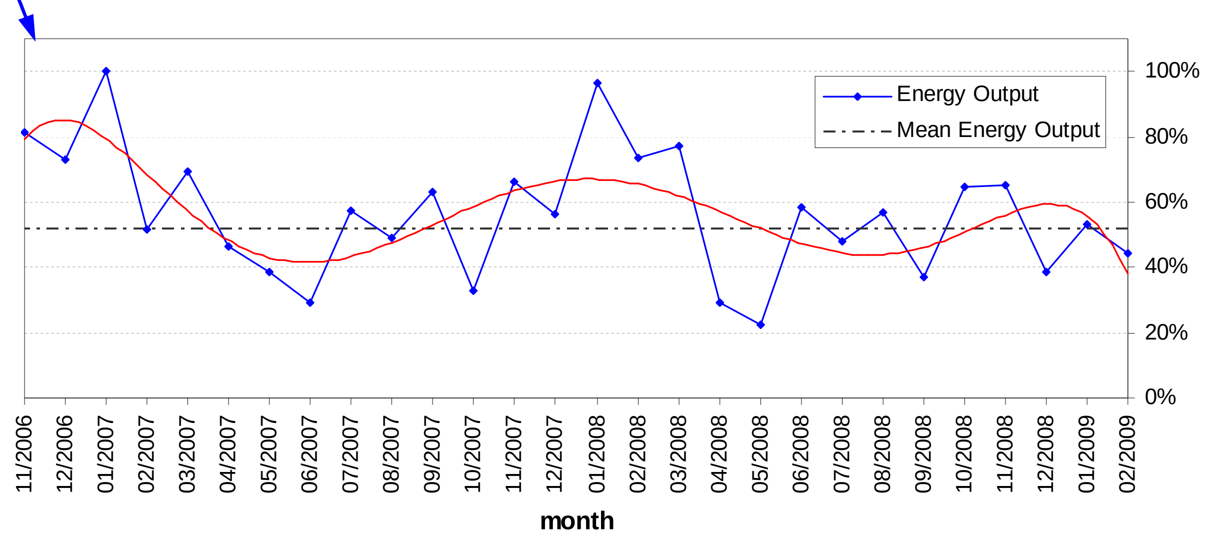


Figure 2.37 Seasonal energy output variation of WF Lübke Koog 06-09

Figure 2.37 provides a closer look at the energy output during the years 2006 to 2009. As mentioned above the seasonal variation has several influencing factors. Therefore the exact

[6] ‚Lübke Koog' is a German onshore-wind farm with one of the highest annual energy revenues. It is located in the north of Germany at the shore of the North Sea, close to the Danish border. The capacity factor of this wind farm is approximately 40%.

relative deviation between operation during summer and winter periods cannot be derived. However, a theoretical approach on how to obtain the deviation factor is presented below.

Interpretation

As mentioned above the seasonal variations are strictly related to single projects. Therefore an exact evaluation regarding time dependent energy output should be done using the measured wind data from the wind farm location.

Why is the energy output and its seasonal variation relevant? The two main wind farm parameters of most interest to the customer are the power curve of the wind energy converters and the availability of the whole system. Now if the actual availability of the WF doesn't meet the guaranteed level the lost financial revenue has to be paid. In order to estimated this liquated damages in an accurate way the seasonal energy output variations have to be taken into account. Furthermore if maintenance times are not included in the availability calculation period, in other words if the time to maintain is considered as system unavailable the maintenance actions should take place in periods with lower energy output.

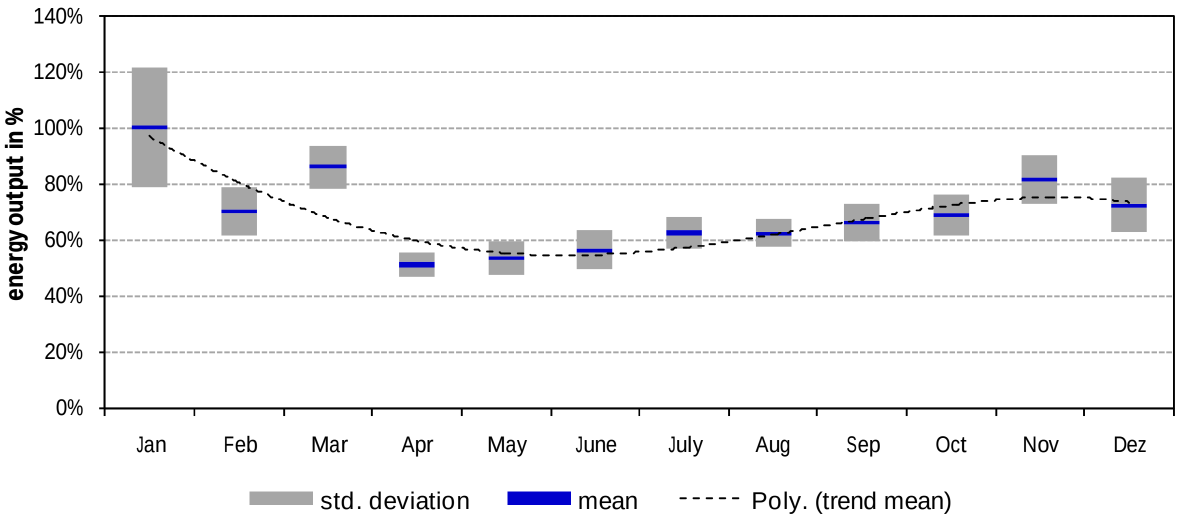


Figure 2.38 Seasonal wind speed and energy output variations

In the previous subchapter, the evaluation of the WECs generation modes and the significance of the wind data were introduced. It should be pointed out that in order to evaluate the seasonal variations in a representative way the wind speed data of locations should be used.

2.4.3.3 Wind Energy Costs

The cost structure of wind energy projects is briefly presented below, in order to get a better understanding of wind and outage related costs.

The main influences on wind energy costs are:

- the mean wind speed
- the power curve of the WEC
- the investment costs, which consists primarily of manufacturing costs of the WEC
- the level of technical availability
- operational costs, basically maintenance costs

The cost structure of large wind farms can be categorized into the following groups:

Investment Costs (C_0):

- Planning, infrastructure, financing ~30% of investment (C_0)
- Cost of WEC (C_{WEC})

Annual Costs:

- Maintenance, Insurance ~4% of C_0
- Credit – Annuity: for i=6% - 8-14% Annuity depends on the calculation period (10-20years)

Annual Energy Revenue:

- 97% availability,~12% technical losses and 5% safety discount:

$$E_{WEC} = P_{r,WEC} \cdot t_c \cdot cf \tag{2.97}$$

- Specific investment regarding annual energy revenue

Operational Costs.

$$C = {}^{C_0}\!/_{E} \tag{2.98}$$

2.5 Failure, Fault and Error

In everyday use the words failure, fault and error almost have the same meaning and therefore are used for similar conditions. However, in engineering disciplines a thorough understanding of signals and systems and their behaviour is needed. In order to evaluate a specific signal accurately a proper definition of the signal states (how the signal can vary with respect to time) and their application is needed. Since the main focus of this investigation is the reliability and availability of components, only the related terms failure, fault and error are discussed in more detail. Figure 2.39 displays a signal (blue curve), how it can vary over time and how it passes through different states.

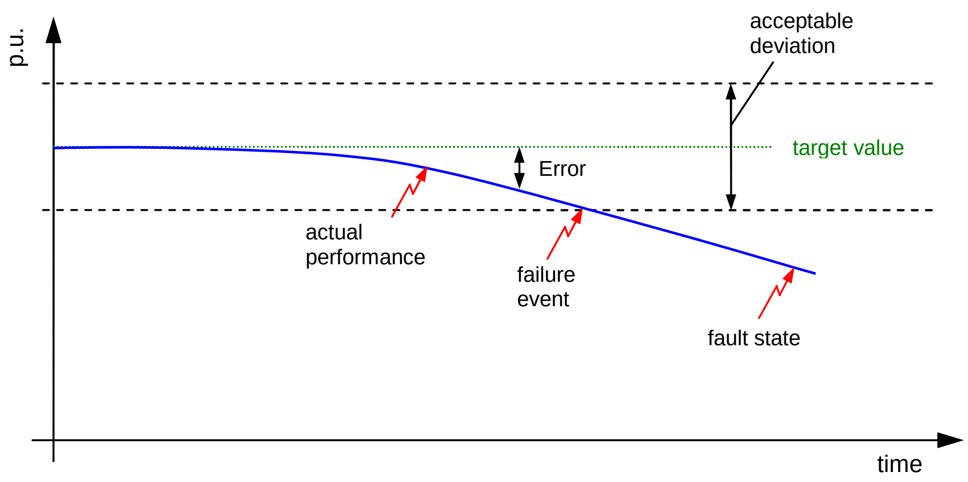


Figure 2.39 Failure, fault and error

Error is the deviation between the actual amplitude and the target value within the acceptable limits (area within the dotted line). A failure on the other hand describes the actual performance at the time the observed value exceeds the given limits. Thus the term failure doesn't refer to an actual state, but to an event. The state, beyond the given limits is denoted as fault.

Basic Faults in electrical power systems are classified in *longitudinal faults* and *transversal Faults.* (see Appendix – D)

Within a wind farm it can be distinguished between three different areas in which a failure may occur:

- HV-Network: *fault ride through* (*FRT*) has to be taken into account.
- MV-Network (Collector System): *FRT* of other WECS has to be considered. Faults have to be cleared selectively in order to protect the WEC and other MV components.
- LV-Network (WEC): Coordination between LV and MV electrical protection to ensure the operation of other WECs during a fault on the LV network.

2.5.1 Common Cause Failures

This type of failure involves the simultaneous outage of two or more components due to a common cause. A main focus of reliability assessments is to highlight this type of failure and its probability of occurrence. If the probability is too high the system should be redesigned. Common mode failures are usually not considered in reliability analysis

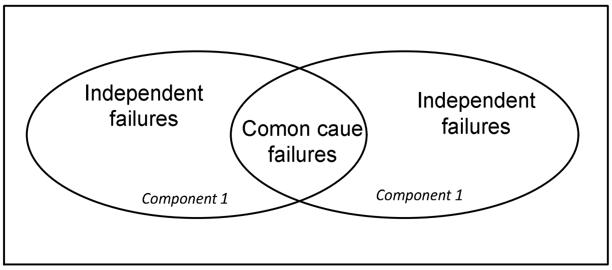


Figure 2.40 Common cause failures

If the failure of any component is not independent of any other, in other words if the failure of components are not mutually exclusive and independent, a common cause failure can be assumed [8]. (See Figure 2.40)

Common cause failures need to be taken into account for redundant systems. The IEEE subcommittee recommend a special common cause factor for electrical power systems applications. This factor will be used in subchapter 0 for the evaluation of redundant power transformer layouts.

2.5.2 Single and Multiple Faults

The probability of occurrence of *k* faults out of *N* (set) within a given period of time can be determined by the Poisson distribution. If λ is the failure rate for a given period of time (t_c), then the following equation applies

$$P(k,t_c) = \frac{(\lambda \cdot t_c)^k \cdot e^{-\lambda \cdot t_c}}{k\,!} \tag{2.99}$$

By looking at equation 2.95 it is obvious, that the Poisson distribution is equal to the exponential distribution for $k=0$.

Probability of occurrence of exactly two faults:

$$P(2) = \frac{(\lambda \cdot t_c)^2 \cdot e^{-\lambda \cdot t_c}}{2!} \approx \frac{(\lambda \cdot t_c)^2}{2} \quad <<< 1 \tag{2.100}$$

If the extension of the grid (e.g. MV collector system) is small the occurrence of multiple failures can be neglected. It can be shown, that the frequency of occurrence of two faults within a time interval of 10 days for the MV collector system is <1%. The time interval was chosen to be 10 days because this represents the worst maintenance case and at the same time is a common time interval for test runs within the commissioning phase. By looking at the reliability figures, the same result can be assumed for MV switchgear and transformers. Since the grid connection of large wind farms is not very complex, compared to, for example, meshed transmission networks, and the failure rate of single components is low, the occurrence of multiple faults within a given time interval can be considered as not relevant.

2.5.3 Types of Faults and their Frequency of Occurrence

The figures are based on the disturbance and availability statistic from the German network [53]. Due to the high rate of overhead lines and the compensated neutral-point treatment of the MV network the frequency of phase to earth faults have to be reconsidered. The statistic distinguishes between faults that lead to an interruption and those who occur but don't affect the function of the system. Since a fault occurs anyway the total number of occurrence is used.

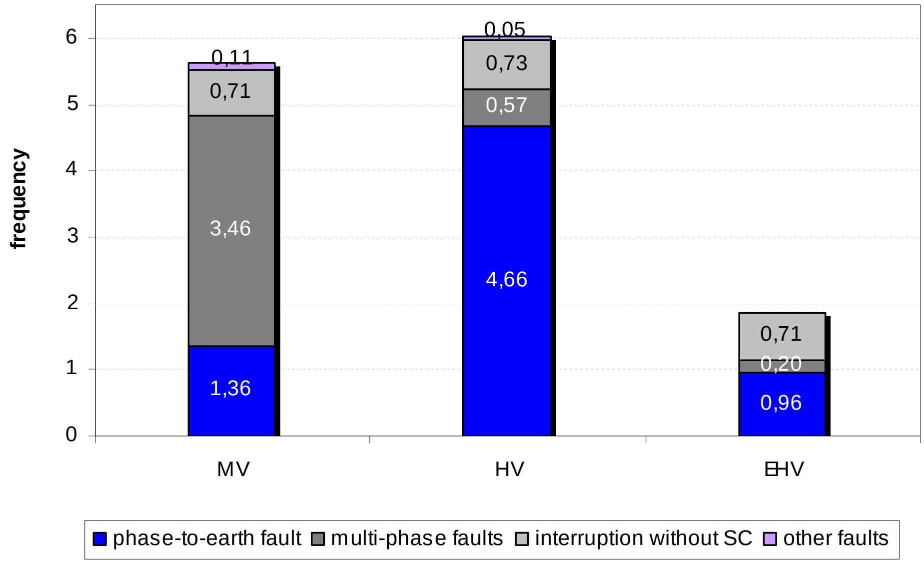


Figure 2.41 Types of faults and their frequency [54]

It can be seen in Figure 2.41 that multiple phase faults and phase to ground faults are the most common faults types within electrical power systems.

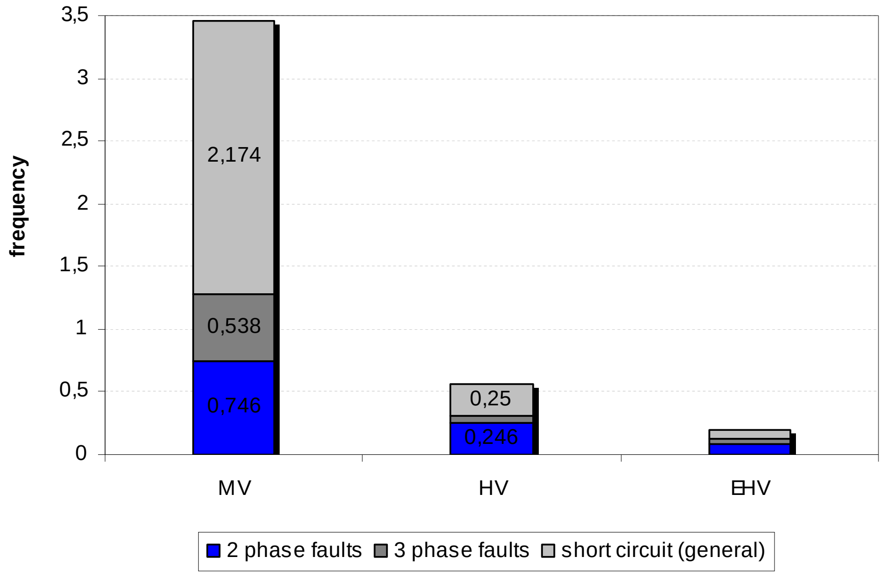


Figure 2.42 Multiple phase faults [54]

The major causes of supply interruptions can be seen in Figure 2.43 without taken any type of short circuits into account.

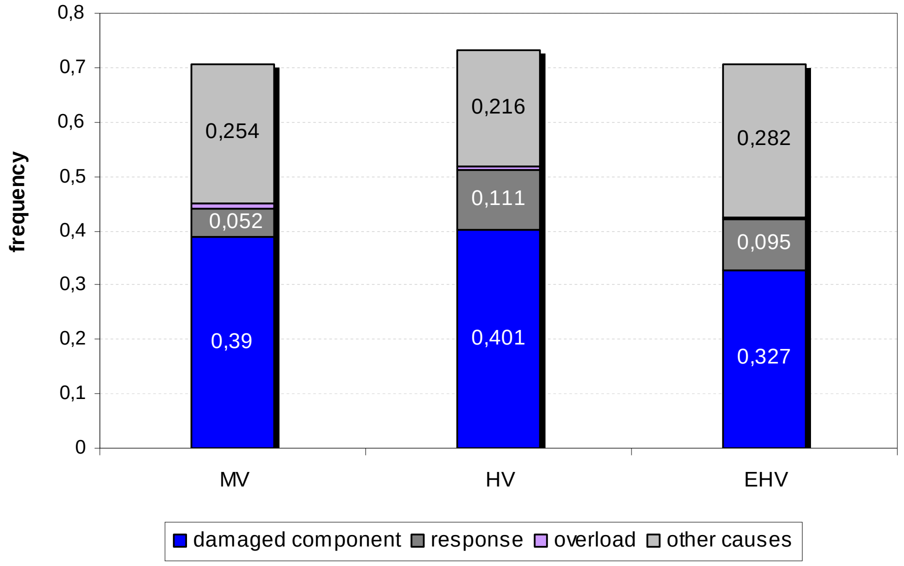


Figure 2.43 Outage causes w/o short circuits [54]

Damaged components that lead to system failure are most likely to happen. Their relative frequency of occurrence can be assumed to be approximately 60%, regardless of the systems voltage level.

As previously mentioned, these figures need to be reconsidered due to the special configuration of the German network. Especially the reliability and failure figures of the MV components are overestimated since they are based on the overall distribution system, which is characterised by an high amount of overhead lines and an arc suppressor coil neutral point treatment.

For further investigations in chapter 4 which focus on the modelling of grid connection components the reliability figures will be revaluated taking unwanted influences into account.

2.6 Restrictions and Assumptions

- Only repairable items with *MTTR*>0 are assumed.

- During the components useful-life period, faults occur at random, which indicates a constant failure rate. Therefore only the exponential distribution function is used to estimate the reliability and availability of components.

- The outage time (*MDT, MTTR*) has an exponential distribution as well.

- As previously mentioned, the failure rate of electrical components is significantly lower than their repair rate ($\lambda << \mu$). The following simplification can be made: *MTTF=MTBF*. (See 2.3.4 Summary of Definitions and Equations p.32)

- The examples and calculations presented in this thesis are based on reliability figures of the German electricity network [53]. Reliability figures from markets in which REpower is operating can be found in the appendix (Appendix C – Reliability Figures).

- In this thesis the terms medium voltage (MV) and high voltage (HV) are referring to 30kV and 110kV. Since the installed capacity of onshore wind farms became larger over the past years the above mentioned voltage levels are common practice nowadays. The MV collector system of offshore wind farms normally operates at the same voltage level (30kV), for the same reasons

3 Reliability Data

To evaluate the reliability of an item in a quantitative way, adequate models as well as accurate data are needed. This section shall give a short introduction on how to obtain accurare reliability data, how to process them and fit them to the adequate model.

Basically there are two major data sources, the electric utilities on the one hand and the manufacturers (subcontractors) on the other hand. In electrical power systems reliability engineering, the use of data from the utility sector is common practise nowadays, not only because of the quantity but also because of their wide range and neutrality. The reliability evaluation and the optimization of components are based on figures from the German power system [53]. For statistical data from other countries as listed below, see Appendix C

3.1 Data Preparation

The easiest method of fitting a set of data to a given distribution function is to directly compute distribution parameters from statistical results. For most distribution function with one or two parameters a reasonable fit can be found by using the mean and variance of the data set.

3.1.1 Method of Moments

In statistics the *Methods of Moments* is used to estimate population parameters like mean, variance …etc. A moment is therefore a quantitative parameter of the shape of a set of data.

The first two moments are the mean and the variance of the set. The sample mean is simply the arithmetic average of a given set of data and is defined as the sum of the set values divided by the set size. (3.1) The mean value is a good point estimate for the expected value.

$$\overline{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad (3.1)$$

n=size of data set
Data Set….[x_1,x_2,…,x_n]

The variance indicates the second moment and is known as the most common way to estimate the dispersion in the data set. It is defined as

$$\sigma^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \overline{x})^2 \qquad (3.2)$$

n-1 – denominator - unbiased

Another parameter for the variation or dispersion of a set of data is the standard deviation.

$$\sigma = \sqrt{\sigma^2} \qquad (3.3)$$

The main advantage of the standard deviation is that it is expressed in the same unit as the set data. According to this the standard deviation is commonly used to estimate the confidence of statistical interpretations.

Additionally, there are two more moments which will not be introduced in this thesis, the *Median* and the *Mode*. (For further information see [3] and [38])

3.1.2 Maximum Likelihood

The likelihood (probability) function for a random sample is the joint probability density function (see Figure 2.2) of the random variables defined as

$$L(\theta; x_1, x_2, ..., x_n) = \prod_{i=1}^{n} f(x_i; \theta) \tag{3.4}$$

The purpose of the maximum likelihood method is to find $\hat{\theta}$ as an estimate of θ such that

$$L(x, \hat{\theta}) \geq L(x, \theta) \qquad -\infty \leq \theta \leq +\infty \tag{3.5}$$

The only value of θ that satisfies this particular inequality is the maximum value of $L(x, \theta)$, denoted as $\hat{\theta}$ called the maximum likelihood estimator of θ [38]. Therefore, to obtain $\hat{\theta}$ the following equation can be used.

$$\left| \frac{\partial \ln L}{\partial \lambda} \right|_{\theta = \hat{\theta}} = 0 \tag{3.6}$$

<u>Example</u>*:*

Given: n…sample of n times to failure,

λ…failure rate (known to be exponentially distributed)

Find the maximum likelihood estimator for λ !

$$L(t, \lambda) = \prod_{i=1}^{n} f(t_i; \lambda) = \prod_{i=1}^{n} \lambda \cdot e^{-\lambda \cdot t_i} = \lambda^n \cdot e^{\left[-\lambda \cdot \sum_{i=1}^{n} t_i \right]_i},$$

$$\ln L = n \cdot (\ln \lambda) - \lambda \cdot \sum_{i=1}^{n} t_i,$$

$$\left| \frac{\partial \ln L}{\partial \lambda} \right|_{\lambda = \hat{\lambda}} = \frac{n}{\hat{\lambda}} - \sum_{i=1}^{n} t_i = 0,$$

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i}$$

According to the above example the point estimate of the failure rate is the number of failures (*n*) divided by the observation time.The maximum likelihood method is the most adequate method for parameter estimation [67].

3.1.3 Chi-Square Test (Goodness-of-Fit Test)

The chi square method is a *Goodness of Fit Test*. In other words, with this procedure can be determined how well a given data sample belongs to a hypothesized theoretical distribution model.

The chi-square test uses the statistic X^2 which approximately follows a chi-square distribution. X^2 is obtained from the equation below.

$$X^2 = \sum \left[\frac{(o_i - e_i)^2}{e_i} \right] \tag{3.7}$$

o_i…expected frequency
e_i…observed frequency

Where, the magnitude of differences between e_i and o_i characterize the adequacy of the fit. Hence, if the observed frequencies differ much from the expected frequencies, X^2 will be large and the fit is poor. The steps of the test process are:

- Hypothesis: X have a known distribution, f(x)
- Determine the significance of the test denoted by α
- Establish the rejection region $R \geq \chi^2_{1-\alpha}(k-1-m)$. (see appendix TableB1)
- If W>R, reject the distribution.

It should be noted, that in the above explanation α denotes the level of confidence.

3.1.4 Confidence Limits

The two most important reliability parameters of components in general are the failure rate and the average outage duration, or repair time. As stated in the previous subchapter the *point estimate* of e.g. the failure rate ($\hat{\lambda}$) may differ from the true value (λ). Hence, it is always advisable to determine a confidence level ($\gamma=1-\alpha$). If λ_l and λ_u denote the lower and upper limits of the confidence interval the following equation applies.

$$\gamma = P(\lambda_l \leq \lambda \leq \lambda_u) \qquad 0 < \gamma < 1 \qquad \textit{confidence level} \tag{3.8}$$

Suppose a normally distributed data sample with mean μ and variance σ^2. Then the standardised random variable z follows a *Student t-Distribution* with *n-1* degrees of freedom, which is independent from μ and σ^2.

$$T = \frac{\bar{x} - \mu}{\sigma / \sqrt{n}} \qquad P(-c \leq T \leq c) \qquad F(c) = \frac{1}{2}(1+\gamma) \tag{3.9}$$

$$a = \frac{\sigma \cdot c}{\sqrt{n}} \qquad P(\bar{x} - a \le \mu \le \bar{x} + a) = \gamma \tag{3.10}$$

Where the character *c* can be obtained from the t-distribution, according to *F(c)*. Failure rate confidence limits are upper and lower values of the estimated failure rate, according to the following equations.

$$P(\lambda_L \ge \lambda) = \frac{1-\gamma}{2} \tag{3.11}$$

$$P(\lambda \ge \lambda_U) = \frac{1-\gamma}{2} \tag{3.12}$$

By use of the chi-square distribution with n degrees of freedom (see Appendix D) the lower (λ_L) and upper (λ_U) confidence limit of failure rate can be expressed as follows:

$$\lambda_L = \frac{\chi^2_{\alpha/2}(2n)}{2T} \cdot \hat{\lambda} \tag{3.13}$$

$$\lambda_U = \frac{\chi^2_{1-\alpha/2}(2n+2)}{2T} \cdot \hat{\lambda} \tag{3.14}$$

The deviation of the upper and lower confidence level from $\hat{\lambda}$ in percent of $\hat{\lambda}$ is

$$dev_L = 100 \cdot \left[1 - \frac{\lambda_L}{\hat{\lambda}}\right] \quad \text{in \%} \tag{3.15}$$

$$dev_U = 100 \cdot \left[\frac{\lambda_U}{\hat{\lambda}} - 1\right] \quad \text{in \%} \tag{3.16}$$

The two sided confidence interval for an exponential distributed failure rate is

$$P\left(\frac{\chi^2_{\alpha/2}(2n)}{2T} \le \lambda \le \frac{\chi^2_{1-\alpha/2}(2n+2)}{2T}\right) = \gamma = 1 - \alpha \tag{3.17}$$

n*…. number of observed failures*
2n…. degree of freedom

For further information regarding confidence limits on λ, *MTBF*, and *R(t)* see [29].

Figure 3.1 Failure rate confidence limits, shows the deviation of the failure rate as a function of the observed failures. It is obvious that as the number of observed failures increases, the confidence limits become narrower and thus the confidence that $\hat{\lambda}$ is a good estimate of λ, the true failure rate increases.

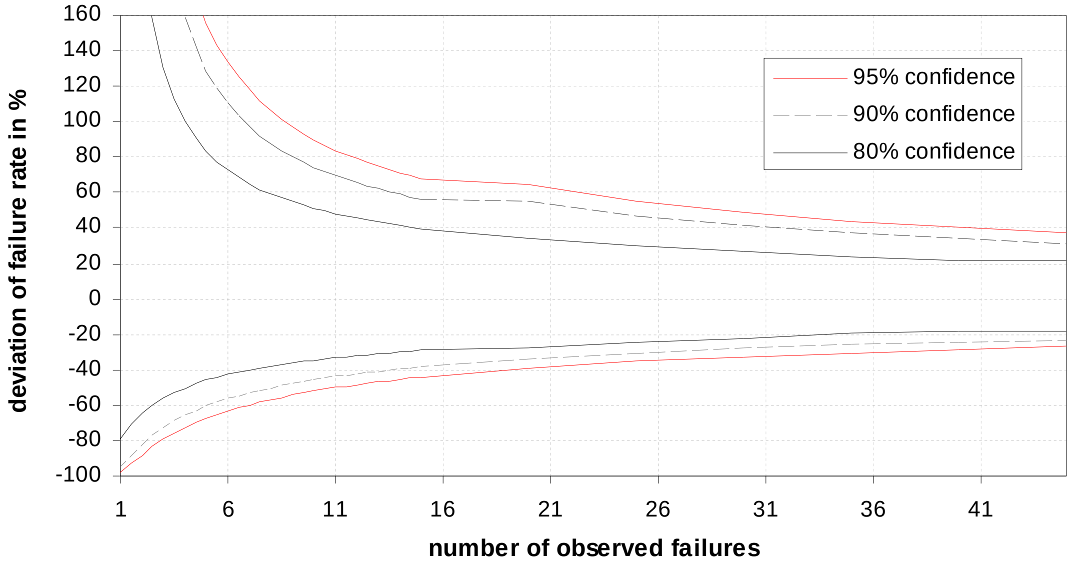


Figure 3.1 Failure rate confidence limits

The IEEE reliability subcommittee recommend a minimum of 8 to 10 observed failures for 'good' accuracy when estimating equipment failure rates [29].

Example: *Low voltage cable for ETS connection.*

Given: Cable below ground in conduit >600V, failures 46, unit years 19525 [yr]
Find $\hat{\lambda}$ and the confidence limits of λ, MTBF and R(20yrs) at 95% confidence level.

From equation (3.7 $\hat{\lambda} = 46/19525 = 0{,}002355$

Two-sided confidence limits on λ $\frac{\chi^2_{0,025}(92)}{2 \cdot 19525} \le \lambda \le \frac{\chi^2_{0,975}(94)}{2 \cdot 19525})$

From Appendix D – Table D.1 $\chi^2_{0,025}(92) = 74{,}22$

$\chi^2_{0,975}(94) = 118{,}14$

Thus, $\underline{1{,}9 \cdot 10^{-3} \le \lambda \le 3 \cdot 10^{-3}}$

Two-sided confidence limits on R(t) $e^{-\lambda_L t} \le R(t) \le e^{-\lambda_U t}$

$\underline{94\% \le R(20) \le 96\%}$

The following equations represent the upper and lower limit of the individual confidence level in Figure 3.1.

$dev_U\% = 455xn^{-0,75}$ 95% upper limit (3.18)

$dev_U\% = 390xn^{-0,74}$ 90 % upper limit (3.19)

$$dev_U\% = 300xn^{-0,74} \qquad \text{80 \% upper limit} \tag{3.20}$$

$$dev_L\% = 19x\ln(n) - 100 \qquad \text{95\% lower limit} \tag{3.21}$$

$$dev_L\% = 19{,}5x\ln(n) - 95 \qquad \text{90 \% lower limit} \tag{3.22}$$

$$dev_L\% = 20x\ln(n) - 85 \qquad \text{80 \% lower limit} \tag{3.23}$$

Equations (3.18)-(3.21) were derived from Figure 3.1 Failure rate confidence limits' and can be used to estimate the confidence limits for different failure rates with given numbers of observed failures in an easy way.

$$\lambda_L = \hat{\lambda} - v_L \cdot \hat{\lambda} \qquad \textit{where} \qquad v = dev_{\%} \tag{3.24}$$

$$\lambda_U = \hat{\lambda} + v_U \cdot \hat{\lambda} \tag{3.25}$$

λ_L and λ_U represent the upper and lower failure rate at a given level of confidence. As a technical note, a 95% confidence interval does not mean that there is a 95% probability that the interval contains the true mean. The interval computed from a given sample either contains the true mean or it does not. Instead, the level of confidence is associated with the method of calculating the interval. The confidence coefficient is simply the proportion of samples of a given size that may be expected to contain the true mean. That is, for a 95% confidence interval, if many samples are collected and the confidence interval computed, in the long run about 95% of these intervals would contain the true mean.

Figure 3.2 presents the upper and lower failure rate of medium voltage XLPE cables with respect to time and observed failures. The confidence level thereby is 95%. As reference point serves the mean failure rate, represented as the dotted black line. The failure rate varies over time, but gets narrower as the number of observed failures increase.

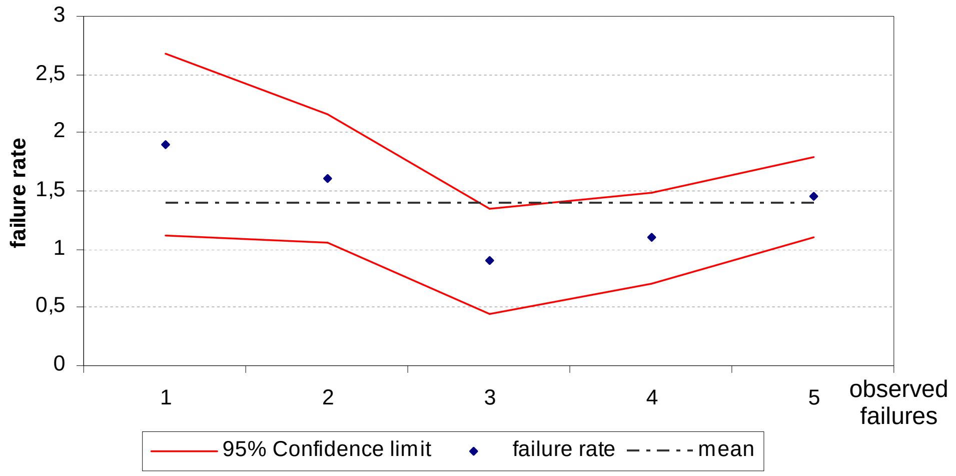


Figure 3.2 XLPE Cable failure rate

The same concept can be applied to any kind of failure rate (e.g. Areva GHA-Switchgear).

3.2 Reliability Statistics

3.2.1 Historical Data from Utilities

Electric utilities have a long history in troubleshooting and maintenance management. Therefore most of them have a well established failure and reliability database of their assets. The association of grid operators of each country usually provide a statistical report with a special focus on interruptions and disturbances of the countrywide, electrical power system. The annual 'disturbance and availability statistic' of the German network is provided by the *VDE(FNN)* [53]. In order to evaluate the figures and use them for further calculation, it is important to understand the particular data acquisition process. The specific instruction for the German process with all its classifications and definitions is available at [53].

Country specific informations

Europe:	Germany	*VDE(FNN)*	*http://www.vde.de/de/fnn/*
	Swiss	*VSE*	*http://www.strom.ch/de/fachbereiche/technik/*
	Austria	*VEÖ*	*http://oesterreichsenergie.at/*
North America:	USA	*IEEE*	*Std. 493-2007 'Gold Book'* [29]
		EPRI	*http://my.epri.com/portal/server.pt*
	Canada	*CEA*	*http://www.electricity.ca/*

3.2.2 Reliability Statistics from Subcontractors

Repower's first source subcontractors regarding electrical components are Siemens AG and Areva T&D. Both companies have large and well known research and development departments and a long history in electrical engineering. Especially Siemens with its internal guideline *SH29500* provide detailed reliability figures. A short overview of reliability data from relevant grid connection components is presented in Table B.1 (Appendix-C 'Reliability Data')

It is common practice nowadays to use data from utilities for reliability evaluations. This is mainly because of the great amount of data obtained from actual performance and their great variety. However, for further evaluations within REpower the use of the actual reliability figures from the manufacturers of the relevant components should be used.

4 Reliability Modelling

The scope of this chapter is the reliability modelling of grid connection components. For this purpose statistical data, introduced in the previous chapter were used to calculate the availability of electrical components throughout their lifetime. Furthermore the concept of ageing due to several factors of influence as well as the failure rate function and its applicability will be introduced. In subchapter 4.3 a wind farm example will be divided into subsystems and evaluated regarding its availability. The results of this evaluation shall serve as a reference for the subsystems optimisation in chapter 5.

4.1 Lifetime of Electrical Components

4.1.1 The Bathtub Curve

The frequency of failures that occur during the lifetime of an electrical component varies with time and can be described with a bathtub shaped curve which can be divided into 3 parts (Figure 4.1 Typical failure rate function). During the first month the failure rate is slightly higher due to damage during transportation, carless handle during installation or due to production failures …etc. After the so called *teething-period* has passed the component is in its *useful-life-period* where failures occur at random (const. failure rate, hence exponential life distribution). The *wear-out-period* where failures occur mostly because of ageing effects of the isolation is the last part of the curve. When exactly the ageing effects will appear depends on several influences. (Thermal-, electrical- and mechanical stress)

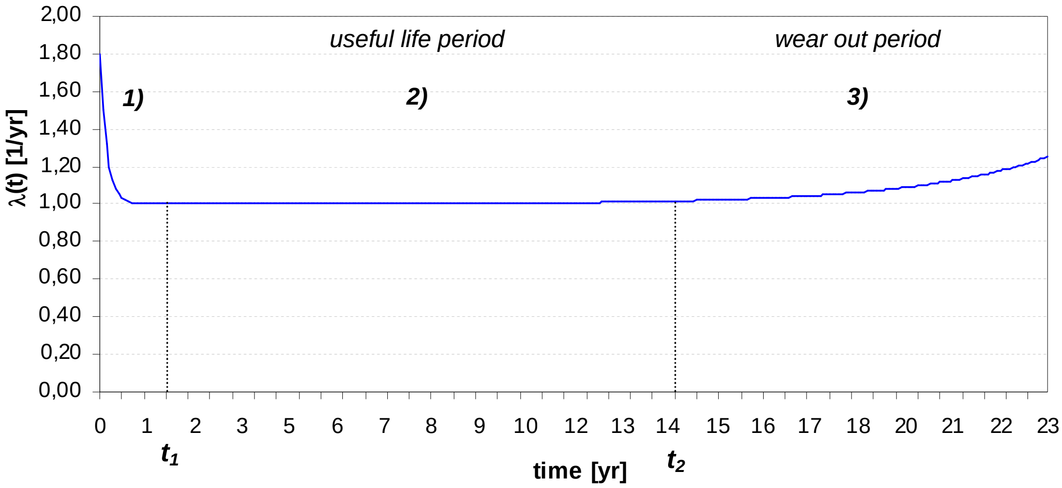


Figure 4.1 Typical failure rate function

The set points for the time dependent failure rate function in Figure 4.1 are listed in Table 5.1. The derived mathematical models for the different sections of the failure rate function with all its restrictions are as follows

$$\begin{aligned} &1) \quad 0 \le t \le t_1 \quad \rightarrow \quad \lambda_1(t) = a_1 \cdot e^{-b_1 \cdot t} \\ &2) \quad t_1 \le t \le t_2 \quad \rightarrow \quad \lambda_2(t) = d = const. \\ &3) \quad t_3 \le t \le t_E \quad \rightarrow \quad \lambda_3(t) = a_3 \cdot e^{-b_3 \cdot (t - t_3)} \end{aligned} \tag{4.1}$$

$$\lambda(t) = \lambda_1(t) + \lambda_2(t) + \lambda_3(t) = a_1 \cdot e^{-b_1 \cdot t} + a_2 \cdot t + a_3 \cdot e^{-b_3 \cdot (t - t_2)} + d \tag{4.2}$$

a…amplitude(>0) *b…slope (>0)*
t_1…start of period 2 (>0) *t_3…start of period 3 (>0)*
t_E…end of lifetime

As mentioned before, the failure rate of electrical components is a function of time, thus the availability is time dependent as well.(Figure 4.2)

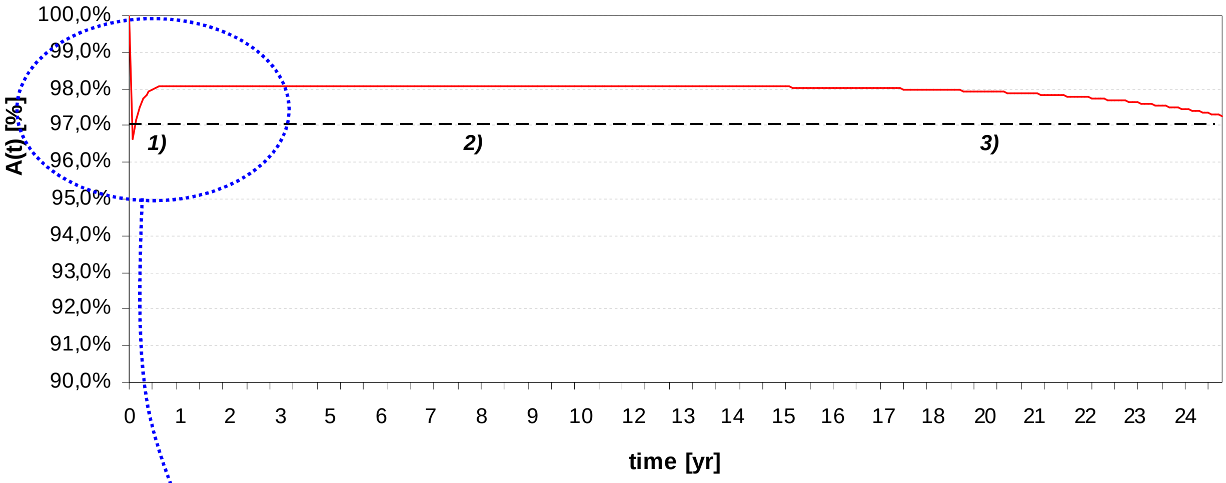


Figure 4.2 WEC, Availability over its expected lifetime

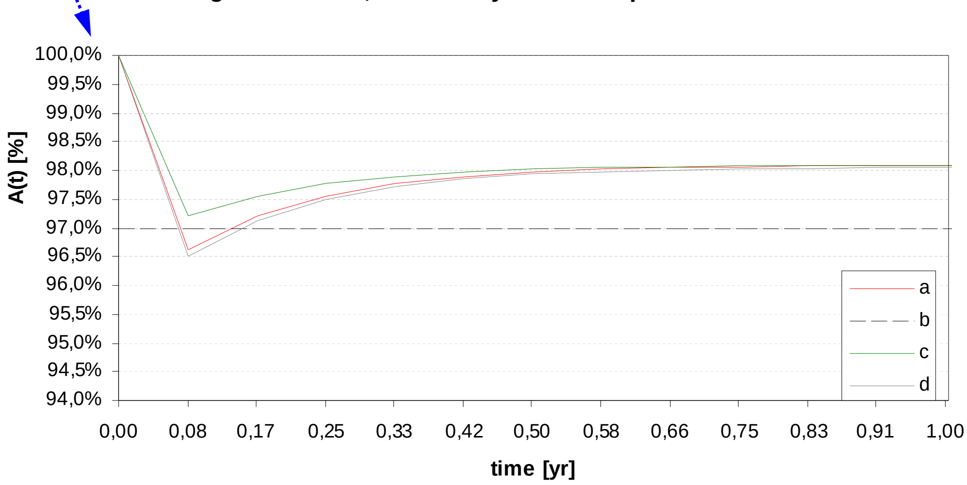


Figure 4.3 WEC, Availability over one year

The above figures show the availability of the WEC (MM Series) over its expected lifetime based on the failure rate function from Figure 4.1 assumed that the number of expected failures during the teething period is approximately 50% higher than the number of expected failures during the useful-life period. Furthermore it was assumed that after fifteen

a_1	0,8
a_3	0,1
d	0,2
b_1	6
b_3	0,3
t_3	15

Table 4.1 Set points for Figure 4.1

years in operation certain ageing effects can be expected.

Hence, t_3 in equation 4.1 is set to fifteen.

a) $$A(t) = \frac{\mu(t)}{(\mu(t)+\lambda(t))} + \frac{\lambda(t)}{(\lambda(t)+\mu(t))} \cdot e^{(-(\lambda(t)+\mu(t))\cdot t)}$$ ***green curve*** (4.3)

b) $$A(t) = \frac{\mu(t)}{\mu(t)+\lambda(t)}$$ ***red curve*** (4.4)

c) $$A(t) = 1 - \lambda(t)\cdot r(t)$$ ***grey curve (if λ<<μ)*** (4.5)

d) *mean availability (reference point/lower limit)*

In order to apply the derived equation easily, it is important to use relative values. In other words, the equations are normalised (p.u.), thus by multiplying the above equations with the actual relevant failure rate of the component, the absolute failure rate function can be obtained. It should be also pointed out, that different components have different bathtub curves. A survey made by IEC come to the conclusion, that the most common shape of the failure rate function is the bathtub curve [29].

The different periods of the failure rate function and their characterisation shall be introduced and discussed in more detail over the next few pages.

Burn-in Period (teething period)

This time interval is characterised by a high initial failure rate which is decreasing over time. The initial high failure rate can be explained by early faults caused by transportation, installation, manufacture and product faults, design faults...etc. This period normally lasts for approximately 1-3 month, depending on the component. Measures that could be taken in order to mitigate the failure rate related higher risk: pre-commissioning tests, process control, quality management.....etc.

Useful-Life Period

The useful-life period is determined by faults that occur at random, for example caused by bad handling, dirt particles, maintenance actions and the related human errors...etc. Measures to be taken: correct handling and maintenance actions...etc.

Wear-Out Period (Ageing)

During this period faults occur due to wear-out and fatigue appearances. These types of faults are caused by degradation of the electrical isolation strength of components. Stress factors that affect the level of degradation are known as ageing stresses, which will be described briefly over the next few pages.

Measures to be taken: Lifetime calculations, ageing tests, monitoring systems....etc.

4.1.2 The Ageing Concept

The lifetime of electrical components is usually determined by the lifetime of its electrical insulation system. Effects like thermal, electrical, mechanical or ambient influences (*TEAM*-factors) can cause loss of isolation strength; therefore lead to lifetime degradation of the component. In terms of components failure rates, the *TEAM*-factors can be described by an increase after a particular time in operation. Figure 4.4 displays the ageing concept of electrical isolation systems. Ageing stresses can either cause intrinsic or extrinsic ageing mechanisms. Intrinsic ageing is the ageing of the isolation material itself due to ageing stress (*TEAM*-factors), whereas extrinsic ageing mechanisms are irreversible changes of isolation system due to ageing stress (*TEAM*-factors) on imperfections (bad spots) in the isolation system. Extrinsic ageing mechanisms, ageing because of imperfections in the isolation system, are the major cause of outages.

It should be noted, that the term 'lifetime of electrical components' refers to the economical lifetime. In other words the lifetime is the time interval the costs for preventive and corrective maintenance of the component are reasonable, compared to its investment costs.

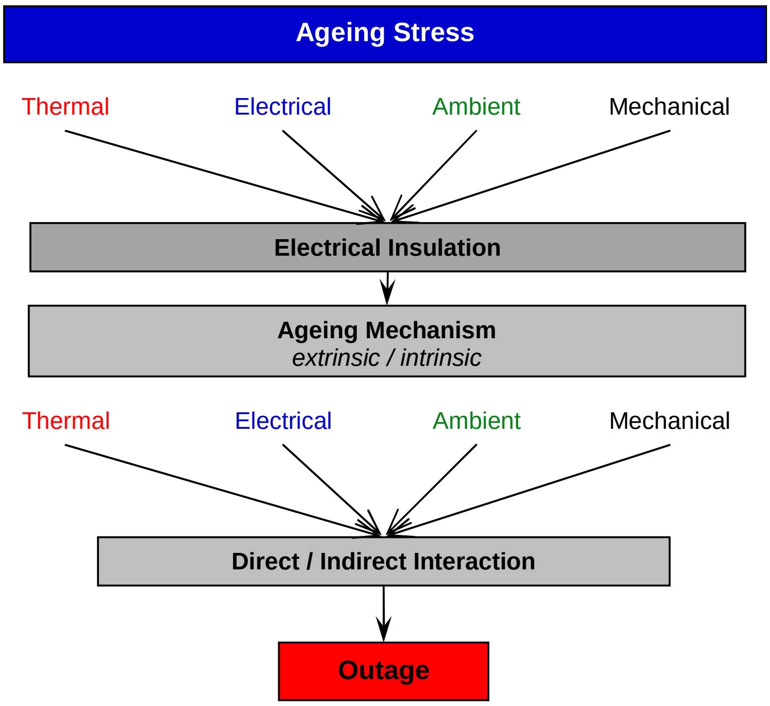


Figure 4.4 The ageing concept according to IEC 60505 [26]

Different ageing stresses can occur individually and independent or simultaneously. Either way will result in degradation of the components residual lifetime. The exact identification of all operational ageing stresses and furthermore the evaluation of the lifetime degradation is very difficult, since the conditions under which certain ageing mechanisms apply are not fully understood yet. In order to compensate this lack of knowledge, a common practice nowadays is to establish specific lifetime models by use of reliability data from past experiences.

To provide a thorough understanding of ageing stress and its influence on the lifetime of components, the *TEAM*-factors will be discussed in more detail within the next few pages.

Thermal Ageing

Thermal ageing consists of chemical and physical mutations caused by degradation reactions, polymerisation, diffusion...etc. as well as thermo-mechanical impacts caused by thermal extension and contraction based forces. Many chemical ageing processes can be modelled with the *Arrhenius* equation, for a limited temperature interval. The *Arrhenius* life-stress model is probably the most common life stress relationship used in accelerated life testing. It is derived from the Arrhenius reaction rate equation:

$$L = A \cdot e^{\left(-E_0 / k \cdot T\right)} \tag{4.6}$$

L… lifetime (the speed)
A…amplitude — *E_0…activation energy*
k…Bolzmann constant — *T… absolute temperature (stress level)*

The activation energy (E_0) is a measure of the effect that temperature has on the reaction. Therefore, the influence of thermal stress to the isolation of electrical components can be evaluated. Assuming that the lifetime is proportional to the inverse of the reaction rate, the life-stress relationship is given by equation 4.6.

The load factor (0,2-0,4) as well as the power flow of wind farms and their influence on the ageing effects need to be discussed and further investigated.

<u>Arrhenius-Exponential</u>

The PDF for the Arrhenius relationship and the exponential distribution f(t) is given by the PDF of the 1-parameter exponential distribution.

$$f(t) = \lambda \cdot e^{(-\lambda \cdot t)} \text{ in} \tag{4.7}$$

It can be easily shown that the mean life for the 1-parameter exponential distribution (presented in detail in subchapter 2.3.2.5) is given by

$$MTTF = \frac{1}{\lambda} \quad \rightarrow \quad f(t) = \frac{1}{MTTF} \cdot e^{\left(-t / MTTF\right)} \tag{4.8}$$

The Arrhenius-exponential model PDF can then be obtained by setting *MTTF=L(n)* in equation 4.8. Therefore

$$MTTF = L(n) \tag{4.9}$$

Equation 4.10 expresses the mean, or mean time to failure of the Arrhenius model of an exponential distribution. Substituting for *MTTF* in equation 4.9, results in a PDF that is both a function of time and stress.

$$f(t,n) = \frac{1}{A \cdot e^{\left(E_0/nt\right)}} \cdot e^{-1/A \cdot e^{\left(\frac{E_0}{nt}\right)} \cdot t} \tag{4.10}$$

The Arrhenius-exponential reliability function R(t,n) is the complement of the cumulated distribution function and is given by

$$R(t,n) = e^{-\frac{t}{A \cdot e^{\left(E_0/n \cdot t\right)}}} \quad \rightarrow \quad t_R = -A \cdot e^{\frac{E_0}{n}} \cdot \ln[R(t_R, n)] \tag{4.11}$$

For the Arrhenius-exponential model, the reliable life, or the mission for a desired reliability goal, t_R, is given by the above equation.

Electrical Ageing

Electrical ageing consists of partial charges, treeing, leak current, electrolyse, higher temperature due to high dielectric losses, space charges. An exact mathematical model for electrical ageing stresses and its influence on the isolations lifetime hasn't been developed yet. If a time dependent disturbance mechanism exists, the load carrying capability of a component (e.g. current carrying capacity) will decrease with increasing time. In case of electrical systems such a mechanism can occur at isolation systems with partial discharges, whereas the electrical field is the disturbance mechanism. This concept in general and the interaction between lifetime of electrical components and their electrical field can be modelled by use of the *inverse power law (IPL).*

$$t \cdot E^n = const. \tag{4.12}$$

E…electrical field *n…number of stresses*
t…stress duration

$$L \cong E^{-n \cdot t} \tag{4.13}$$

The IPL implies a linear relationship between lifetime and electrical stress, for a logarithmic representation. Accelerated life tests use a higher frequency to advance the ageing mechanisms. Further should a mathematical relationship between stress level and stress interval be developed in order to get the chance to compare different components with respect to stress level or stress interval.

<u>IPL-Exponential</u>

The *PDF* for the Inverse Power Law relationship and the exponential distribution can be derived by setting *MTTF = L(n)* in equation 4.13. The obtained IPL-exponential PDF is

$$f(t,n) = \lambda \cdot e^{(-\lambda \cdot t)} \qquad \lambda = s \cdot n^k \tag{4.14}$$

Note equation 4.14 is a 2-parameter model. The failure rate (the parameter of the exponential distribution) of the model is simply a function of stress. Hence, the mean time to failure for the IPL of exponential distributions is only a function of stress as well.

The IPL-exponential reliability function is the complement of the cumulative distribution function and is given by

$$R(t,n) = e^{-t \cdot E^{n} \cdot \cdot} \tag{4.15}$$

For the IPL-exponential model , the reliable life or the mission duration for a desired reliability goal, t_R is given by:

$$t_R = -\frac{1}{E^n} \cdot \ln[R(t_R, n)] \tag{4.16}$$

An overview of parameter estimation concepts for the IPL- and the Arrhenius models can be looked up in the appendix.

Note: Ageing effects due to mechanical and ambient influences shall not be considered within this investigation. For further information on this particular topic see [26], [7] and [50]..

Residual Life Time

The residual lifetime of components under certain stress levels were introduced in subchapter 2.3.2.5, page 22.

4.2 Grid Connection Components

As previously described the availability of a component over a period of one year can be calculated using equation 4.17 under the restriction $\lambda << \mu$.

$$A = \frac{T_U}{T_C} = 1 - (\lambda_F \cdot r) \cdot 100 \text{ in [\%]} \qquad A^* = 1 - (\lambda_F \cdot r + \lambda_M \cdot m) \cdot 100 \text{ in [\%]} \quad (4.17)$$

[7]

For long observation times the above equation is an adequate evaluation method, however a more accurate calculation method, which can be applied without any restrictions was introduced in subchapter 2.3.2.

The reliability figures in the tables presented below are based on the disturbance and availability statistics from the German power system [53]. Whereas only events are taken into account that lead to an interruption or to a switching action. The *mean time to repair* (*MTTR*) and the *mean time to maintain* (*MTTM*) are related to the project location, the manufacturers and their experience and other influencing factors. Hence they can vary within a broad range. The repair and maintenance rates in this investigation were obtained from phone calls with ABB's and AREVA's service departments.

Note: Unless stated otherwise, the reliability figures in this chapter are only valid for onshore wind farms. Nevertheless each subchapter provides a short overview of reliability figures regarding offshore components as well.

4.2.1 The Wind Energy Converter

The reliability figures of the turbine were provided by the REAG service department and can be seen in table 2-3. The failure rates of the turbine vary extremely over time and they are related to several influences (season, country,…etc) hence they are extremely unstable. With this background and due to the evaluation methods that were used to estimate these figures, these data need to be discussed and furthermore used very carefully.

MTBF - Global All Contracts	Nov 09 [h]	Dez 09 [h]	Jan 10 [h]	Feb 10 [h]	Mrz 10 [h]	Apr 10 [h]	Mai 10 [h]	Jun 10 [h]	Jul 10 [h]
total[8]	385	341	296	322	351	400	424	383	382
Indoor	745	585	501	550	676	859	878	578	726
Outdoor	798	821	724	780	729	747	819	1.138	805
MM total	325	299	275	269	304	375	377	407	523
MM Indoor	587	478	443	436	543	742	730	554	932
MM Outdoor	730	802	722	700	690	760	777	1.534	1.190

Table 4.2 WEC MTBF rates

[7] A* denotes the technical availability considering the time to maintain as unavailability.

[8] Referring to all WEC's in operation.

The terms indoor and outdoor are referring to the applied troubleshooting. If the appeared failure can only be repaired onsite the troubleshooting is considered as outdoor (onsite). Contrariwise, if a failure can be fixed from remote (REguard) it is considered as indoor. This concept becomes more obvious by looking at the mean times to repair in Table 4.3.

MTTR-Global All Contracts	Nov 09 [h]	Dez 09 [h]	Jan 10 [h]	Feb 10 [h]	Mrz 10 [h]	Apr 10 [h]	Mai 10 [h]	Jun 10 [h]	Jul 10 [h]
total	11,7	13,6	10,0	8,3	8,6	9,1	10,3	11,5	11,4
Indoor	3,8	4,3	3,8	3,9	4,4	2,8	3,3	4,4	4,6
Outdoor	22,5	29,2	20,9	15,9	14,2	16,2	18,7	20,1	21,3
MM total	12,0	13,1	8,7	7,5	7,9	8,8	9,4	10,7	10,8
MM Indoor	4,0	4,2	3,5	4,1	4,7	2,7	3,3	4,7	5,2
MM Outdoor	23,0	30,9	18,9	14,1	12,9	16,8	17,5	18,1	20,4

Table 4.3 WEC MTTR rates

All technical failures that lead to an outage of the WEC were taken into account thus the time to maintain was not considered as unavailability. Table 4.4 WEC availability shows the availability of the wind energy converter.

Global All Contracts	λ_F [1/yr]	MTBF [h]	MTTR [h]	λ_M [1/yr]	MTTM [h]	A* [%]	A [%]
total	24	360	11	2	8	96,93	97,11
Indoor	13	658	4	2	8	99,30	99,39
Outdoor	11	821	21	2	8	97,35	97,51
MM total	26	332	10	2	8	96,95	97,13
MM Indoor	15	565	4	2	8	99,18	99,28
MM Outdoor	10	854	20	2	8	97,59	97,74

Table 4.4 WEC availability

The threshold for the turbine is 97% and it can be seen that the evaluated long-term availability is beyond the required threshold. If the customer signed an additional maintenance contract (ISP/WSV) the slightly lower availability during the first month is covered by the contract due to the fact that the first 3 month are not included for the availability calculations.

The frequency of faults and the dedicated fault locations within the WEC will be evaluated to provide a better understanding of critical components. The actual down times as well as the observed number of faults are based on several product reports over a period of one year [68].

The number of observed disturbances varies between 7 and 13 failures per WEC, per month, with a related lumped down time of 20-55h. The most frequent status codes are:

- Status code number 4500 'tower resonance'
  ~7 status messages per WEC per month, ~5h duration
  (Start-up failure, decrease of status message due to parameter adjustment)
- Status code number 3110 'converter'
  (Lumped status message w/o exact failure specification)

in the past auto reset, but due to damage of several WECs - remote converter reset -> ~1,5 status messages per WEC per month, ~2h down time per status messages

The component based evaluation of WEC failure causes over the past years of observation shows that four components are the key failure source. The converter (*SEG, Converteam*), the pitch system, the hydraulic system and the DFI-generator (*VEM, Winergy*). The actual down time of each component is shown in Table 4.5

Component	T_D [h/month]	Ranking
Converter	4,0	1
Pitch System	3,5	2
Generator (DFIG)	0,8	3
Hydraulic System	0,5	4

Table 4.5 MM failure causes and mean down time [68]

In order to improve the number of failures and their related down time a project (performance improvement) has been established within REAG. The main difference of this project is the high additional maintenance and its support effort, which obviously affects the project specific operational wind farm costs. Such performance improvement processes provide good results very fast but should be just used as a short term means. For long term improvements changes should be made within the early project development process. (Layout, support structure, quality management....etc.)

Performance vs. Availability Guarantee

There are two basic availability guarantee approaches to ensure the customer that the WEC or the whole wind farm is a premium product that operates at a very high standard and therefore guarantees certain, predictable financial revenues. The first approach is time based, whereas the second one is energy based. The later one guarantees a certain performance over a stated period of time, in other words for a given time interval a certain energy output is guaranteed. The time based availability guarantee on the other hand ensures that the product is available over a certain percentage of a stated time interval.

- <u>Time Based (Availability guarantee)</u>

Time related guarantee of technical availability. The actual guaranteed level of availability depends on the project details and the customer. Any kind of project specific guarantee is always related to a specific risk distribution, therefore the guaranteed level of availability changes for different project locations. The most common levels of availabilities for onshore projects are between 95 and 97 and 95 to 96% for offshore projects due to the higher risk. (E.g. environmental influences)

Pros

- Long experiences with mechanisms
- No additional measurements
- Simple contract and availability structure

Cons

- Repower pays *liquid damages* (*LD*) on flatrate based on time
  (no difference between high and low wind speeds)
- Customer calculates conservatively
- Not attractive to customer, as revenue is based on energy yield and not time
- No incentive/benefit for REpower to place O&M in low wind speed periods

- Energy Based (Performance guarantee)

Energy related guarantee of performance, based on yield models. The actual guaranteed performance level is commonly given as percentage of the theoretical production (yield over one year). Typically the guaranteed level is round about 93 to 95%, depending on the project location.

Pros

- Very attractive to customer
- High incentive to customer to purchase efficient turbines
- Takes the seasonal energy variations into account

Cons

- Complicated technical realisation
  - Extremely difficult measurement issues
  - Dependence on theoretical models (Wake effects…etc.)
  - Necessity to store and analyse extreme weather data
- High risk of inaccurate measurement data and high measurement costs
- High general effort to establish method
- Higher failure rate at higher wind speeds (although not verified yet)

Furthermore it should be checked at which mean wind speed the energy based approach is more reasonable than the time based approach. Relevant investigations have shown that if the mean wind speed exceeds approximately 8m/s, the advantages of the performance guarantee are predominant. If the entire wind farm is out of service pre-agreed production estimates apply. The related lost production can either be caused by the customer, by RE-power or by Repower but covered by energy credit for maintenance. It can be calculated by the following equation.

$$LP = \frac{AP}{WEC - WEC_{Down}} \cdot WEC_{Down} \tag{4.18}$$

LP	*lost production*	*AP*	*actual production*
WEC	*number of WECs*	WEC_{Down}	*number of WECs out of service*

Note: In case of turnkey projects the above approaches apply for whole wind farms as well as for single WECs.

4.2.2 Medium Voltage Equipment

Over the next few pages the reliability and availability figures of MV components are presented. It should be pointed out, that the MTTR and the investment costs (C_0) are average values which can be treated as accurate valuations.

4.2.2.1 MV-Cable

The state of the art insulation system for MV cables nowadays is cross linked polyethylene (XLPE), mainly because of its lower loss factor (tanδ). Due to economical reasons is the most common conductor material is aluminium. Table 4.6 shows the reliability and maintenance figures for different kinds of insulated MV cables.

Component	λ_F [1/km yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [k€/km]
XLPE	0,0061	165,0	72	0,05	10	4	60.
PE	0,0533	18,7	72	0,05	10	4	50.
Oil filled	0,0308	32,5	96	0,2	5	8	80.

Table 4.6 MV-cable reliability figures

The synthetic insulated cable systems can be assumed to be maintenance free. However, in this investigation it is assumed that particular parts of cable systems, for example the terminations or the junction boxes should be inspected at least every ten years (mean time between maintenance MTBM). Therefore the maintenance rate (λ_M) in Table 4.6 is 0,05 per year. The evaluated reliability (*R(20)*) and availability (*A*) of the different cable systems using the figures from Table 4.6 are presented in the following table.

Component	R(20) [%]	A* [%]	A [%]
XLPE	88,59	99,992	99,995
PE	34,41	99,953	99,956
Oil filled	54,01	99,948	99,966

Table 4.7 MV-cable availability

The reliability (*R(20)*) is equal to the probability that one kilometre of the relevant cable system doesn't experience a failure within a period of twenty years. The availability on the other hand is calculated twice. Once, where only the failure rate is taken into account (*A*) and another time, where the maintenance time is considered as unavailability (*A**).

Regardless of the significantly different failure rates of the cable systems, their level of availability in general is very high. Although the failure rates can be assessed as above-average, due to the external urban influences which are the main failure cause for cable systems within the German distribution network. Thus the evaluated reliability and availability represents a worst case scenario. Outages of cable systems typically are caused by failures on the conjunction between two separated systems, for example on joints, terminations, junction boxes.....etc. The number of joints per kilometre cable length depends on the cross section of the cable. However, a distribution of one joint every 0,8 kilometres is a good estimate, which result in 3,5 joints per kilometre cable system length. Different failure mechanisms of cable systems and their impact are discussed in detail at the end of this section.

In order to get a better understanding of different insulation systems, their general properties are listed in the following table.

Parameter	XLPE	PVC	PE	OIL
Loss factor	*very low*	*very high*	*high*	*low*
Temperature threshold	*high-*	*low*	*medium*	*medium*
Isolation strength	*very high*	*medium*	*medium*	*low*
Relative permeability	*medium*	*high*	*high*	*low*

Table 4.8 Properties of insulation systems [53]

An important parameter for the design of cable systems is the ampacity, also known as current carrying capability of different cross sections and the related load losses. The load losses of cable systems can be evaluated by the following equation:

$$P_L = I^2 \cdot R_{=20} \cdot (1 + \alpha \cdot (\vartheta_C - 20°C)) \cdot y_S \cdot y_P \qquad (4.19)$$

$R_{=20}$ DC resistivity for 20°C — *α temperature coefficient of resistance*
ϑ_C conductor temperature — *y_S skin-effect factor (for cross sections >185mm^2)*
y_P proximity-effect factor (>185mm^2)

In subchapter 5.3 (Active Power Losses) the above equation is used to evaluate the load losses for a given wind farm. It should be noted, that the proximity factor as well as the skin-effect factor may be left out, due to the cables cross section. If the cable shields are grounded just at the beginning and the end, the shield losses can attain 40% of the cable losses [46]. In order to minimise the shield losses the concept of cross-bonding, where the shields are additionally crossed and grounded after every third of the cable length, should be applied so the shield voltages can compensate themselves. The inductivity of the positive-, negative- and zero-sequence of cables is determined by the cable design (shield) and the laying (flat vs. trefoil) The concept of cross-bonding is graphically illustrated in Figure 4.5.

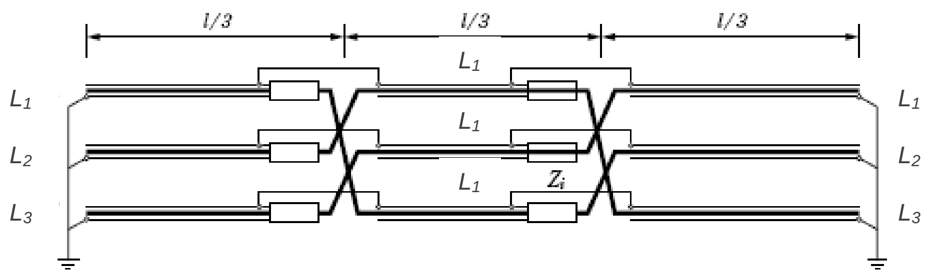


Figure 4.5 The concept of cross-bonding

The influence of different parameters on the design and operation of cable systems is presented in Table 4.9 below. It can be seen that the treatment of the shield-grounding has a major influence on the operational capabilities of cable system.

Parameter	Invest-ment	Logis-tics	Excavation laying	Installa-tion	load ability	note
Cross-bonding	-	-	-	-	++	especially for big cross sections
Flat vs. trefoil	-	-	+	(+)	+	no effect for small axial distance
Axial distance	-	-	+	(+)	+	For cross sections <300mm^2
Depth	-	-	++	-	(-)	Standard depth (1,2-1,5m)
Thermal	-	-	+	(+)	++	recommended
Cross section	+	(+)	-	-	+	With applied cross-bonding
Diameter	+	(+)	-	-	(+)	With higher isolation strength

Table 4.9 Influences on loading capability of cables[46]

Regarding the failure caused down time of cable system one can distinguish between down time related to damage or down time due to faults without damage. Both classifications are common practice in disturbances and availability statistics from utilities [54]. The average failure caused down time of cable systems of the German distribution system is shown in Table 4.10.

Fault	MTTR) [h]
w. damage	56,7
w/o damage	30,4

Table 4.10 MTTR of MV-cables

These figures are not quite applicable for wind farms, since the support structure and the site accessibility are usually different. Therefore a slightly higher MTTR was chosen for this investigation, which can be seen in Table 4.6. In order to keep the MTTR low a thorough support and logistics structure as well as a certain amount of spare parts (e.g. joints, terminations...etc.) is needed. With such simple measures the mean down time of cable systems can be improved significantly.

Table 4.6 also provide the average investment costs of cable systems with different insulations. These costs include the actual cable price, which depends on the metal price, and the costs for excavation and lying (flat formation). There are various other methods for excavation and lying, which would result in lower investment costs per kilometre. However, the cable trench together with a flat formation of the cable system is the most common excavation and lying type. It is obvious that the civil works take a large contribution to the overall costs. Approximately fifty percent of the total investment is necessary for excavation and lying.

Failure Mechanisms

The most common failure cause of synthetic insulated cables is water trees [47]. Trees in general develop over a long period of time and accelerate the failure rate of cables.

Trees in cable insulation systems can occur in two ways

- Water Trees

Water trees are the major failure cause of polyethylene (PE) insulated cables and their low MTBF. Water trees are small voids in the insulation system filled with water. The time until a water tree has grown in a way that leads to a failure of the insulation system is rather long (years) and independent of the electrical stress level.

Figure 4.6 Water tree in an PE isolated MV cable [63]

Figure 4.6 shows water trees in a PE insulated medium voltage cable. It is obvious that this type of tree needs moisture to grow, the actual growing rate depends on the temperature, the voids, contaminants and voltage variations. Hence the occurrence of water trees within the MV collector system of wind farms is assumed to be very likely because of the seasonal variations and the low load factor which results in a high absolute temperature variation However, water trees can easily be prevented by use of waterproof cables.

The use of longitudinal or transversal waterproof cables is strictly project related. Thus in case of rocky soil conditions the use of waterproof cables should be preferred. The additional costs for transversal waterproof cables are rather low compared to those for longitudinal waterproof cables.

- Electrical Trees

Electrical trees develop from high electrical stress and typically grow over a rather short period. (Hours or days) The major cause of electrical treeing are partial discharges that took place in discrete voids and irregularities of the insulation system.

It should be noted, that water trees don't need to cause failure of the insulation system, since the water filled voids usually can maintain the insulation strength. Failures occur when a water tree converts into an electrical tree where charges are trapped in the cables insulation system. The main fault locations of cable systems are joints, terminations, elbows etc. where the insulation is not always homogeneous and the electric field strength can be higher.

Especially under switching stress the frequency of failures is significantly higher.

Current surveys have shown that the failure rate of XLPE cables and accessories are significantly lower than those provided by the individual utility statistics. For MV XLPE cables the average failure rate can be assumed to be 0,084 annual failures per hundred kilometres system length. According to the same report the failure rate of XLPE joints is 0,028 annual failures per hundred joints [77]. Thus the total failure rate of MV XLPE cable systems is 0,112 failures per hundred kilometres system length, which is approximately six times lower than the values from the German distribution system in Table 4.6. If failure caused by external events (e.g. diggers) can be prevented the actual failure rate would be additionally improved at a rate of approximately 40%. In order to achieve this goal the focus has to be on the excavation and lying of the cable system. (See Figure 4.7)

Reliability Improvement Measures

A thorough lightning protection concept is essential for the reliable operation of the MV collector system in order to limit the electrical stress level. The second most important measure which can be applied to improve the reliable function of the MV cable system is the excavation and lying type. Figure 4.7 shows a sketch of a cable trench and a flat formation of the single core cable system.

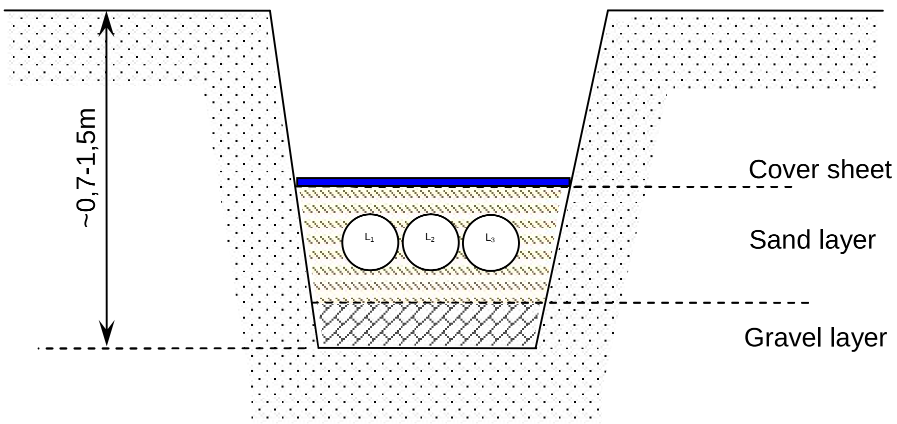


Figure 4.7 Sketch of a cable trench (excavation and laying)

For further improvement measures, like filled strand conductors, silicon injection or Increase of the insulation thickness see [22],[47],[50] and [63].

Ageing Effects

Most of the MV XLPE cable systems experience a failure within the first five years in operation [76]. Certain ageing effects can be observed after twenty years in operation, thus ageing of XLPE cables is not further discussed in this investigation. Certain diagnostic tests can be looked up in [47],[50] and [72].

LCC of MV Cables

The life cycle costs of cables mainly consist of lost revenue caused by active power losses and costs for corrective maintenance, whereas preventive maintenance actions and their related costs are rather low (See Table 4.6).

4.2.2.2 MV-Transformer

MV transformers in wind farms are also known as step-up transformers which connect the Generator to the MV collector system. In general one can distinguish between internal transformer systems (ITS) where the transformer and the related switchgear is located within the tower and the external transformer system (ETS) where the transformer and the secondary switchgear is located in a separated enclosure next to the WEC. The ITS transformer is a dry transformer (casting resin), due to fire protection requirements. Whereas the transformer used for ETS is oil insulated. The reliability figures of both types of transformers are represented in the following table.

Component	λ_F [1/yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [€/kVA]
Trafo	0,0023	432,9	96	0,25	4	6	20
Oil-Trafo	0,0543	18,4	96	0,25	4	6	20
Dry-Trafo	0,0381	26,3	96	0,25	4	6	20

Table 4.11 MV transformer reliability figures [29][53]

The properties of standard network transformers are presented in the above table by the term trafo. Oil / Dry is used for REAG ITS/ETS transformers. The evaluated reliability and availability is given in Table 4.12. It should be pointed out, that the mean time between maintenance (MTBM) for ITS and ETS systems are four years and regulated by law [64].

Component	R(20) [%]	A* [%]	A [%]
Trafo	95,49	99,979	99,996
Oil	33,76	99,938	99,955
Dry	46,69	99,941	99,958

Table 4.12 MV transformer availability

The failure rate of MV transformers within distribution systems can be assumed as rather high, because of the high amount of pole-mounted transformers with low rated power which are vulnerable for external influences. (E.g. lightning) Thus the failure rates can be assumed to be slightly overestimated for the purpose of wind power applications. The MTTR figures of MV transformers are from historical data and on the basis of a good support structure.

Failure Mechanisms

In order to evaluate the failure mechanisms of transformers in general, the impact of several subcomponents has to be considered. Transformers can be divided into the following subcomponents:

- Core

A failure of the core would result in a reduced efficiency of the transformer. The major causes are mechanical faults due to improperly use during construction or due to low material quality.

- Windings

Dielectric stress and thermal requirements as well as mechanical stress cause failure of the winding system. Mechanical stresses can either occur during short circuits and lightning strikes or during transportation. A significant influence on the proper function of the winding system is their insulation system, which usually consists of cellulose layers. This insulation system can lose its strength through various thermal or electrical ageing mechanisms or through material faults or falls handling during construction. However, in case a failure occurs on the winding system, either the failed winding or the whole transformer needs to be changed. This decision is made in terms of economical and technical restrictions. In case of MV transformers, the replacement of windings can be done onsite and at a respectively low repair time. Therefore Repower keeps a certain amount of winding systems in stock.

- Bushings

There are various kinds of bushings according to their application. Basically it can be distinguished between capacitance-graded bushings and solid bushings [79]. The purpose of the bushings is to connect the windings to the power system and at the same time to isolate the tank against the windings. The major failure mechanism of the windings is the loss of isolation strength due to ageing effects of the material or material faults which lead to partial discharges and short circuits. Bushings are also very sensitive to mechanical stress, which can occur during transportation and installation.

- Tap Changer

Tap changers of transformers can be divided into on-load types, where the tap position can be changed during operation without an interruption of supply and off-load types, which can only be adjusted in case the transformer is out of service. On-load tap changers (OLTC) in general have a much lower MTBF because of its mechanical deterioration. Thus the main failure modes of Tap changers are mechanical damage (unable to change the voltage level) and contact failure (short circuit).

- Insulation System
    - *Solid*

As previously mentioned, solid insulation systems of transformers are based on cellulose. (Paper, board...etc.) It is obvious, that such an isolation system is vulnerable to certain ageing effects, whereas thermal ageing mechanisms apply the most. The solid insulation is the weakest spot of the transformers insulation system due to the irreversible degradation of the cellulose and the fact that a replacement is usually not economical [79]. The arrhenius lifetime model can be used to evaluate the thermal ageing effects and the residual lifetime of the solid insulation system, which was introduced in subchapter 4.1.2.

- *Liquid (Oil)*

The purpose of the oil insulation is first of all the electrical insulation between different parts of the transformer and secondly the cooling of the active parts. It is obvious that the quality of the oil directly affects the insulation strength and the load ability (cooling) of the transformer. In case the oil contains undesirable particles like oxygen, water etc. the insulation deteriorates which increases the probability of short circuits. The major causes of oil pollutions are ageing effects within the insulation system. Hence, the two main failure modes of liquid insulation systems are short circuits due to deteriorated oil and overheated due to failed oil circulation or failed cooling system.

- Cooling System

The cooling system of transformers can either be based on natural or forced circulation of oil and air or water. Whereas the air or water is used as cooling medium of the secondary circulation. (ONAN/ONAF) It is obvious that pumps or fans are needed for forced cooling systems. The two failure causes of the cooling system, whether it’s forced or natural, are the breakdown of the oil circulation and that the temperature of the second cooling medium is too high. The later cause can either occur due to broken pumps or fans or because of high ambient temperatures. However, it should be noted, that the design of the cooling system has a major impact on the overload factor of the transformer.

These classification and failure mechanisms of subcomponents are generally valid, regardless of the transformers rated power or field of application. An evaluation of failure causes of MV transformers and their frequency of occurrence is given below.

Most faults occur on mechanical subcomponents of transformers, like the on-load tap changer or the bushings. However, step-up transformers typically have an off-load tap changer, which cannot be adjusted during operation. It turned out that the windings and the bushings are the main fault locations of MV transformers. Due to the relatively low investment costs and the high amount of MV transformers within a wind farm a fundamental stock of spare parts is essential. (Windings and bushings)

Reliability Improvement Measures

As mentioned above, the most efficient measure to keep the MTTR low and therefore the overall availability high is a thorough level of maintenance support. Especially spare parts of subcomponents with a rather low MTBF should be stocked. Preventive maintenance actions on MV transformers shall be performed after a stated time interval, which is four years for German transformer systems. These maintenance actions typically include visual inspection, cleaning and various stress tests if required.

In order to keep the active power losses down and thus the overall efficiency high, the ratio between no-load losses and load losses needs to be optimised taken the low load factor into account.

Another technical possibility to improve the availability of transformers are hermetic sealed vessels. Hermetic sealed transformer vessels reduce the ageing effects of the liquid and solid insulation system and more important reduce the maintenance efforts significantly [80]. This technology is not very reasonable for MV transformers but will be discussed in more detail for HV applications.

Furthermore, the protection concepts regarding voltage surges and overload need to be designed in a way that keeps the electrical stress level at a minimum.

Ageing

The ageing of MV transformers will not be taken into account within this investigation.

LCC of Transformers

The life cycle costs of transformers in general consist mainly of lost revenue caused by active power losses and maintenance actions and can be calculated by use of equation 2.93, which was introduced in subchapter 2.4.3. [78]. The costs of erection and infrastructure will be neglected within this thesis. The evaluation of the costs of preventive and corrective maintenance as well as the outage related costs were introduced in subchapter 2.4.2. The operational costs or in other words the costs for active power losses can be evaluated by the following equation

$$C_O = (c_P + cf \cdot T_c \cdot c_E) \cdot P_{NL} + (c_P + lf \cdot T_c \cdot c_E) \cdot \left(\frac{S_{max}}{S_r} \right)^2 \cdot P_{LL} \qquad (4.20)$$

c_P	*price for installed power*
c_E	*electricity price (subsidies)*
cf	*capacity factor*
T_c	*calculation period*
P_{NL}	*no load losses*
lf	*loss factor*
P_{LL}	*load losses*

The concept of evaluating the active power losses is discussed in more detail in subchapter 5.3.The criteria used in such an economic analysis also indirectly consider the following topics: safety; condition of the assets; age; operation condition; availability; maintainability; environmental and risk (consequential costs at fault).

4.2.2.3 MV-Switchgear

There are two different types of MV switchgear within a wind farm. The MV switchgear that connects the feeders to the power transformer, which is typically located within the wind farm substation, called the primary MV switchgear. The secondary MV switchgear on the other hand denotes the switchgear of the ITS/ETS system that connects each WEC to the MV collector system. There are various kinds of primary and secondary switchgear which shall not be further discussed in this investigation. Only relevant reliability figures for the MV switchgear used by Repower are shown in the table below.

Component	Type	λ_F [1/bay yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [k€/unit]
Built-in GIS	primary	0,0020	510,2	72	0,25	4	6	30.
Compact GIS	secondary	0,0013	800,0	72	0,25	4	6	30.
Areva GHA	primary	0,0104	96,0	72	0,25	4	6	25.

Table 4.13 MV-switchgear reliability figures [53]

The evaluated reliability and availability of the primary and secondary MV switchgear is presented in the following table.

Component	R(20) [%]	A* [%]	A [%]
Compact GIS	96,16	99,981	99,998
Built-in GIS	97,53	99,981	99,999
GHA	81,19	99,974	99,991

Table 4.14 MV switchgear availability

From the above table, it can be assumed that the availability of MV switchgear in general is very high. Furthermore, maintenance actions don't really affect the availability of individual switchgear panels, since the maintenance time is very small. However, due to the vast amount of secondary MV switchgear these figures have to be reconsidered.

Failure Mechanisms

The basic types of MV switchgear regarding their type of insulation are magnetic air, minimum oil, vacuum and SF6 insulated switchgear. Whereas, vacuum and SF6 insulated types are the most common ones nowadays because of economical and technical reasons. Thus the following failure mechanisms and their frequency of occurrence focus on these two types in particular.

- <u>Loose Connections</u>

Loos or faulty connections can cause a higher resistance which lead to an increasing temperature, according to ohm's law. Thus thermal ageing effects apply and reduce the lifetime significantly. Approximately 25% of all switchgear failure causes are due to lose connections and thermal breakdown [83].

<u>Insulation Breakdown</u>

- o *Busbar*

Most MV switchgear types use solid insulation barriers to separate adjacent switchgear panels and to support the busbar. These barriers may have small voids and air gaps between the busbar and the insulation, which cause a higher electrical stress level and can lead to partial breakdown and furthermore to failure of the whole switchgear.

- *Switchgear*

The breakdown of the insulation of the switching device results in a failure to clear the actual fault. The mechanical parts of the breaker will operate properly, but the breaker is unable to interrupt the fault current (arc) due to lost insulation strength. Manufacturers typically recommend blocking of the breaker tripping mode in case of loss of insulation strength in order to prevent mechanical or electrical damage [84].

- Failure to Trip

The breaker contacts do not open after the relevant circuit has been energised by the protection scheme. These failures are usually caused by the mechanical parts of the breaker. However, when evaluating such fault conditions the impact of the overall protection concept (relay, wiring, power supply etc.) needs to be taken into account (See subchapter 4.2.4.2).

Reliability Improvement Measures

In order to keep the availability of the secondary MV switchgear at a high level, a well considered maintenance support is essential. Furthermore, the maintenance related inspection and testing of the mechanical parts of switching devices are an important mean to evaluate the actual condition of the switchgear. Since the outage of a primary MV switchgear panel has a major impact on the proper function of the wind farm, the use of reliable and redundant systems is important to keep the outage time down. An additional switchgear panel for example can be installed at low costs and would ensure a fast troubleshooting.

Ageing

The lifetime of switching devices (e.g. circuit breakers) is typically denoted by their switching cycles. According to which type of switchgear is used the lifetime can vary significantly. Since the main functional parts of switching devices operate mechanically, the wear-out period is characterised by mechanical ageing effects.

LCC

The lifecycle costs of MV switchgear are determined by the costs for preventive and corrective maintenance and not so much by the operational costs. Especially the costs for preventive maintenance have to be taken into account (see subchapter 5.5). Thus the development of a particular maintenance strategy is of vast interest.

4.2.3 High Voltage Equipment

The share of HV components of the wind farm depends on the property boundary between the owner of the wind farm and the HV grid owner, therefore it is strictly project related. Since the HV grid connection (HV line) usually doesn't belong to the owner of the wind farm the main focus will be on the power transformer.

4.2.3.1 HV-Cable

The insulation properties of HV cables are vitally important due to the significantly higher electrical stress level compared to MV cables. Especially the loss factor (tanδ) has a major impact on the operation of HV cables. Nowadays, XLPE is the most common insulation material for HV cables because of its low loss factor. A general overview of the properties of different insulation systems of cables are presented in subchapter 4.2.2.1 'MV Cable'. Table 4.15 shows the reliability figures of different types of HV cables.

Component	λ_F [1/km yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [k€/km]
XLPE	0,0014	719,4	72	0	0	0	350.
PE	0,1478	6,8	72	0	0	0	300.
Oil filled	0,0124	80,6	96	0,2	5	8	~

Table 4.15 HV-cable reliability figures

It can be assumed, that solid insulated HV cables are maintenance free, whereas oil insulated cables are not due to their construction. Recent studies have shown that over 55% of corrective maintenance actions of HV XLPE cables are done in less than one week. Only in 5% the repair lasts longer than one month [77]. The average failure related outage time of extra high voltage (EHV) cables is 25 days. The MTTR of HV cable is assumed to be three to four days, based on figures from subcontractors.

The availability and reliability of different HV cable types are presented in the table below.

Component	R(20) [%]	A* [%]	A [%]
XLPE	97,26	99,998	99,998
PE	5,21	99,878	99,878
Oil filled	78,04	99,968	99,986

Table 4.16 HV cable availability

The availability and especially the reliability of PE insulated HV cables are significantly lower, because of the poor properties of PE. (Subchapter 4.2.2.1)

Failure Mechanisms

Recent studies have shown that the frequency of external failures of HV cables is equal to the frequency of internal failures, unlike the failure statistic of MV cables [77]. Furthermore, the share of internal failures of HV joints is significant, but needs to be reconsidered since the number of observed failures is rather small. The failure rate of HV cable systems (incl. accessories) is approximately 3 times higher than those of MV cable systems. However, compared to the German availability and disturbance statistic the overall failure rate of XLPE HV cables is approximately 50% lower.

LCC of HV Switchgear

The cost structure of HV cable systems is quite different to those of MV cable systems. Especially the investment costs, which basically consist of costs for material. Thus the excavation and laying concept has less influence on the investment. Therefore, the whole cross section optimisation process used to keep the operational costs (active power losses) at a minimum need to be reconsidered.

For information about general properties (e.g. reliability improvement measures, ageing, tests, insulation system...etc.) of HV cable systems see 4.2.2.1.

4.2.3.2 Power Transformer

Power transformers connect the MV collector system to the upstream transmission network and therefore are essential components for the proper function of the whole wind farm. Their reliability is a key factor in profitable generation. Table 4.17 shows reliability figures for large oil transformers in general and for their on-load tap changers (OLTCs) in particular.

Component	λ_F [1/yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [€/kVA]
Trafo	0,0182	55,1	168	1	1	8	15
OLTC	0,0082	150	168	0,14285714	7	168	n.q.

Table 4.17 HV transformer reliability figures [53]

The reliability of power transformers can be assumed to be at a high level, according to Table 4.18. However, there is a probability of thirty percent that the power transformer experiences a failure within twenty years.

Component	R(20) [%]	A* [%]	A [%]
Trafo	69,54	99,873	99,965
OLTC	85	99,87	99,97

Table 4.18 HV transformer availability

Recent studies have shown that the transformers subcomponents in general and the OLTC in particular are major failure causes. Since the time to repair a failed OLTC is approximately one week, regardless of factors like location, type...etc. the overall availability of power transformers is very high. Figure 4.8 shows failure causes of power transformers and their related frequency of occurrence. It can be seen, that almost eighty five percent of all failures that lead to an outage are either caused by the OLTC, the Windings or the Bushings.

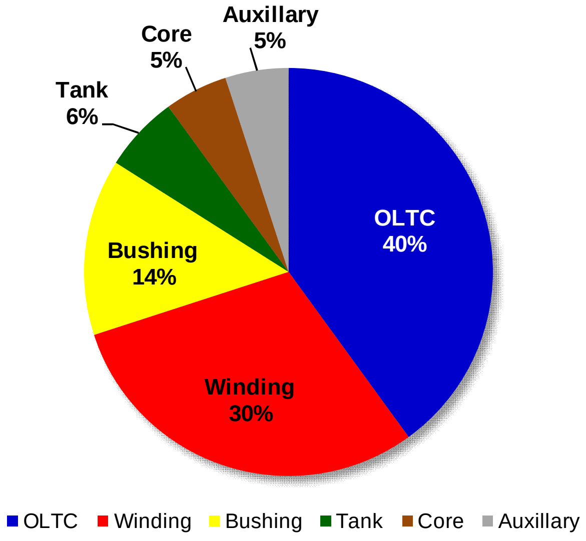


Figure 4.8 Failure causes of power transformers

The reliability figures of OLTCs in table 4.17 are from historical data and operational experience of utilities. In order to get a better understanding of different types of OLTCs and their specific availability, the MTBFs of the most common OLTC types are presented in the following table. Additionally the related switching cycles are shown, in order to provide a better understanding.

OLTC	MTBF [yr]	Switching Cycles
Oiltap-M	1389	200.000
Oiltap-R	1313	200.000
Vacutap-VR	651	300.000
Vacutap-VV	2326	300.000

Table 4.19 MTBFs of OLTC types

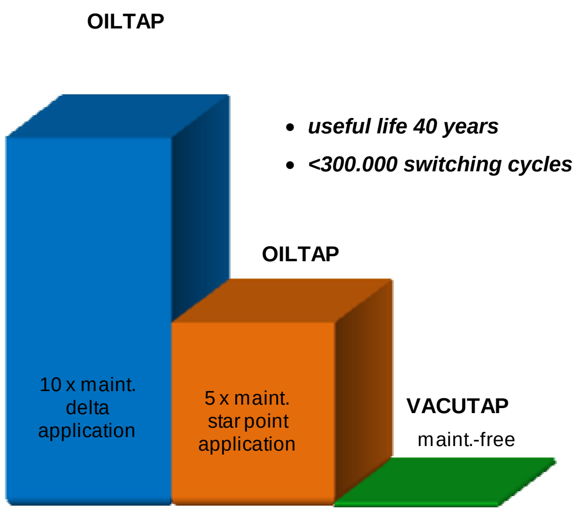


Figure 4.9 MTBM of different OLTC types[80]

It can be seen, that the failure related outage time of different OLTC types over the useful lifetime of a wind farm is rather low. After all, for availability reasons the maintenance related outage time is of vast significance. Figure 4.9 provides an overview of MTBM of common OLTC types and their application. The availability calculation in subchapter 4.3 is based on an OILTAP with star-point application, hence the MTBM is assumed to be six years with an average time to maintain of one week.

Since the power transformer is of high interest for the proper function of the wind farm, a brief overview of mean repair times for different power transformer failure causes and mechanisms is provided below.

Failure location	Info	MTTR [weeks]
OLTC	on-site	1
Windings/Tank	on-site	~20
	off-site	30-52
Bushings, Auxilliary....etc.		n.q. (<2)

Table 4.20 MTTR of different failure causes

The different failure mechanisms of power transformers and MV transformers can be assumed to be similar, thus for more information see 4.2.2.2 MV-Transformer.

Reliability Improvement Measures

The bushings and the tap changer are the first parts that experience a higher failure rate during operation due to ambient and mechanical effects. The higher risk of these items can easily be covered with spare parts because of the low investment costs (e.g. bushings). Further reliability improvement measures are:

- Protection Concept
- Hermetic vs. Liquid Tank
- Repeated Testing
- Maintenance Activities

Diagnostic and Monitoring System

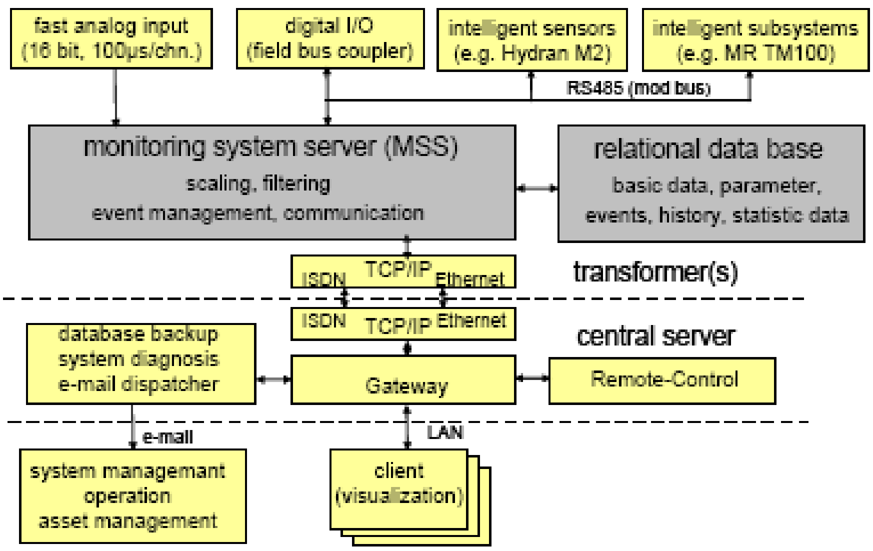


Figure 4.10 Concept of an online monitoring system for power transformers

Figure 4.11 shows a basic concept of an online monitoring system for power transformers with all the significant interfaces. The influence of such a system on the overall life cycle costs can be seen in the table below. It should be pointed out, that the additional investment costs are the only negative impact of monitoring systems on LCC. For more information on diagnostic and monitoring systems for power transformers see [85][80].

Ageing

Recent surveys have shown that network short circuits have no relevant impact on the transformers thermal ageing. Even if the load factor is 1,2 p.u. and the short circuit lasts five seconds the reduced lifetime due to thermal ageing would be twenty one days, which is neglectable compared to other effects. The overload of power transformers compared with the low load factor due to the high wind fluctuation is a major factor when designing power transformers of wind park applications. However, the exact impact of the rather high and fast temperature deviations caused by the load factor is hard to estimate.

Figure 4.12 shows the relative failure rate over the lifetime of HV transformers. It can be seen, that ageing effects can be expected after 25 years in operation.

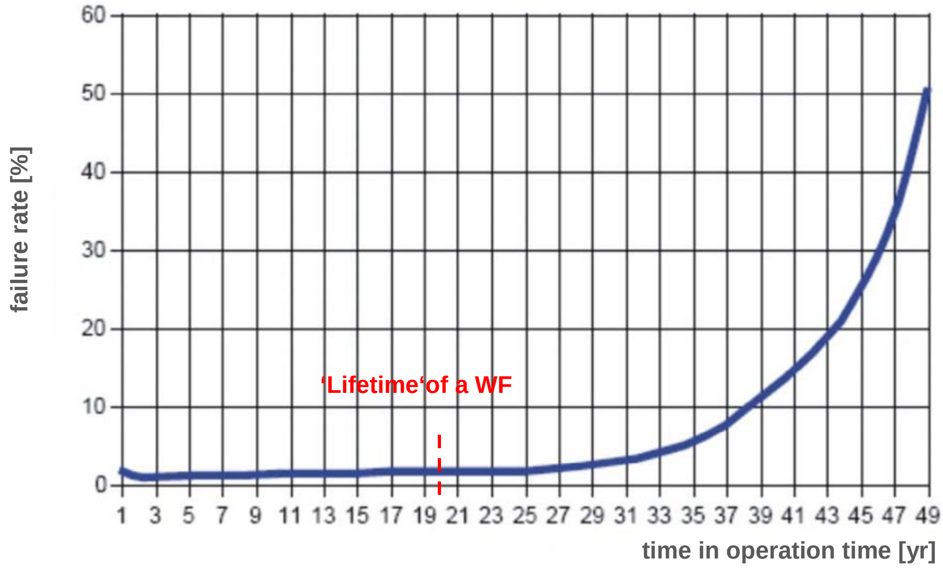


Figure 4.11 Transformer bath tub curve [5]

Compared with the lifetime of the whole wind farm the ageing effects of HV transformers can be neglected.

LCC of Power Transformers

LCC of power transformers are basically the same as those of MV transformers, except the maintenance related costs. The costs for preventive maintenance actions are much higher for power transformers, due to the mechanically operating parts (OLTC) as well as the higher stress level during operation.

4.2.3.3 HV-Switchgear

For the proper function of the wind farm the HV switchgear is as important as the power transformer. There exist various types of HV switchgear, for economical and environmental reasons gas insulated switchgear types are most frequently used for wind farm applications. Reliability figures for GIS types indoor as well as outdoor and for interior AIS types are presented in table 4.22 below.

Component	λ_F [1/yr]	MTBF [yr]	MTTR [h]	λ_M [1/yr]	MTBM [yr]	MTTM [h]	C_0 [k€/panel]
GIS Indoor	0,0171	58,5	96	0,25	4	6	70.
GIS Outdoor	0,0139	71,9	96	0,25	4	6	60.
Interior AIS/open	0,0054	186,2	72	0,25	4	6	50.

Table 4.21 HVswitchgear reliability figures

The reliability over a period of twenty years of HV switchgear is higher than 71% and thus the overall availability can be assumed to be very high. Even if the maintenance time is taken into account the availability is beyond 99%.

Component	R(20) [%]	A* [%]	A [%]
GIS Indoor	71,03	99,959	99,976
GIS Outdoor	75,73	99,963	99,981
Interior AIS/open	89,82	99,975	99,992

Table 4.22 HV switchgear availability

Since HV switchgear often belongs to the grid operator’s responsibility (property boundary) it will not be discussed any further.

Failure Mechanisms

Failure mechanisms of different switchgear types were discussed in general in subchapter 4.2.2.3-MV switchgear, which can also be applied for HV components.

Ageing

HV Switchgear has rather low switching cycles during operation compared to primary and secondary MV switchgear. Thus certain aging effects on current-carrying parts (e.g. contact pin) are very rare. Nevertheless, the proper function of the isolation system should be checked from time to time due to the high electrical stress level.

4.2.4 UPS and Protection Systems

4.2.4.1 Uninterruptable Power Supply

Within a wind farm there can be distinguished between *uninterruptable power supply* facilities (*UPS*) for the WEC and the substation. The requirements for both applications extremely differ from each other. However, since a specification for the WEC’s UPS system already exists, the main focus here is on the evaluation of UPS systems for substations. Since the continuous operation of emergency and safety systems (e.g. protection devices) depends on the capabilities of the UPS, these systems together with the auxiliary power supply are a major factor in availability and risk evaluation. The two most important design parameters for UPS systems are the rated power and the time interval the system should be in operation. In order to take the mean administrative delay and the travel time of service teams into account a reasonable operational time interval for UPS systems is between 4 and 7 hours. Battery based systems and emergency power generators are the most common UPS systems nowadays. In most cases, the battery based system is more suitable. Nevertheless, it is useful to evaluate both system with respect to their LCC and availability.

Static UPS

Static UPS systems consist of accumulators to store the relevant amount of energy. These accumulators usually use lead acid batteries. The mean lifetime of this kind of batteries commonly lies between 8 and 10 years. Thus it can be assumed, that battery based UPS system for wind farm applications need to be replaced at least once. Another issue of lead acid batteries is, that in order to optimise their lifetime they should be put under stress at least once a year. The second type of batteries, which should be considered, are the wet batteries with a mean lifetime of 14 years. Although their lifetime is significantly higher, the additional effort regarding maintenance actions and structural measurements should be taken into account. Furthermore, wet batteries generally should operate under constant ambient temperature. (20-25°C) Figure 4.12 shows a sketch of a static UPS system with an additional design example.

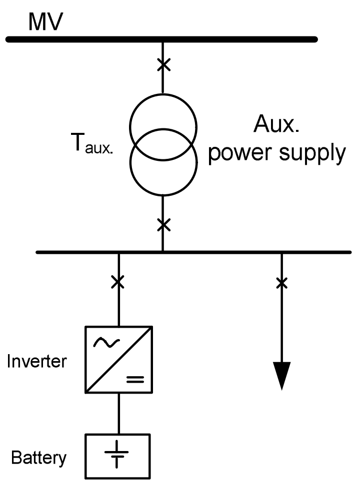


Figure 4.12 Static UPS

Design Example of a static UPS system for substations:

P_r=100kVA (80-90kW),

t_r=3h full load (note: operating life is a function of stress)

Implementation with lead-acid batteries would require 4 x 32 battery blocks (physical dimensions: 4m x 2m framework), investment 66.000 Euro.

Converter including all accessories would cost 15.000 Euro.

Overall investment costs ~80.000 Euro

λ=0,007 [1/yr], MTBF=125 [yr], MTTR=30 [h]

A=100,00%, R(20)=85%

The overall investment for static UPS systems for large wind farm substations is approximately 80.000 to 100.000 Euros without taking maintenance actions into account [21]. Depends on the rated power, the operation time and the type of batteries. Furthermore, static UPS systems have a low mean time between failure at first sight but the mean time to repair is very low. Thus the availability of such systems is very high [21].

Emergency Power Generator

Fuel driven *emergency power generators* (*EPG*) should be designed in a way that the load doesn't exceed 60-70% of the generators rated power, because of reactive power reserve issues and switching actions. The additional investment costs regarding structural measures, air ventilation, fire protection or mitigation of exhaust gases should be taken into account. Figure 4.13 shows a schematic single line diagram of an EPG unit with an additional design example for a wind farm substation application.

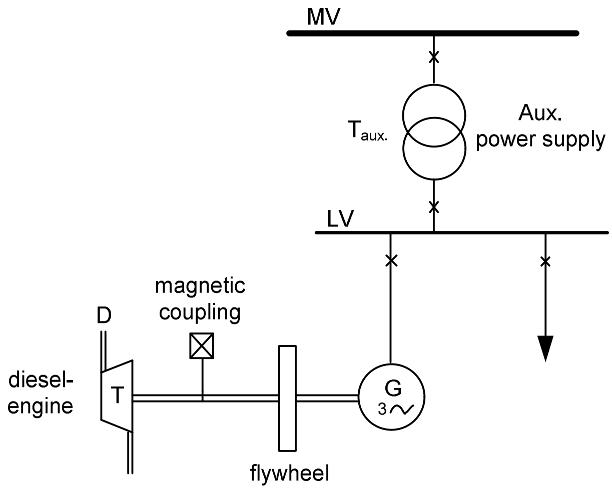


Figure 4.13 Emergency power generator

EPG unit, design example:

P_r=200kVA (160kW)

t_r depends on the size of the fuel tank and the load (specific fuel consumption: 40 litre per hour at full load)

EPR investment costs: 24.000 Euro

Including accessories: 5.000 Euro

Annual maintenance costs: 1500 Euro

Overall investment costs ~30.000 Euro

λ=0,1235 [1/yr], MTBF=8 [yr], MTTR=18 [h], A=99,97%, R(20)=8%

The overall costs of emergency power generation systems including a combustion engine, electrical generator; electrical switchgear and start up equipment are lower for high energy demands compared to a static UPS system. However, the LCC of both Systems are similar considering the additional maintenance and fuel effort for EPS and the relatively short life-time of the UPS batteries. Due to technical reasons, it should be pointed out, that the immediate readiness for use of both systems can differ significantly. Static systems commonly operate online with additional bypasses for maintenance and automatic control issues. Whereas EPS systems can operate either online or offline, which depends on the design implementation. (E.g. with flywheel, rotary converter...etc.) Therefore a exact specification of the preferred operation mode is necessary due to the very high investment costs for online systems. A combination of both systems with different operation ranges would be a cost optimised solution to this problem.

It is a necessity that the coordination between the different UPS systems within a wind farm is carried out thoroughly. Especially the coordination between the WECs and the substation should be investigated in more detail.

Further investigation:

- Static UPS vs. emergency power generator?
- WECs that are close to the substation may be used for the substations auxiliary power supply?

4.2.4.2 Protection Devices

Fault trees are widely used to estimate the reliability of different protection configurations of electrical power systems. (See chapter 2.3.3 and [59]) Figure 4.15 shows such a fault tree for a simple protection system. (E.g. Instantaneous overcurrent protection device)

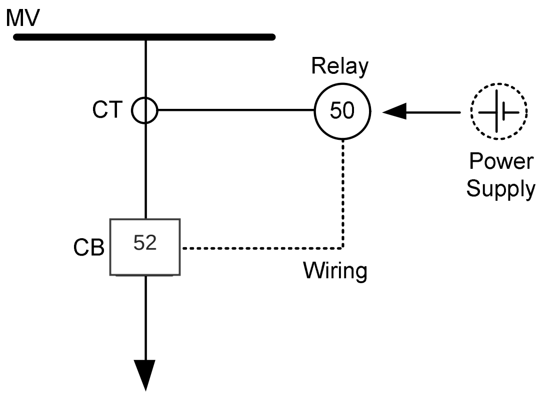


Figure 4.14 Protection System

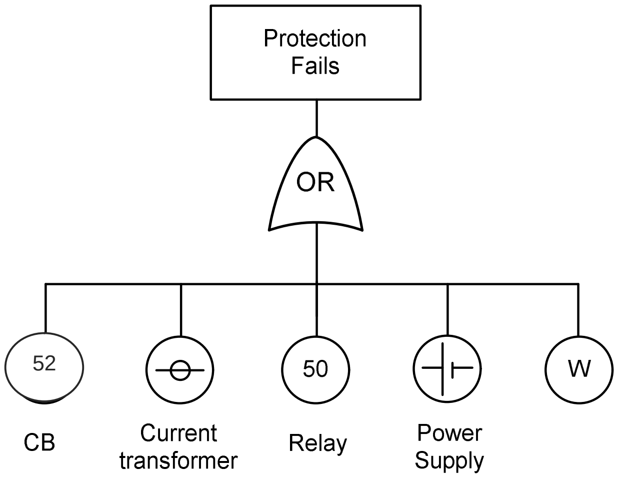


Figure 4.15 Fault tree of a protection system

The OR gate indicates that if any of the events occur, either the current transformer, the relay, the battery, the wiring or the circuit breaker fails the whole protection system is going to fail. The power supply of the relay can either come from the current transformer (Normally used for LV protection devices) or from the 24V direct current network which is also connected to the uninterruptable power supply (Normally used for MV protection devices). Because of the semi redundant design of the power supply it can be assumed that their failure rate is very low. The same can be assumed for measurement transformers.[29] Thus the main fault cause of protection systems is the relay and the circuit breaker itself. Protection devices using relays with supervision, and with monitored alarm contacts have a better level of availability if periodic testing is not performed, since the expected loss of service due to automatically detected failures is much lower [58]. The MTBF of modern digital relays can be assumed to be 100 years, which is conservative. If the relay has a monitoring system regarding loss of voltage and loss of current the effectiveness increase to 98% due to the additional coverage of the measurement transformers. Routine testing of protective relays has been the primary method of detecting failures in relays. The only other way of determining that a relay has failed is to actually observe a failure. Computer-based relays are often equipped with automatic self-test functions that verify the correct operation of the relay. Improving the reliability of protection systems can either be managed through redundancy, through the use of back-up systems or by overlapping the protection zones. Since the most critical components of protection systems are the relay and the circuit breaker, redundancy as well as overlapping protection zones should be consider. Back-up systems on the other hand would require a higher investment. .(General info: low MTBM ~ 5-10 years → low LCC)

4.3 Subsystems

This subchapter is intended to show the evaluation methods discussed in the previous chapters applied to a wind farm example. The single line diagram of evaluated wind farm is shown in Figure 4.16. This typical wind farm consists of 50 MM92 Wind turbines with a rated power of 2,05MW per WEC. The collector system is designed with five feeders due to short circuit capabilities and the optimised cable length for the interconnection of the turbines. Furthermore, a static reactive power compensation is connected to the medium voltage bus bar to meet the utilities predetermined grid code requirements regarding reactive power control and voltage stability capabilities….etc. A power transformer is used to connect the wind farm to the high voltage grid, which is a common substation layout for wind farms at this level of installed capacity.

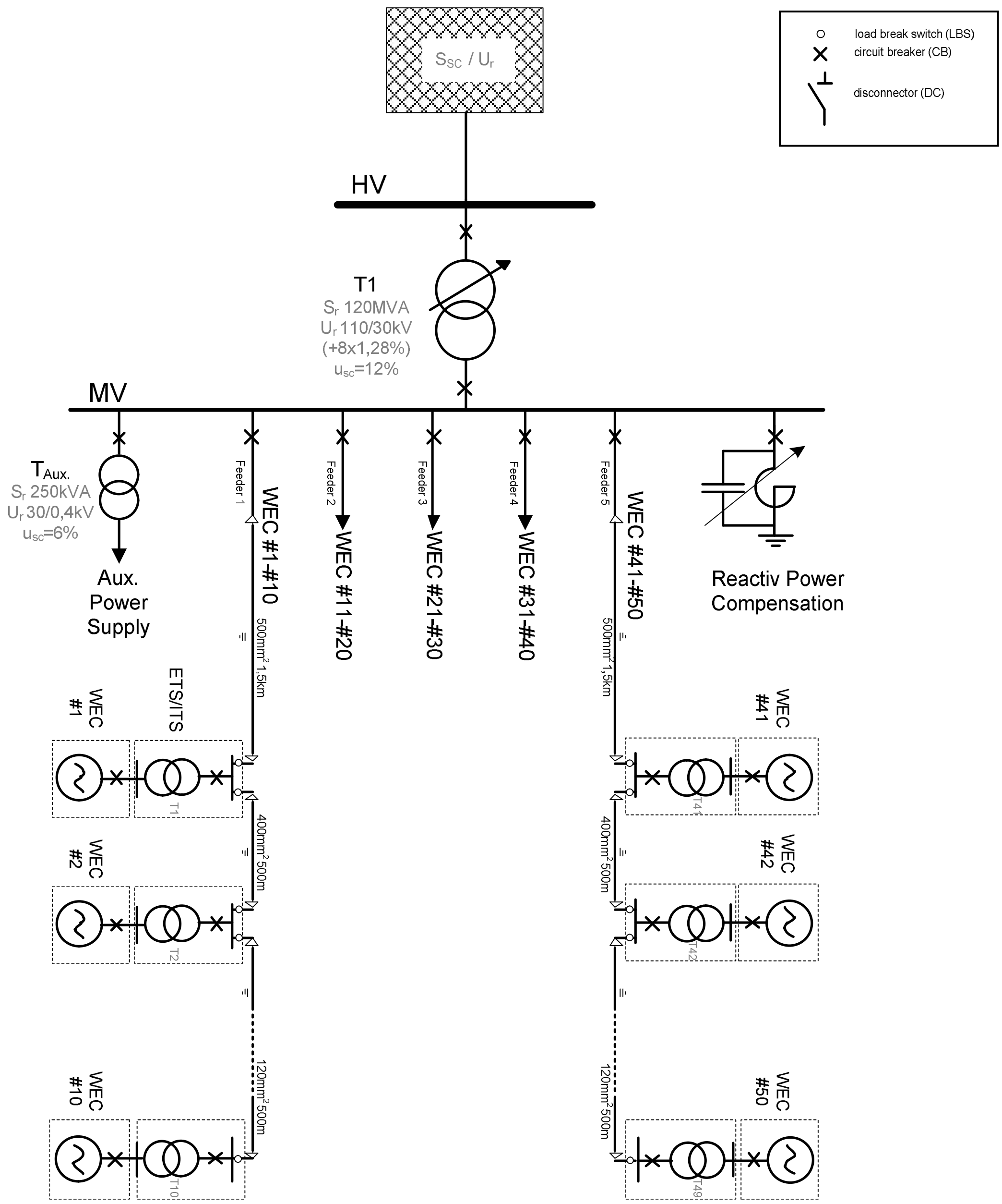


Figure 4.16 Wind farm SLD (*P_r=102MW*)

4.3.1 The Wind Energy Converter

The different capacity levels and the associated probabilities of nonexistence can be seen in Figure 4.17. The *Capacity Outage Probability* (*COP*) can be easily obtained using the binomial distribution. The probability that all turbines are in an up state (functioning) is according to Figure 4.17 ~35%. Considering any unit can be out of service the probability that all the other turbines are functioning is round about 70%, or in other words 70% of the time more than 98% of the installed capacity is available.

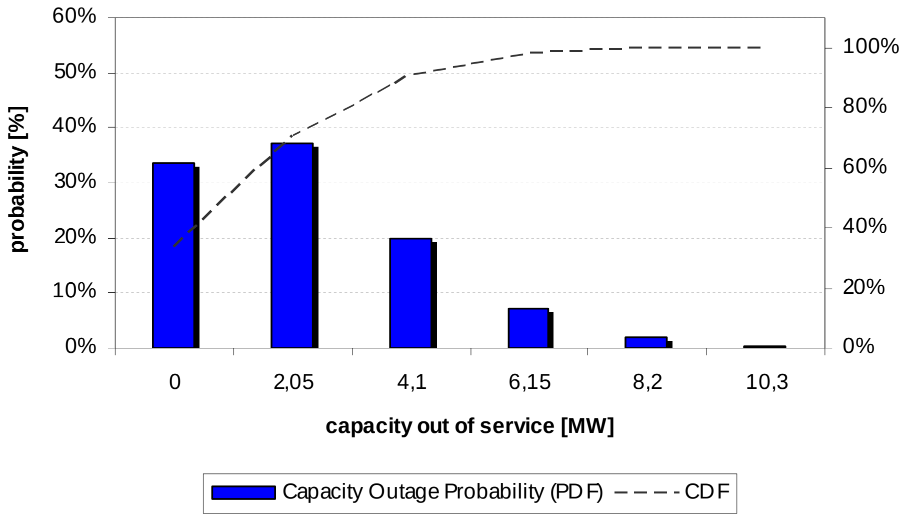


Figure 4.17 Capacity outage probability

$$f(x) = P(X = k) = \binom{n}{k} \cdot p^k \cdot (1-p)^{n-k} \tag{4.21}$$

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!} \tag{4.22}$$

k = 1,2,….,n
p = U…unavailability
X = MW (capacity out of service)

$$F(x) = \sum_{i=0}^{k} \binom{n}{i} \cdot p^i \cdot (1-p)^{n-i} \qquad 0 < k < n \tag{4.23}$$

Applied to the capacity outage probability, the probability of how many WECs (k out of n) are out of service at time t is obtained by using equation (4.21). Whereas, equation (4.23) provides the probability that maximal k WECs (out of n) are out of service. (See CDF in Figure 4.17) The expected capacity out of service for this particular wind farm is 2,16MW, in numbers of turbines this would be one turbine which can be expected out of service at an arbitrary time. The standard deviation for the expected capacity out of service therefore is:

$$E(X) = n \cdot U \qquad \sigma(X) = \sqrt{n \cdot p \cdot (1-p)} \tag{4.24}$$

$$E(MW) = 49 \cdot (1 - 0{,}975) = 2{,}16 MW$$

$$\sigma(MW) = \sqrt{49 \cdot (1 - 0{,}975) \cdot 0{,}975} = 1{,}45 MW$$

The probability that any WEC is out of service is according to Figure 4.17 70%, or in other words there is a 30% risk, that more than just one WECs are out of service.

Now since the guaranteed availability over a period of one year is 97% and the reliability figures from Table 4.4 WEC availability' exactly meet this value, for further calculations an average availability of 96% is assumed. Thus, the failure rate of the WEC is assumed to be 0,5-1 failure per year with a mean down time of approximately 85 hours.

Due to the fact that these assumptions (λ_{WEC}=0,5, MTTR=85h) are very rough the WECs will not be taken into account in further calculations

4.3.2 MV Collector System

The MV collector system of the wind farm has a radial topology which consists of 5 feeders to connect the wind turbines to the substations medium voltage busbar. The electrical single line diagram of such a feeder is shown in Figure 4.18.

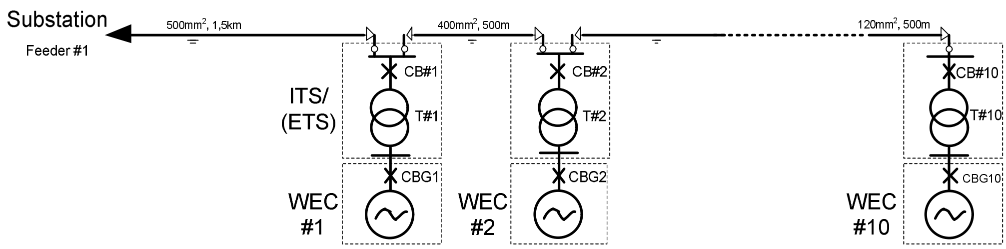


Figure 4.18 Single line diagram of one feeder (#1)

To calculate the reliability parameters of the collector system shown in Figure 4.18 a reliability block diagram is used. In order to keep all wind turbines connected to the medium voltage busbar each electrical component between the turbine itself and the busbar has to be in an up state (functioning). This indicates a series structure of the components. Figure 4.19 displays the reliability block diagram of one feeder.

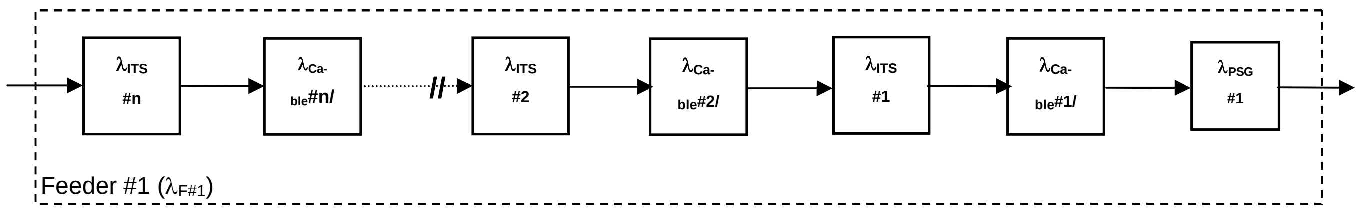
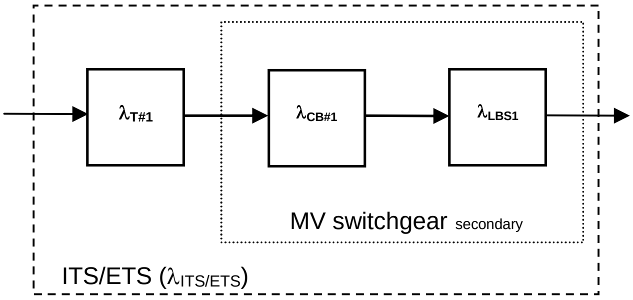


Figure 4.19 Feeder-reliability block diagram

In this reliability block diagram ITS denotes the internal transformer system which contains the generators step-up transformer and the necessary MV switchgear. (See subchapter 2.3.2) The model for the ITS is shown in Figure 4.20. Furthermore the most important equations to calculate the failure rate, the mean repair time and the unavailability of the system are summarised below.



$$R_{F\#1}(t) = \prod_{i=1}^{n} R_i(t)$$

$$\lambda_{F\#1} = \sum_{i=1}^{n} \lambda_i \qquad U_{F\#1} = \sum_{i=1}^{n} \lambda_i \cdot r_i$$

$$r_{F\#1} = \frac{U}{\sum_{i=1}^{n} \lambda_i}$$

Figure 4.20 ITS-reliability block diagram

The results for the collector system are shown in subchapter 4.3.5 'Availability and Expected Energy Not Supplied', page 99.

4.3.3 Substation

The common substation layout for wind farms is very simple, because of the budget restrictions and the lower reliability requirements of generation systems compared to the supply reliability requirements of distribution systems. Figure 4.21 shows such a typical substation layout for the 102 MW wind farm example. For simplicity reasons the disconnectors (DC00, DC01 ect.) below to their respective circuit breakers are not shown in the following single line diagram.

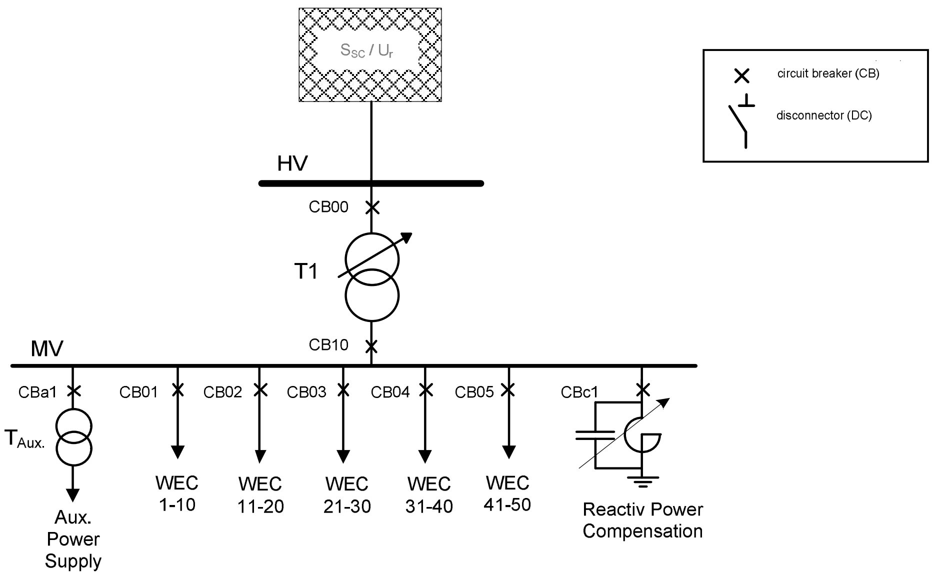


Figure 4.21 Windfarm substation SLD

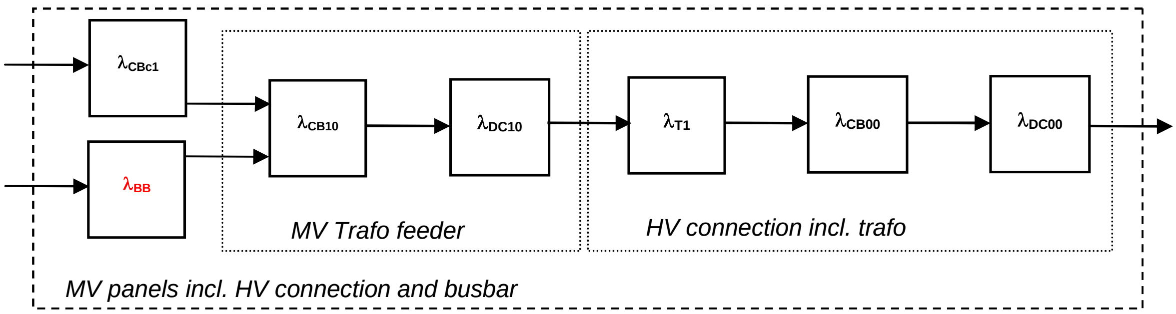


Figure 4.22 RBD of the substations power trafo connection

The model of the power transformers HV and MV connection is presented in Figure 4.22, which also considers the MV busbar. The reactive power compensation and its influence on the reliability of the substation was thereby modelled as a parallel branch within the reliability block diagram since an outage of the compensation doesn’t necessarily cause the whole system to fail (see subchapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). A simplified model of the whole wind farm substation is shown in Figure 4.23. This figure focuses on the primary components.

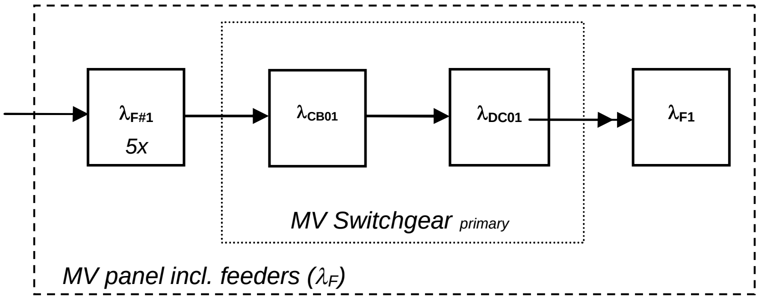


Figure 4.23 RBD of the MV part of the substation

Details like, the auxiliary power supply, the UPS system etc. are not displayed in this figure, in order to keep it simple.

4.3.4 Protection System

A wind farm can be divided into 3 different protection zones, the HV grid connection, the MV collector system and the WEC (LV side) itself. It is obvious, that the protection systems of these three protection zones must be coordinated adequately. Otherwise certain fault events, for example a *Fault Right Through (FRT)* that has its origin within the upstream grid, can cause undesired interactions between protection zones. Figure 4.24 shows a schematic single line diagram of the basic protection concept for wind farm substations with one power transformer. The main protection of the power transformer is usually realised by a differential protection. The general protection settings used for the HV connection are: instantaneous, directional and time delayed phase overcurrent, instantaneous and time delayed neutral overcurrent, directional earth fault, over- and under-voltage and circuit breaker fail as well as line differential protection for the power transformer MV cable connection. The protection settings for feeder circuit breakers usually consist of: instantaneous, directional and time delayed phase and neutral overcurrent, directional and sensitive earth fault, metering and circuit breaker fail.

The protection concept of a wind farm is shown in Figure 4.24 for the substation and in Figure 4.25 for the ITS(ETS) system. The power supply for the WECs protection devices in particular for their relays are directly from the onsite current transformer unlike the protection relays within the substation which are connected to the local UPS system.

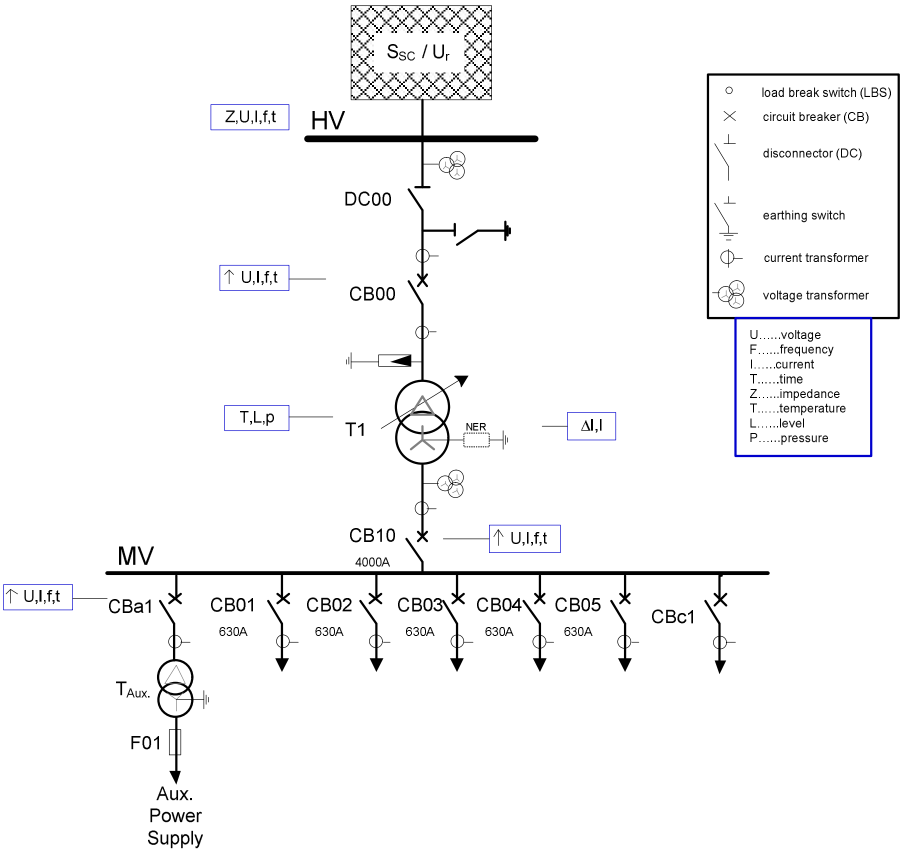


Figure 4.24 Substation protection concept

The protection concept of WEC step up transformer system is shown in Figure 4.25. The Protection settings of several protection devices can be seen in Table 4.24.

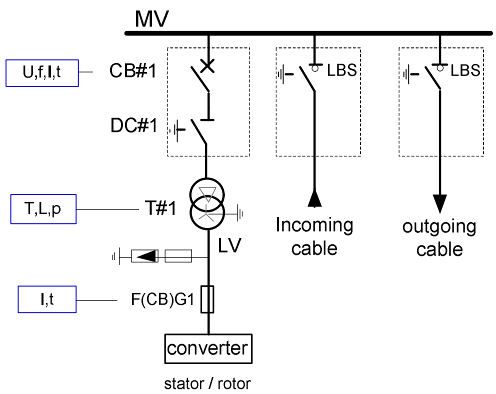


Figure 4.25 ITS/ETS Protection concept (alternative 1)

Protection Device	Description	t_R [ms]	t_I [ms]	I_T [A]	ANSI Index
CB00-01	Diff.protection	150	200	n.q.	87
CB#1-10	Instantaneous overcurrent protection	40	100	n.q	50
CB01-CB05	Inverse time overcurrent	100	160	n.q.	51

Table 4.23 Protection settings

t_R……response time *t_I……interruption time* *I_T……current threshold*

Zone Branch Concept

The zone branch concept can be used to evaluate the reliability of protection concepts and therefore determine their share of system faults. This method assumes that all occurring faults are permanent and the protection devices perfectly isolate all faults immediately. Moreover the protection devices are perfectly coordinated, thus perfectly selective [12]. The main advantage of the zone branch method is that it can immediately identify incorrect protection concepts including all components and at the same time estimate the reliability of the system. Figure 4.26 represents the zone branches of the wind farm example. The zone number represents the number of protective devices between the source (utility) and the observed location.

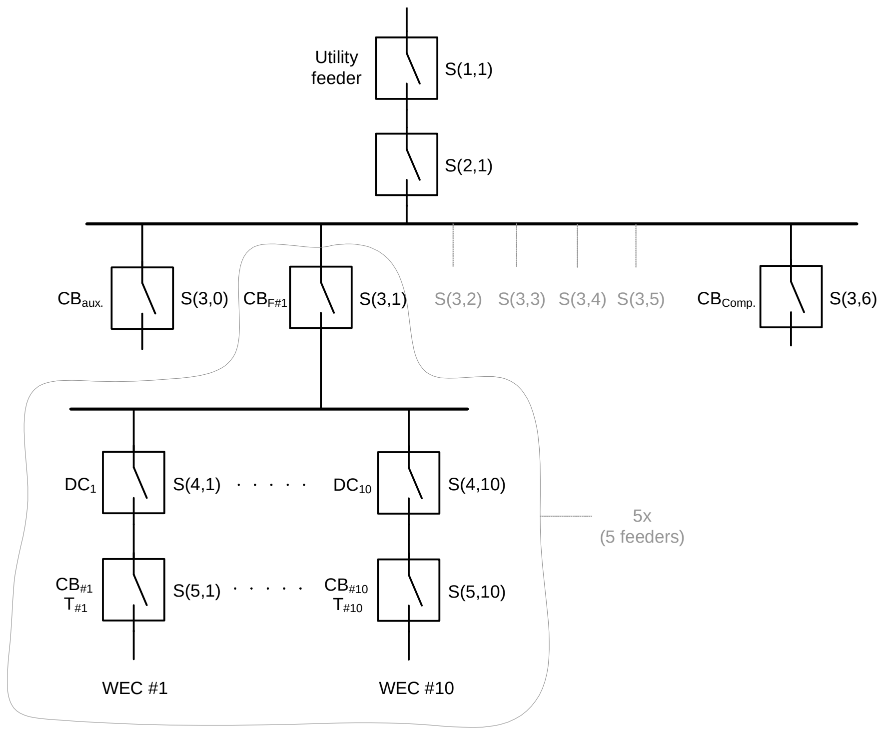


Figure 4.26 Wind farm zone branches

The failure rates of the individual protection devices and their related unavailability is shown in Table 4.24. Zone branch (1,1) in Figure 4.25 refers to failures that occur within the upstream HV grid (utility) and affect the performance of the wind farm.

The exact evaluation of each zone branch is shown on the next page.

Component	Info	λ_F [1/yr]	MTTR [h]	U [h/yr]
CB00 - 10	HV	0,01371	12	0,012
CB01-05	Feeder#	0,00105	10	0,01
DC01-05	Feeder#	0,001	10	0,01
CB a1	Aux.PS	0,001	10	0,01
CB c1	Compens.	0,001	10	0,01
CB#1-50	WEC#	0,001	8	0,008
LBS #	WEC#	0,001	8	0,008
DC#	WEC#	,0005	8	0,004
CBG	WEC#	0,001	8	0,008
MV busbar		0,01371	8	0,008
utility		1	12	12

Table 4.24 Reliability figures of protection devices

Zone 1 - Branch 1				
$\lambda(1,1) = \lambda_u+\lambda_{cb00}+\lambda_{hvc}+\lambda_{t1}+,5\ \lambda_{cb10}$				**HV Connection**
$\lambda(1,1)$	0,026255	[1/yr]		
λ x r	1,44948	[h/yr]		
r	55,2077699	[h]		
Zone 2 - Branch 1				
$\lambda(2,1) = \lambda_{mvbb} = ,5\ \lambda_{cb10}+\lambda_{bb}+,5\ (\lambda_{cb01}-\lambda_{cb05})$				**MV Busbar**
$\lambda(2,1)$	0,01048	[1/yr]		
λ x r	0,20402	[h/yr]		
r	19,4675573	[h]		
Zone 3 - Branch 1				**5 Feeders**
$\lambda(3,1)$ = F#1 = $,5\ \lambda_{cb01}+\lambda_{mvc}+,5\ \lambda_{lbs1}$				
$\lambda(3,1)$	0,001025	[1/yr]		
λ x r	0,0103	[h/yr]		
r	10,0487805	[h]		
Zone 3 - Branch 2				
$\lambda(3,2)$ = F#2 = $,5\ \lambda_{cb02}+\lambda_{mvc}+,5\ \lambda_{lbs}$				
$\lambda(3,2)$	0,001025	[1/yr]		
λ x r	0,0103	[h/yr]		
r	10,0487805	[h]		
Zone 3 - Branch 3				
$\lambda(3,3)$ = F#3=$,5\ \lambda_{cb03}+\lambda_{mvc}+,5\ \lambda_{lbs}$				
$\lambda(3,3)$	0,001025	[1/yr]		
λ x r	0,0103	[h/yr]		
r	10,0487805	[h]		
Zone 3 - Branch 4				
$\lambda(3,4)$ = F#4 = $,5\ \lambda_{cb04}+\lambda_{mvc}+,5\ \lambda_{lbs}$				
$\lambda(3,4)$	0,001025	[1/yr]		
λ x r	0,0103	[h/yr]		
r	10,0487805	[h]		
Zone 3 - Branch 5				
$\lambda(3,5)$ = F#5 = $,5\ \lambda_{cb05}+\lambda_{mvc}+,5\ \lambda_{lbs}$				
$\lambda(3,5)$	0,001025	[1/yr]		
λ x r	0,0103	[h/yr]		
r	10,0487805	[h]		
Zone 4 - Branch 1				
$\lambda(4,1)$= ITS#1 = $,5\ (\lambda_{lbs1}+\lambda_{lbs2})+\ \lambda_{mvbb}+,5\ \lambda_{cb\#1}$				**50 ITS/ETS**
$\lambda(4,1)$	0,0025	[1/yr]		
λ x r	0,02	[h/yr]		
r	8	[h]		
Zone 5 - Branch 1				
$\lambda(5,1)$ = WEC#1 = $,5\ \lambda_{cb\#1}+\lambda_{T\#1}+\lambda_{cbG}$				**50 WEC**
$\lambda(5,1)$	0,007905	[1/yr]		
λxr	0,17712	[h/yr]		
r	22,4060721	[h]		

The evaluated reliability parameters of the individual zone braches according to Figure 4.26 are presented in Table 4.23 below. The upstream HV grid (utility) can be identified as the major failure source that causes the wind farm to fail. The actual down time due to utility failures was evaluated 13 hours per year. If the HV grid is not taken into account, the second most important failure causes are the WEC itself and the MV part of the substation with almost equally likely mean down times.

Zone Branch	λ_F [1/yr]	MTTR [h/f]	$U=\lambda_F$ x r [h/yr]
(1,1)	1,026	13,11	13,449
(2,1)	0,01048	19,47	0,20402
(3,1)	0,001025	10,05	0,0103
(3,2)	0,001025	10,05	0,0103
(3,3)	0,001025	10,05	0,0103
(3,4)	0,001025	10,05	0,0103
(3,5)	0,001025	10,05	0,0103
(4,1)	0,003	8,000	0,020
(5,1)	0,008845	20,02	0,17712

Table 4.25 Zone branches and their unavailability

The influence of the whole protection concept on the performance of the wind farm can now be estimated by summarizing the individual braches in Table 4.23. The wind farm failure rate due to protection relay faults can then be obtained by the following equation.

$$\lambda_F = \lambda(1,1) + \lambda(2,1) + 5 \cdot \left[\lambda(3,1) + 10 \cdot \left(\lambda(4,1) + \lambda(5,1)\right)\right] \tag{4.25}$$

The reliability parameters of the protection system with and without taken failures from the utility side into account are shown in Table 4.24. The number of failures on the upstream transmission system that have an impact on the performance of the wind farm was assumed to be one failure per year.

Component	Info	λ_F [1/yr]	MTBF [yr]	MTTR [h]	U [h/yr]	A [%]	R(20) [%]	R(1) [%]
Protection system	w/o utility	0,116	9	18	2	99,98	13	90
Protection system	W utility	1,116	9	10	12	99,86	0	33

Table 4.26 Protection system availability

The MTBF of the whole wind farm protection system is approximately 20 years with a MTTR of 40 hours per failure, thus the mean (operational) availability is 99,97% and the probability that the protection system survives a period of 20 years with a failure is 35%. These results can be assumed as accurate, since disturbance statistics show quite similar results. (See [54] and [29])

4.3.5 Availability and Expected Energy Not Supplied

The results of the wind farms reliability evaluation using the derived models from the previous subchapters are presented within the next few pages. The basis for this evaluation is the failure rate of the individual electrical component, which were introduced in chapter 4.2 Grid Connection Components'. To be able to evaluate the influence of different disturbances, three scenarios of the failure rate were taken into account. The *worst case scenario* (*WC*) where all observed disturbances are considered. The *most likely case* (*MLC*) scenario considers only disturbances that were followed by any kind of switching action. And failures that cause system damage were taken into account in the *damage case* (*DC) scenario.* In Figure 4.27 the lumped failure rates for the different scenarios are illustrated.

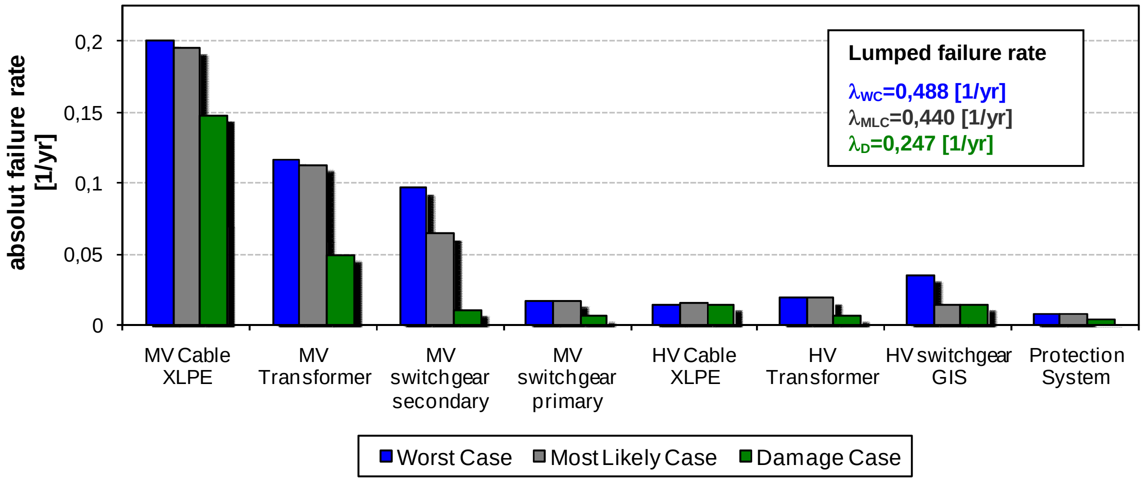


Figure 4.27 Lumped failure rate of components

The frequency of occurrence of wind farm failures and the influence of the WECs towards the grid connection is presented in the following pie chart.

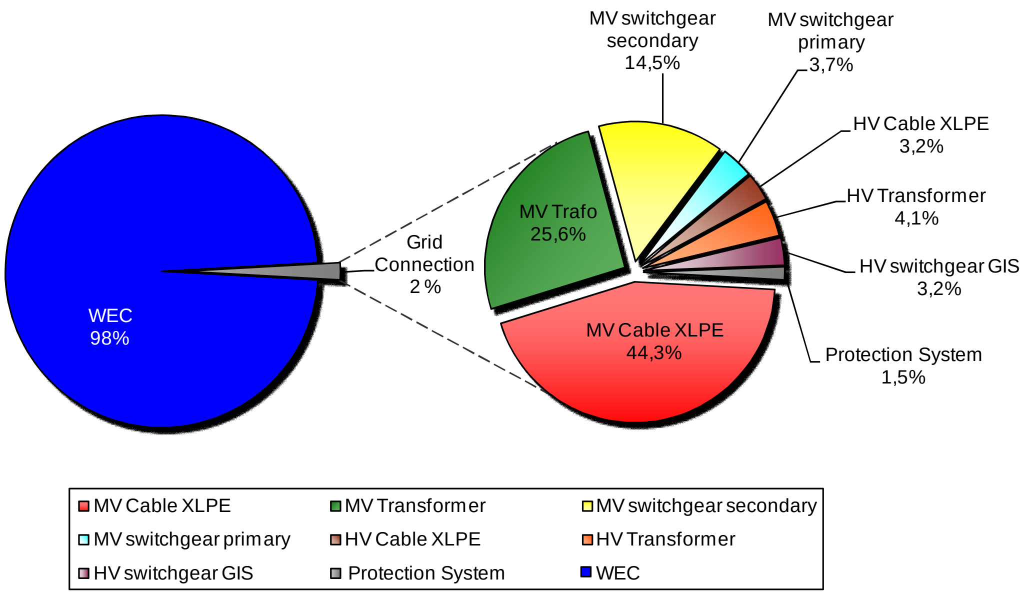


Figure 4.28 Wind farm failure causes

This particular pie chart just compares the lumped failure rates of electrical components and the turbines. The following Tables (4.25, 4.26) present the evaluated availability for each subsystem as well as for the whole wind farm. The table on the left takes the WEC into account, whereas the table on the right only considers the grid connection.

Availability

Feeder	**A** [%]	**λ_F** [1/yr]	**MTTR** [h]
1	95,82	5,08	72,06
2	95,82	5,08	72,06
3	95,82	5,08	72,06
4	95,82	5,08	72,06
5	95,23	4,58	72,06
HV	99,96	0,049	77,63

Feeder	**A** [%]	**λ_F** [1/yr]	**MTTR** [h]
1	99,932	0,078	76,18
2	99,932	0,078	76,18
3	99,932	0,078	76,18
4	99, 32	0,078	76,18
5	99,932	0,078	76,18
HV	99 96	0,049	77,63

System	**A** [%]	**λ_F** [1/yr]	**MTTR** [h]
Wind farm	81,10%	24,943	72,3

Table 4.27 Availability of the grid connection

(Most likely case w WEC)

System	**A** [%]	**λ_F** [1/yr]	**MTTR** [h]
Grid connection	99,618%	0,4387	76,3

Table 4.28 Availability of the grid connection

(Most likely case w/o WEC)

These values were calculated using the equations from Table 2.4. In order that the whole subsystem (e.g. feeder1) is in an up state (functioning) it is assumed that each component is in an up state (functioning) as well. Hence a series structure can be used to calculate the availability.

Figure 4.28, on the previous page, shows the wind farm failure causes taken into account just electrical components. In other words this particular pie chart just compares the lumped failure rates of electrical components without considering the consequences and the significance of the individual component itself. In order to estimate the availability in an accurate way not only the time dependent operation, hence the failure rates shall be taken into account, but the *Expected Energy Not Supplied* (EENS) and the related financial consequences, the *lost revenue* (LR) shall serve as basis for the availability evaluation and optimization in the following subchapters.

$$EENS = \sum_{i=1}^{n} (L_{a(i)} \cdot U_i) \tag{4.26}$$

$$LR = \sum_{n=1}^{20} \left(\frac{EENS \cdot C_S}{(1+i)^n} \right) \tag{4.27}$$

$L_{a(i)}$…average energy load connected to the load point i
U_i unavailability, annual down time (FOR) in [h/yr]
C_S…revenue (subsidies, stock market, vNNE) in [€/kWh]

The EENS and the LR can be obtained by the above equations. The calculation period of the lost revenue is equal to the expected lifetime of the wind farm, as shown in subchapter 4.1. (Twenty years)

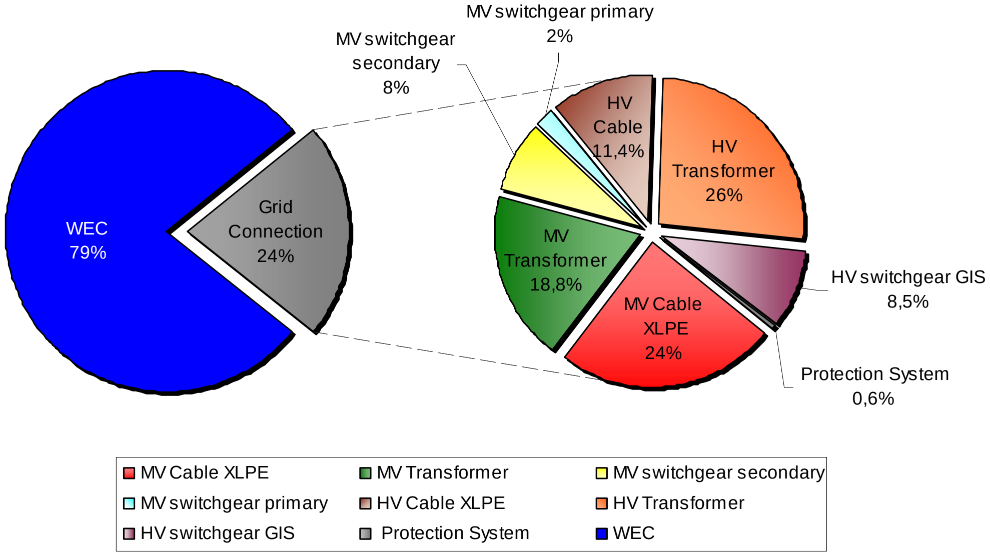


Figure 4.29 EENS of components

The causes of the expected energy not supplied at PCC can be seen in the pie chart above. More than 45% of the EENS are caused by faults on the HV connection, which is obviously the bottleneck of the grid connection since it contains just one power transformer. The MV collector system including primary and secondary switchgear as well as the step up transformers have relatively low failure rates, but due to their quantity they have a great share of EENS. However, the major cause of reduced power output at PCC is still the WEC itself.

Lost Revenue

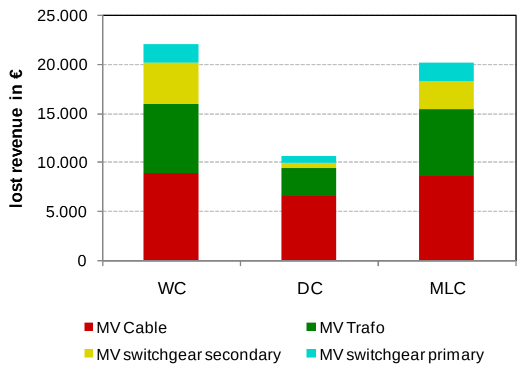


Figure 4.30 lost revenue caused by MV components

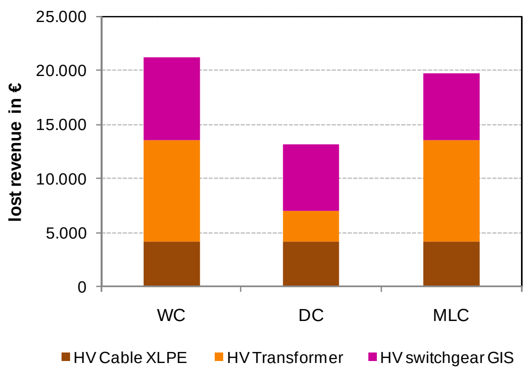


Figure 4.31 lost revenue caused by HV components

The lost revenue in Figure 4.29 and Figure 4.30 was calculated for one year of observation and with above introduced failure rate scenarios. To estimate the lost revenues over the lifetime of the wind farm equation 4.26 should be used.

4.4 Human and Environmental Factors

4.4.1 Weather Effects

Atmospheric effects on the proper operation of electrical power systems are very difficult to quantify. Thus their influence on the availability of wind farms can only be evaluated under certain restrictions and with an undesirable high level of uncertainty. Most of these effects like lightning, wind or the influence of temperature are relative to the wind farm location; therefore the weather effects on each wind farm project have to be estimated individually. However, a general assessment of certain weather effects and their influence on the availability of wind farms is given below.

Wind and Storms

The probability of component failures usually increases with increasing wind speed, not only since the pressure on exposed components is proportional to the square of the wind speed but also because the wind turbines operate at their limit. Hence a sudden additional gust of wind can cause undesired mechanical and electrical conditions, e.g. voltage surge. Furthermore, exposed components may get in motion due to extreme wind speeds (e.g. conductor swinging) and become reliability concerns. The relationship between base case wind speeds (v_B) and extreme wind speeds (v_{EX}) is given by the following equation.

$$v_{EX} = v_B \cdot \sqrt{\frac{inherent\ overload\ factor}{extreme\ wind\ overload\ factor}} \tag{4.28}$$

The extreme wind rating of a structure is the maximum extreme wind speed that can be applied, still meeting the specific requirements [11].

The frequency of failures caused by storms and effecting MV distribution systems is according to [54] 0,235 per year and per 100 km system length. Applied to the wind farm example in the previous chapter this would result in a MTBF of ten years. Since the share of MV overhead lines within the whole system is very high (35%), their contribution to the failure rate will be not taken into account. Thus the influence of storms on MV collector systems can be summarised with a MTBF of 16 years and a 30% probability of surviving 20 years without a failure. The same evaluation was carried out for HV networks. The overall frequency of failures caused by storms is 0,021 failures per year and per 100km system length. The share of HV cables is within HV networks significantly lower, as within MV networks and is approximately 4%. However, since the frequency of occurrence is very low, the influence of storms on HV systems can be neglected.

Commonly storms are excluded from reliability calculations because the real performance is without storms, during storms working in difficult conditions, increases the fault clearing time. Thus the MTTR is much higher.

For further investigations, the relationship between high wind speeds and failure rates of components should be evaluated in more detail.

Thunderstorms

Basically the major influencing factor during thunderstorms are lightning strokes that can cause not only undesired electrical conditions but also system damage. The most verified model of lightning strikes to power systems in open ground was developed by *Erikson* [47]. In this model the number of strikes is a function of the object height. The equation below shows the relationship between height, flash density and ground wire separation.

$$N = N_g \cdot \left(\frac{28 \cdot h^{0,6} + b}{10} \right) \tag{4.29}$$

N	*number of flashes per 100km per year to the object*
N_g	*ground flash density per km² per year*
h	*height of the object in [m]*
b	*overhead ground wire separation (if existent)*

A thorough coordination of the overvoltage protection devices within a wind farm is vital to the proper function and safety of the system. Especially at the junction between different components (e.g. cable terminations, power transformer) in order to mitigate the impact of travelling waves caused by direct or indirect lightning strokes. It should be pointed out, that a deliberate protection concept is necessary but can't fully prevent the system from fail.

The number of observed failures within a MV distribution system, caused by thunderstorms, leads to an actual failure rate of 1,75 failures per year and per 100km system length. The related MTBF for the wind farm example therefore is 1 year. Taken only the share of MV cables into account the MTBF changes to 2 years. The influence of thunderstorms on the HV connection can be evaluated by the same means. The MTBF for wind farm HV systems is 2 years, with a failure rate of 0,764 failures per year and system length.

Temperature

The design requirements of electrical components regarding their operating location are very high. Therefore the influence of different temperatures on the wind farms availability is assumed to be insignificant, thus can be neglected. For different wind farm locations where the temperature during winter seasons becomes very cold, certain icing effects on the WECs rotor blades have to be considered. Such icing effects can be measured through a decreasing efficiency of the turbine. Possibilities like specific coatings, chemical substances, heating wires or convection of warm air within the blade can be applied to improve the blades anti-icing sensitivity. Recent surveys showed that the icing on rotor blades can cause a decrease of the turbines efficiency of up to 40%.Furthermore, it should be pointed out, that the air density in general is a function of the regional temperature and altitude. Whereas the wind turbines power curve is a function of the air density, since the wind related power is proportional to the mass. Thus the WECs power curve is also a function of the air density.

The required time to perform certain maintenance actions within wind farms is strictly related to weather effects and environmental factors. It should be also noted, that the MTTM between onshore and offshore locations extremely differ. The maintenance costs for offshore wind farms are evidently much higher due to the additional efforts for maintenance support.

4.4.2 Human Factors

Humans are directly responsible for many operational interruptions, some may be intentionally (e.g. scheduled maintenance) others may be unintentionally (e.g. switching errors). Recent surveys showed that approximately 20-30% of all system failures in power plants are caused by human errors and the related maintenance errors account for nearly 50% of the power plants annual lost revenue. However, human failures during maintenance and product failures (hardware and software) are quite different from each other. The time to detect and repair human errors is undefined, whereas the time to detect and repair hardware failures is very low [11]. To provide a better understanding of what is meant by human errors and human reliability, their definition is given as follows [14].

Human reliability: this is the probability of accomplishing a specified task successfully by humans at any required state in system operation within a defined minimum time (if the time required is specified)

Human errors: this is the failure to perform a specific task (or the performance of a forbidden action) that could result in disruption of scheduled operations or damage to equipment and property.

It can be seen from the above definitions, that the reliability concept is the same for humans and products. The definition of human errors, however, is different as the performance error definition of components. In sense of human factors an error means human induced faults, whereas in sense of electrical components and their performance an error is the deviation of the target value within a certain thresholds. The term human factors include all psychosocial and biomedical considerations. Therefore it is a superior term which also includes personal selection, staff training, helping means for task performance, life support......etc.

The general expression for the evaluation of human reliability, whether the human failure rate is constant or not, is given by equation 4.30. It can also be applied if human errors are described by certain statistical distributions.

$$HR(t) = e^{-\int_0^t \lambda(t)\,dt} \tag{4.30}$$

For exponentially distributed random variables, additional reliability parameters may becalculated using the equations derived in subchapter 2.3.2.5.

Humans may have certain limitations in performing specific engineering tasks (time, budget…etc.). Experiences indicate that when these limitations are violated, the probability for a human error significantly increases. In order to reduce this probability the various limitations and characteristics should be carefully considered. Some of these characteristics are:

- Performing tasks at high speed
- Poor feedback concerning the correctness of the performed tasks
- Short decision making time
- Working hours or tasks that require a long sequence of steps
- Stress level

It is obvious that a moderate stress level can be helpful to achieve a higher effectiveness of human performances, otherwise the required task could be seen as unimportant and the concentration would decrease significantly. Although a certain stress level is promotive, it is also obvious that a very high stress level would result in considerable low performance effectiveness. This concept is graphically illustrated in Figure 4.32.

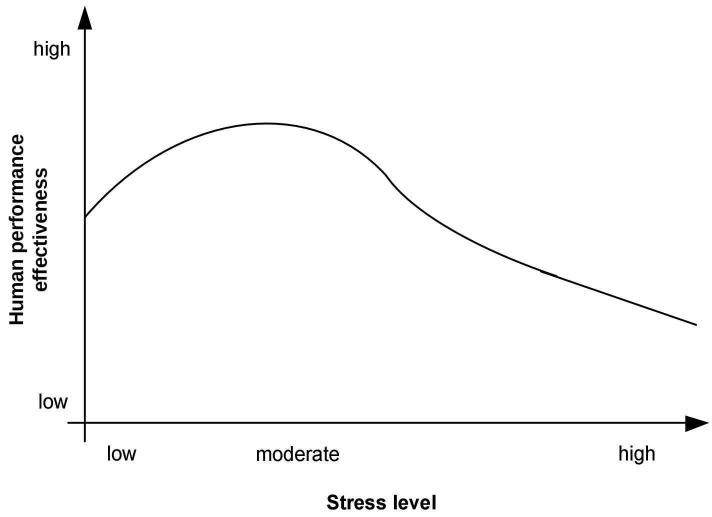


Figure 4.32 Human performance vs. stress level

Typical human behaviours and their corresponding considerations are shown in following table.

Human Behaviour	Corresponding countermeasures
Tend to hurry	Develop design such that meets the element of human hurry
Confused by unfamiliar items	Avoid designing totally unfamiliar items
Use sense of touch to explore the unknown	Item handling aspects
See manufactured items as safe	Design products that can be used incorrectly
Accustomed to certain colour meanings	Meet existing colour code standards
Expectation of how thinks work	Design products as per human expectation (e.g. switches)

Table 4.29 Human behaviours and their corresponding considerations [14]

The above table just covers the most common human behaviours that may result in a lower system reliability. The corresponding considerations focus mostly on the products design and development process. The main factors to reduce human induced consequences and their probability of occurrence are:

- Better recruitment and selection
- Staff Training
- Better design of procedures and work environment

Basically the failure rate of systems is subdivided into hardware failures and human induced maintenance errors. The probability of occurrence of either hardware failures or maintenance errors will be evaluated next.

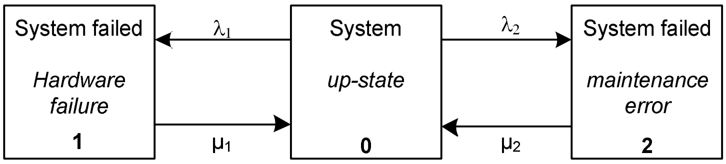


Figure 4.33 System state space diagram incl. human errors

Markov methods and their application to reliability engineering were introduced in subchapter 2.2.2, page 15. The probabilities of entering a specific system state from Figure 4.33 can be calculated by applying Markov methods shown in the following equations.

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2) \cdot P_0(t) = \mu_1 \cdot P_1(t) + \mu_2 \cdot P_2(t) \qquad (4.31)$$

$$\frac{dP_1(t)}{dt} + \mu_1 \cdot P_1(t) = \lambda_1 \cdot P_0(t) \qquad (4.32)$$

$$\frac{dP_2(t)}{dt} + \mu_2 \cdot P_2(t) = \lambda_2 \cdot P_0(t) \qquad (4.33)$$

$$P_0(t) + P_1(t) + P_2(t) = 1 \qquad (4.34)$$

For long time intervals (*t*>>), equations 4.30-33 become the steady-state probability (asymptotic probability) and simplifies to:

$$P_0 = \frac{\mu_1 \cdot \mu_2}{(\mu_1 \cdot \mu_2 + \lambda_2 \cdot \mu_1 + \lambda_1 \cdot \mu_2)} \qquad (4.35)$$

$$P_1 = \frac{\lambda_2 \cdot \mu_1}{(\mu_1 \cdot \mu_2 + \lambda_2 \cdot \mu_1 + \lambda_1 \cdot \mu_2)} \qquad (4.36)$$

$$P_2 = \frac{\lambda_1 \cdot \mu_2}{(\mu_1 \cdot \mu_2 + \lambda_2 \cdot \mu_1 + \lambda_1 \cdot \mu_2)} \qquad (4.37)$$

P_0, *P1* and P_2 are the steady-state probabilities of the system in Figure 4.33 being in state *0* (up state), *1* and *2*. The common dominator of equations 4.30-33 is also known as the asymptotic availability of the system.

The presented state space diagram is just a general model to evaluate the influence of maintenance failures and hardware failures; it doesn't provide information about the cause of maintenance failures. However, certain models that present the performance of a maintenance worker under certain influences, for example under fluctuating environment (weather), may be elaborated in the same way to calculate the human reliability, the humans failure rate etc. [14].

For further information on how to model human factors in engineering applications see [14].

Application to Wind Farms

Disturbances due to outside influences usually cover human factors, animals, construction machines as well as fire. Thus the range of reliability data from outside influences is very large. According to the German disturbance and availability statistic [54], the frequency of occurrence of outside effects is for MV systems approximately 0,9 failures per year and per 100 km system length (*MTBF=1 year*). Taking only the human influences into account the failure rated decreases to 0,15 failures per year. In other words, within a wind farm a failure caused by human influences occur just once every 18 years. (*MTBF=18 years*).

Typically most of the human failures occur during inspection periods and maintenance actions. In order to prevent certain undesired events detailed operating instructions are very useful. Especially in foreign countries or if the maintenance work is performed by subcontractors additional training and instructions can be essential, not only to reduce the probability of human induced failures, but also to keep the down time and respectively the MTTR low.

At the beginning of this subchapter it was mentioned, that human errors are very hard to detect and further more that they usually take a long time to repair. Thus the results from the calculation example can be used as a reference point but should be handled very carefully.

5 Availability Optimisation

The reliability and availability of systems can be improved by finding better components, which mean to lower the individual failure rate, by establishing different designs, by adding redundancy, or by maintenance actions. The Redundancy approach as well as the quality approach require a higher initial investment and can be seen as short term measures. The concept of improving the quality of individual components requires adequate quality management processes and the support of reliable subcontractors. The implementation of maintenance strategies for whole wind farms on the other hand requires not only the manpower, which can also be established with subcontractors, but more significantly some experience. Both measures, the quality of products and the maintenance actions, are long term improvement possibilities.

The main focus of this chapter is to evaluate the availability of several layout alternatives of wind farm subsystems, according to the classification made in the previous subchapter. In addition the impact of different maintenance strategies on the availability and the LCC of wind farms will be elaborated.

5.1 Optimisation Methods

The relationship between the investment of a wind farm and its availability is non-linear. The incremental availability of a redundant system, for example a second MV step-up transformer, decreases as the investment costs increase. This concept can be described by the ‘diminishing marginal unit’. In other words the marginal costs don’t decline as availability increases. Thus there exists a point where additional benefit (availability) meets the additional costs. This particular point is the optimum.

The optimum of the systems availability has been reached if the marginal benefit of the given investment is equal to the marginal costs.

Marginal Benefit: is the increase of benefit for an infinitesimal additional investment.
Marginal Costs: are the incremental costs due to the infinitesimal additional investment

Calculation Steps

Optimisation is the search for the systems balance state where a objective function reaches a desired quantity. Besides the maximisation of the objective function, certain constraints have to be fulfilled. (E.g. guaranteed level of availability)

The simplest optimisation problem is given, if the revenue (N) is the difference of benefit (B) and costs (C) and both are regulated by just one variable (x).(e.g. investment costs)

This concept is mathematically expressed as follows.

$$N(x) = B(x) - C(x) \tag{5.1}$$

The marginal benefits (N_x) as well as the marginal costs (C_x) are therefore:

$$N_x = \frac{dN(x)}{dx} \tag{5.2}$$

$$C_x = \frac{dC(x)}{dx} \tag{5.3}$$

It is important to note, that the assumption that the costs are proportional to the investment is made (scale costs), which is valid for wind power projects.

$$C(x) = c \cdot x \qquad c \approx C_x \qquad c \sim const. \tag{5.4}$$

The optimisation problem is now to find the maximum of the function N(x), with the restriction that the rate of return (*RR*) of the investment at least reaches the stated target value at this maximum. The definition of the optimisation problem is given by equation 5.5 and 5.6.

$$N(x) = \max. \qquad \textit{with the restriction} \qquad RR_{\min} \leq N/x \tag{5.5}$$

$$N_x = B_x - C_x = 0 \quad \rightarrow \quad B_x = C_x \qquad \textit{marginal benefits = marginal costs} \tag{5.6}$$

The concept of marginal costs and marginal benefits are graphically illustrated in Figure 5.1.

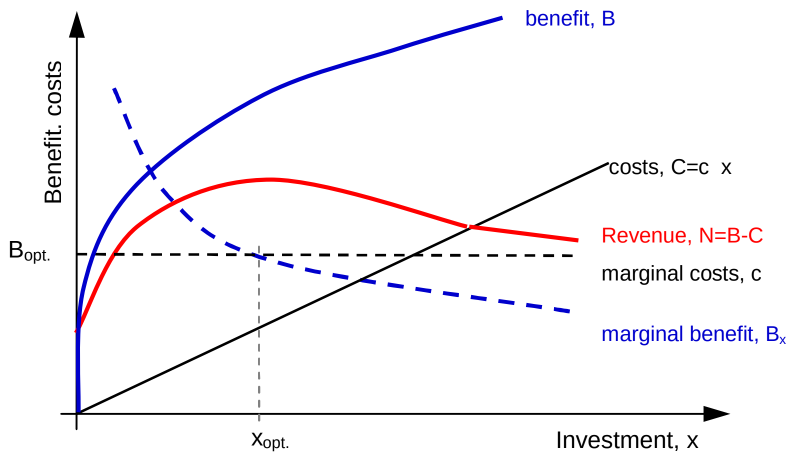


Figure 5.1 Marginal costs vs. marginal benefits

The intersection between the marginal benefit curve and the marginal costs curve represents the optimum of the investment.

<u>Summary:</u>

- The marginal benefit of an investment is the incremental benefit per additional investment
- The marginal costs of an investment are the additional costs per additional investment
- The optimum of the revenue of an investment is given by the point the marginal costs are equal to the marginal benefits

The above presented optimisation method is a typical approach used in electrical engineering. However, it is simple optimisation concept. For more optimisation problems especially for evaluations with more than one variable, for example optimisation with respect to investment and availability, more accurate calculation methods are needed. (e.g. Lagrange)

Within this investigation the optimisation of wind farms refers to choosing the best element out of a set of available alternatives. The availability of the system and its related EENS are the variables or in other words the functions that shall be optimised under the restriction of lowest investment costs and LCC.

Thus the concept of NPV, which was introduced in subchapter 2.4.1, will be used to estimate the profitability of different layouts. Since the NPV method evaluates the difference between LCC and investment costs of a system, the layout with the lowest NPV should be chosen.

Furthermore, a sensitivity analysis will be performed, which will handle down times of components. A sensitivity analysis is appropriate to use when input data suffer from a high degree of uncertainty. The main objective for this sensitivity analysis is the uncertainty in outage time, due to influences like delivery time of new components, bad weather conditions…etc.. Therefore, the failure rate of the different components is assumed to be the same (λ_{MLC}) in the sensitivity analysis, only the MTTR will be altered.

Note: Unless stated otherwise the evaluation is based on the MLC scenario for the failure rate (subchapter 4.3.5, p.99), on the generation duration curve for shore regions.(subchapter 2.4.3.1, p.41) and on an interest rate of 7% (subchapter 2.4, p.33).

5.2 Grid Architecture

According to the classification made in the previous chapter, the grid connection is subdivided into two main parts. The MV collector system and the substation, whereas the substation is further divided into the MV and the HV part. For each subsystem different layout alternatives will be proposed and evaluated regarding their availability and LCC.

The design of wind farms depends on a several design considerations. The most important ones are:

- The cost and availability of physical space
- The optimal layout of the WEC itself with certain restrictions, like minimizing the interaction between adjacent WECs (wake effects)
- The type of excavation and laying for the MV collector system
- The results of electrical engineering studies such as load flow and short circuit analysis.
- Environmental factors (weather, soil…etc.)
- The property boundary of the wind farm
- Reliability and economic effects

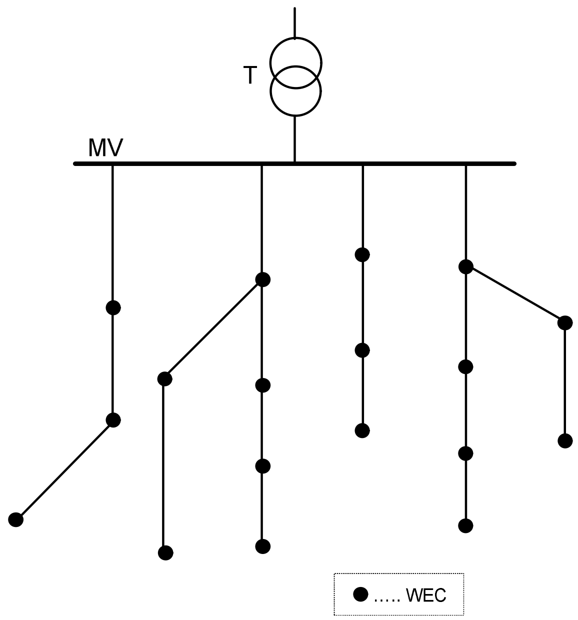
Within this chapter the focus will be on the reliability and economic effects.

5.2.1 MV Collector System

The proposed layouts for the MV collector system will be evaluated with respect to their availability and their additional investment costs for redundancy. (E.g. investment for additional interconnections) The general requirements when designing networks are: proper reliability, adequate power quality and economic efficiency. The following layout alternatives for the MV collector system deal with reliability parameters and their economic efficiency.

5.2.1.1 Radial Collector System

This configuration is widely used for MV collector systems due to its simple structure and therefore its low technical and economical efforts. Figure 5.2 shows a schematic concept of a radial configuration. It should be noted that this layout serves as reference for layout alternatives which will be introduced later on.



Properties of radial networks:

- Easy to operate
- Low design complexity
- Low investment costs
- Outage of downstream components
- 100% load under normal conditions
- No redundancy
- Low maintenance required
- High losses, can’t be optimized
- Voltage regulation
- Line protection with over current relay and CB at the point of entry

Figure 5.2 Radial MV collector system

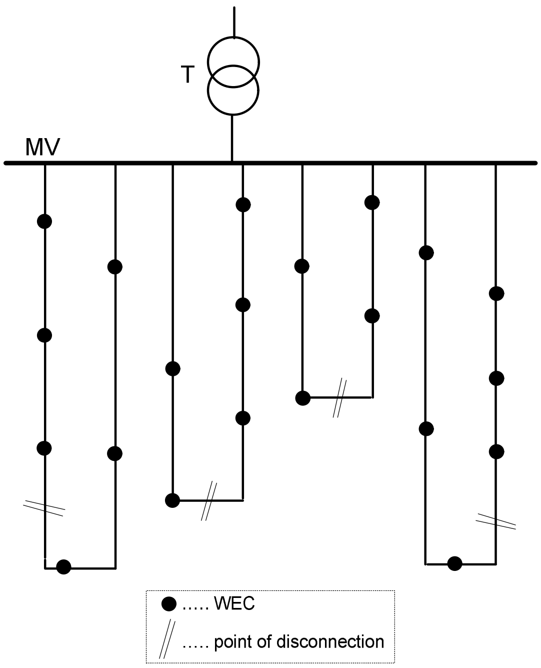
Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [€]	EENS [MWh/yr]	LCLR [k€]
w/o maintenance	0,476	2	23	99,87	62	0	343	398
w. preventive maintenance	0,476	2	23	99,57	62	0	882	991
w. preventive and corrective maintenance	0,476	2	23	99,57	62	0	882	973

Table 5.1 Radial collector system

ΔC_0 additional investment [€]
R(1) probability that the wind farm survives one year without a failure
EENS expected energy not supplied per year [MWh/yr]
LCLR life cycle lost revenue over a period of 20 years [k€]
λ_F wind farm failure rate

5.2.1.2 Redundant Collector System (Looped network)

There are various kinds of ring networks for electrical power systems; Figure 5.3 shows the simplest application of a redundant collector system. The terminations of the MV feeders are connected to the MV substation. The load break switches at the point of disconnection are normally open due to the easier operational handling.



Properties of looped networks:

- open LBS / LDC
- Normally with partial load (~50% P_r)
- Medium design complexity
- Easy to operate (open loop)
- Redundancy
- Medium investment costs
  (can be less if CB on the line are reduced)
- Low maintenance efforts
- Loss optimization through variation of disconnecting point

Figure 5.3 Looped MV collector system with single substation (open loop)

The feeders must be designed in a way that if a failure occurs on one part of the feeder, the other half has to be capable of carrying the load of the other half as well. Thus the load factor of the feeder under normal conditions shouldn't exceed 50%.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/y]	LCLR [k€]	NPV
w/o maintenance	0,278	4	2	99,99	75	1.800	22	25	-1.200
w. preventive maintenance	0,278	4	2	99,97	75	1.800	757	800	-1.300
w. preventive and corrective maintenance	0,278	4	2	99,97	75	1.800	757	800	-1.300

Table 5.2 Redundant collector system

It should be pointed out, that the additional costs for the redundant collector system only take the additional MV cable and the additional secondary MV switchgear into account. The additional costs for changes of primary equipment within the substation (e.g. circuit breakers with higher rated breaking current) were not considered.

Table 5.2 presents the evaluated parameters. It can be seen, that the failure rate of the redundant system is approximately half the failure rate of the radial system. The influence of the reduced failure rate is reflected in the EENS, which reduced significantly. This layout is nowadays common practice for offshore wind farms due to the lower EENS but most of all because of the reduced repair efforts.

In Figure 5.4 the concept of a redundant collector system with main and transfer station is presented. This layout is applicable for wind farms with a long distance between the WECs and the possibility of a second substation nearby.

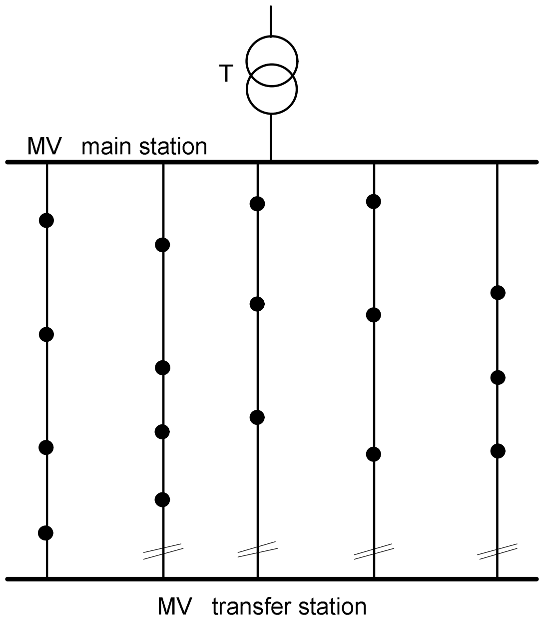


Figure 5.4 Redundant collector system with main and transfer substation

The properties of the redundant collector system with main and transfer station are basically the same as for the normal redundant collector system. Thus this layout doesn't really provide an incremental increase of availability.

However, it should be noted, that the points for disconnection (LBS-normally open) have to be designed and implemented thoroughly due to short circuit and load flow considerations.

The evaluated parameters are presented in the table below. Although the figures look very similar to those of the previous redundant layout, the additional investment costs are higher and therefore the NPV is significantly lower for this layout.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/y]	LCLR [k€]	NPV
w/o maintenance	0,274	4	2	99,99	76	600.	16.	19.	-443.
w. preventive maintenance	0,274	4	2	99,79	76	600.	555.	626.	-442.
w. preventive and corrective maintenance	0,274	4	2	99,79	76	600.	555..	601.	-436

Table 5.3 Redundant collector system, main and transfer substation

5.2.1.3 Radial MV Collector System with Interconnections

This layout alternative represents a compromise between the radial configuration and the fully redundant configuration. The advantages of this particular layout are the minor lost revenue and the possibility to realise the interconnection with respect to the lowest distance in contrast to the looped configuration. In Figure 5.5 a MV collector system with interconnections (feeder ties) is schematically illustrated.

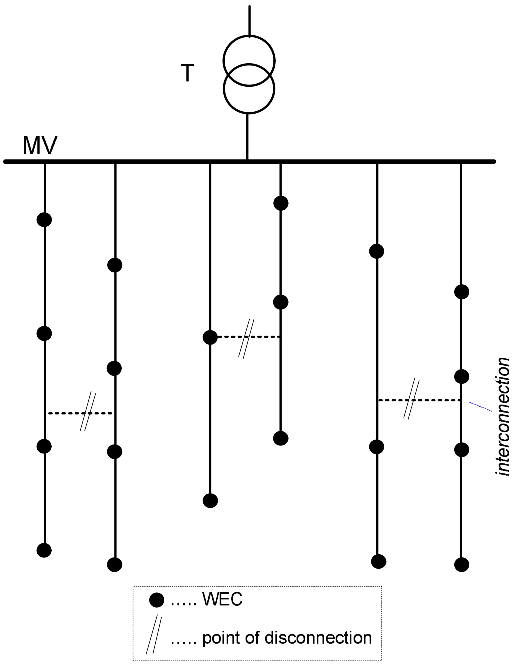


Figure 5.5 MV collector system with interconnections (feeder-ties)

Properties of radial networks with feeder-ties

- Partial redundancy
- Low additional investment
- Low maintenance efforts
- Easy to operate
- Loss optimisation is difficult
- Outage of 50% of the downstream components
- In case of faults, higher switching actions required
- Medium design complexity
- Applicable for x<700m (interconnection length)

This configuration is especially reasonable for long feeders, or for HV connections of the wind farm.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/yr]	LCLR [k€]	NPV
w/o maintenance	0,275	4	2	99,99	75	400	22.	25.	-27.
w. preventive maintenance	0,275	4	2	99,79	75	400	565.	636.	-38
w. preventive and corrective maintenance	0,275	4	2	99,79	75	400	565.	624.	-46

Table 5.4 MV collector system with interconnections (feeder ties)

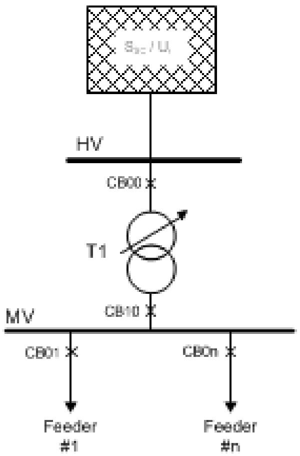
5.2.2 Substation

Usually the design practices for substations and distribution systems of utilities are quite different than those for MV collector systems, substations and HV connections of wind farms. This is because of the different economical issues and purposes of these two applications. For example, the performance efficiency of wind farms is commonly measured by its availability, whereas utilities focus on the systems reliability, which requires an higher level of redundancy [72]. Furthermore, the penalties for wind farms have to be considered. Due to the variability of the wind the wind farm can be seen as a variability source of energy. Thus, the requirements for reliability of grid connections concepts of wind farms are not as critical as for utility systems [42].

5.2.2.1 HV Part

- **Single Power Transformer**

Figure 5.6 shows a single line diagram of a HV connection with one single power transformer



Properties of non-redundant HV Connection:

- No redundancy in case of occurrence of any failure or required maintenance actions
- Transformer operates at full load
- No flexibility during operation
- No feeder circuit breakers needed

Figure 5.6 Single power transformer

The calculated availability parameters are presented in the table below. The NPV for this layout alternative is zero, since it is the reference layout.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/y]	LCLR [k€]	NPV
w/o maintenance	0,050	20	88	99,94	95	0	136.	155.	0
w. preventive maintenance	0,050	17	88	99,34	95	0	1.536.	1.616.	0
w. preventive and corrective maintenance	0,050	17	88	99,34	95	0	1.536.	1.343.	0

Table 5.5 Single power transformer

- **Parallel Power Transformers with Tie Breaker**

The fully redundant layout with two parallel power transformers is shown in Figure 5.7.

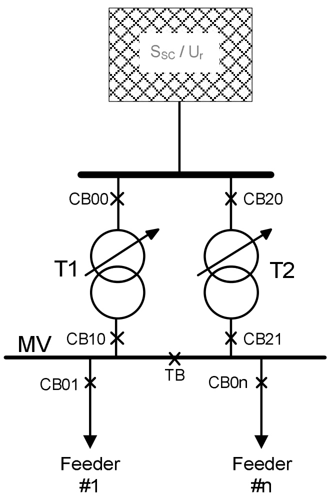


Figure 5.7 Redundant power transformers

Properties of Parallel Power Transformers

- The tie breaker can either be a load break switch or a circuit breaker.
- 50% Redundancy in case of failures on the busbar,
- Redundancy in case of failures on one power transformer
- Flexibility during operation
- For radial networks it may be realised w/o a CB at the beginning of a feeder

The power transformers can either be designed for 100% installed capacity or less than

100% installed capacity. The NPV of this layout is very low because of the high additional investment of the second power transformer. However, if the maintenance time over the period of 20 years and the related EENS is taken into account, the NPV changes significantly. This is carried out in more detail in the sensitivity analysis.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/yr]	LCLR [k€]	NPV
w/o maintenance	0,010	113	43	99,99	99	1.750	11.	12.	-1.637.
w. preventive maintenance	0,010	113	43	99,99	99	1.750	11.	12.	-777
w. preventive and corrective maintenance	0,010	113	43	99,99	99	1.750	11.	n.q.	-777

Table 5.6 Redundant power transformers

Furthermore should be noted, that the active power losses of this particular layout are lower than those of the layout with one power transformer if the installed capacity is >100MW and the capacity factor of the wind farm location is beyond 35%. (See subchapter 5.3, p.121)

5.2.2.2 MV Part

The simplest assembly of MV switchgear of a substation is the single busbar, single disconnectors, shown in Figure 5.8. This layout has no additional redundancy what so ever and serves as reference layout for this investigation.

- **Single Busbar, Single Disconnectors**

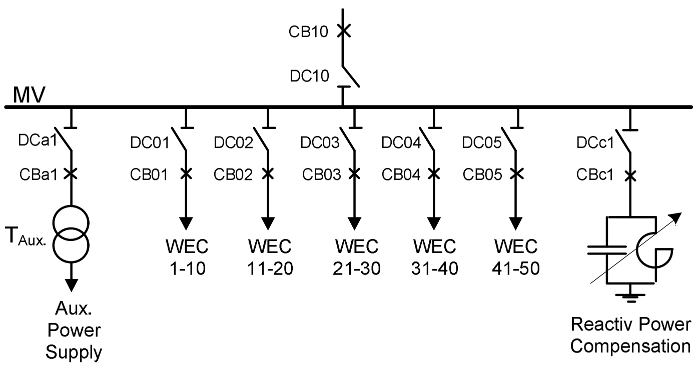


Figure 5.8 MV part of the substation, single busbar

Single bb without a tie breaker:

- no redundancy
- To isolate the bb an outage is needed
- no flexibility during operation
- No CB on the busbar required
- Make sense with an outstation

Bus bar with tie (switchable bb)

- LDC or CB
- HV-configuration-H-set-up

The availability and the related costs are presented in Table 5.7. Although this layout is very simple the estimated availability and therefore the lost revenue is very high.

Layout alternative	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	R(1) [%]	ΔC_0 [k€]	EENS [MWh/yr]	LCLR [k€]	NPV
w/o maintenance	0,007	137	13	99,99	99	0	3.	3,3	n.q.
w. preventive maintenance	0,007	137	13	99,98	99	0	10.	9.	n.q.
w. preventive and corrective maintenance	0,007	137	13	99,98	99	0	10.	8.	n.q.

Table 5.7 MV Substation, single busbar

Reliability figures from REpowers standard primary switchgear (ABB, AREVA) are the basis for these calculations. This type of switchgear is characterised by a very low failure and maintenance rate, because of its design. (GIS compact switchgear)

- **Double Busbar, Double Disconnectors, Single Breakers**

A redundant layout of the MV substation is shown in Figure 5.9. The investment costs for this design are higher and thus just for important substations, or for substations with an high energy density (installed capacity).

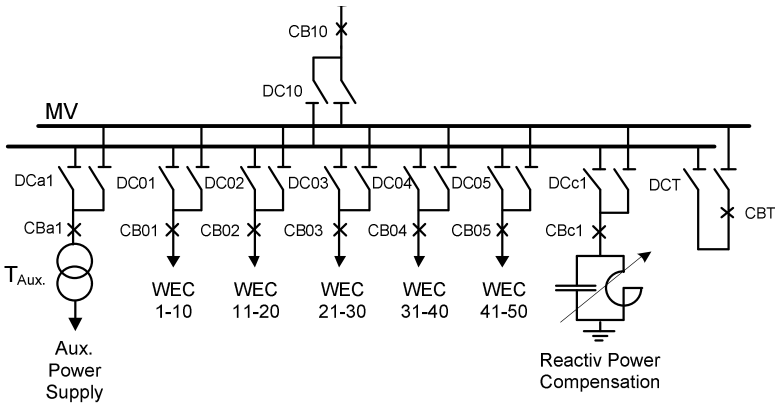


Figure 5.9 MV part of the substation, double busbar, single breakers

The incremental increase of the level of availability compared to the single busbar design is very low. This results in an significantly higher NPV. (See table below)

Layout alternative	**λ_F [1/yr]**	**MTBF [yr]**	**MTTR [h]**	**A [%]**	**R(1) [%]**	**ΔC_0 [k€]**	**EENS [MWh/yr]**	**LCLR [k€]**	**NPV**
w/o maintenance	0,003	381	14	99,99	99	380	1,3.	1,5.	-378.
w. preventive maintenance	0,003	381	14	99,99	99	380	1,3.	1,5.	-372.
w. preventive and corrective maintenance	0,003	381	14	99,99	99	380	1,3.	1,4.	-670.

Table 5.8 MV Substation, double busbar, double disconnectors

- **Double Busbar, Double Disconnectors, Double Breakers**

This special substation design won't be considered in this investigation since the other layouts for the MV part of the substation already show a very high level of availability. The fully redundant layout would need a significantly higher investment that wouldn't pay off during the life time of the wind farm. This concept is especially for very important substation within distribution or transmission networks with a high energy density.

5.2.3 Summary of Layout Alternatives

Table 5.9 and Table 5.10 represent the availability and financial decision parameters for the different layout alternatives. Layout redundancies are marked in the tables as ‘d’ (double, redundant) whereas the single layout is labelled as ‘*s’* (single). Furthermore should be noted, that the availability parameters of the layout considering maintenance actions as system unavailability are presented by characters with a star (e.g. *A*).* The probability that the layout will survive one year without any failure is given by *R(1).*

Layout Alternative				Info	λ_F [1/yr]	MTBF [yr]	MTTR [h]	A [%]	A* [%]	R(1) [%]
#	*substation* HV	*substation* MV	*F*							
A	*s*	*s*	*s*	Ref.	0,529	2	29	99,82	99,28	58
B	*d*	*s*	*s*		0,490	2	24	99,86	99,65	61
C	*s*	*d*	*s*		0,525	2	29	99,82	99,31	59
D	*d*	*d*	*s*		0,486	2	24	99,86	99,66	61
E	*s*	*s*	*d*		0,324	3	14	99,94	99,59	72
F	*d*	*s*	*d*		0,285	4	3	99,98	99,95	75
G	*s*	*d*	*d*		0,320	3	14	99,94	99,42	72
H	*d*	*d*	*d*		0,281	4	2	99,99	99,97	75

Table 5.9 Layout alternatives of the grid connection, availability

The main financial parameters for the layout alternatives can be seen in Table 5.10. As previously mentioned layout #*A* serves as reference since this layout is the most common one. The additional investment costs (ΔC_0) are therefore referring to the investment costs of layout #*A*. This process is also valid for the net present value (*NPV*). The lost revenue over the life cycle of the wind farm (*life cycle lost revenue LCLR*) is based on the expected energy not supplied (EENS). The LCLR* (with maintenance action) therefore includes the maintenance induced EENS as well as the manpower costs for preventive and corrective maintenance. The NPVs were determined by use of equation 2.82 (page 37).

Layout Alternative				ΔC_0 [k€]	EENS [MWh/yr]	EENS* [MWh/yr]	LCLR [k€]	LCLR* [k€]	NPV [k€]	NPV* [k€]
#	*substation* HV	*substation* MV	*F*							
A	*s*	*s*	*s*	0	484	1.890	548	1.724	0	0
B	*d*	*s*	*s*	1.830	368	914	418	739	-1.656	-515
C	*s*	*d*	*s*	380	482	1.881	546	1.958	-378	-611
D	*d*	*d*	*s*	2.210	367	905	416	989	-2.034	-1.142
E	*s*	*s*	*d*	405	144	1.556	163	1.618	-1.286	-1.568
F	*d*	*s*	*d*	2.235	28	579	32	624	-2.942	-2.073
G	*s*	*d*	*d*	785	142	1.541	161	1.597	-1.664	-1.923
H	*d*	*d*	*d*	2.615	17	570	34	641	-3.324	-2.469

Table 5.10 Layout alternatives of the grid connection, lost revenue

The LCLRs, the additional investment costs and the NPVs of the layout alternatives are graphically illustrated in Figure 5.10 (without taking maintenance into account) and in Figure 5.11 (with maintenance actions)

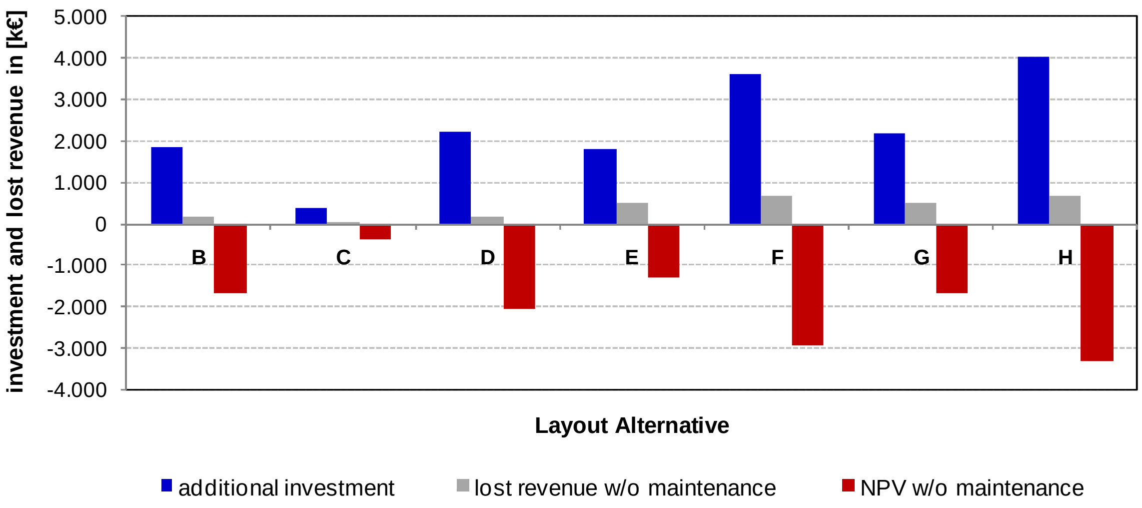


Figure 5.10 Lost revenue, investment costs and NPV of layout alternatives w/o maintenance

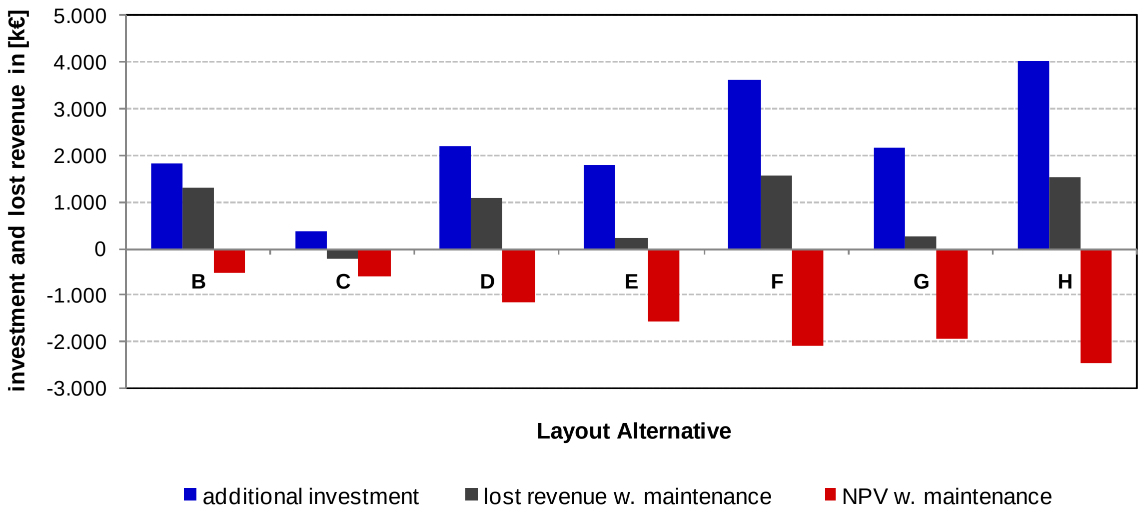


Figure 5.11 Lost revenue, investment costs and NPV of layout alternatives w. maintenance

MTTR and MTTM used for this evaluation:

Component	λ_F [1/yr]	MTTR [h/yr]	MTTM [h]	MTBM [yr]
HV cable	0,00139	48	n.q	n.q
HV Trafo	0,0182	168	168	6
MV Busbar	0,001	8	n.q	n.q
MV Cable	0,0061	24	n.q	n.q
MV Trafo	0,0023	48	6	4
MV switchgear primary	n.q	24	12	10
MV switchgear sec.	n.q	48	6	4
HV switch ear	n.q	n.q	12	
WEC	n.q	n.q	16	1
Protection devices				
See subchapter 4.3.4, p.94				

Table 5.11 MTTR and MTTM

The MTTR and MTTM figures that were used in the previous evaluation are shown in Table 5.1. These figures are very conservative estimates. In order to quantify their impact on the layout decision (NPV) a sensitivity analysis will be carried out over the next few pages.

5.2.4 Sensitivity Analysis

The sensitivity analysis is intended to provide a better understanding of the relevance of the different reliability parameters and their impact on the layout decision process. During this analysis the failure rate of components is assumed to be constant and equal to the previously presented most likely failure case scenario. Thus only the MTTR, the MTTM and the investment costs will be altered.

Figure 5.12 shows the net present value and its variation under different MTTM. It is obvious that the layout alternative with the redundant HV connection is directly related to the maintenance induced expected energy not supplied, since the whole wind farm would be out of service without the redundancy. Therefore this layout has a positive NPV for maintenance times that exceed 150% of the normal MTTM.

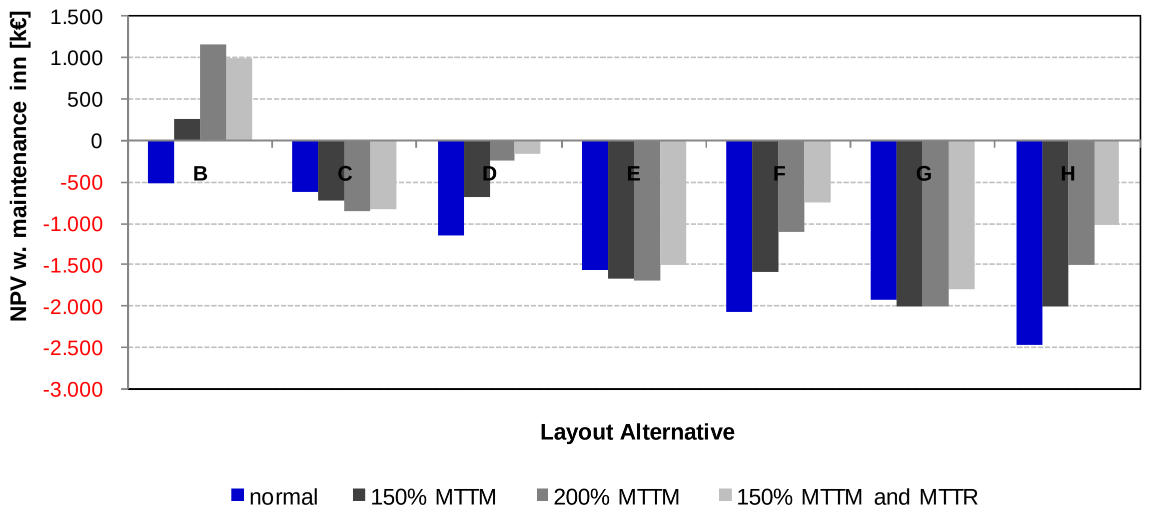


Figure 5.12 NPV* for MTTM variations

In other words, the additional investment for the second power transformer in layout *B* will be compensated by the additional revenue due to operation during maintenance actions, if the MTTM is about 1,5 times the normal time.

The same concept was used to prepare Figure 5.13, which shows the NPVs of the layout alternatives under variation of the MTTR without taking maintenance actions into account. It can be assumed, that the layouts with the redundant MV collector systems vary the most, since this part of the wind farm has the highest lumped failure rate due to the high MV cable length and the amount of MV transformers. The most profitable layout alternatives, for uncertain repair times can be assumed to be layout number *C, E* and *F.* Whereas layout *E* only has a positive NPV for the configuration with interconnections (feeder ties), where the additional investment for the redundancy of the MV collector system is profitable over the lifetime of the wind farm.

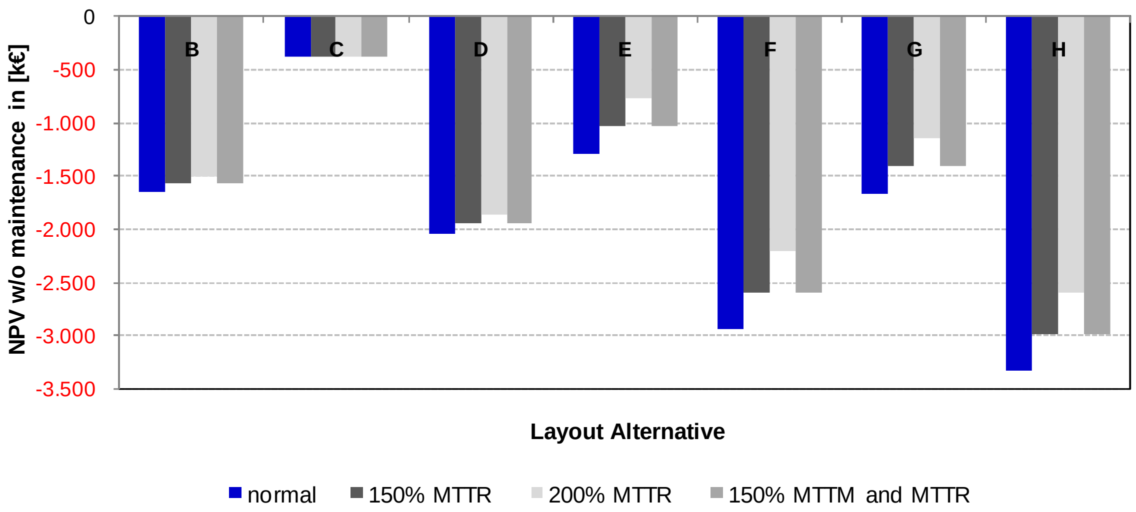


Figure 5.13 NPV for MTTR variations

Since the MTTR is proportional to the failure rate, Figure 5.13 is also valid for failure rate assumptions.

Onshore vs. Offshore Wind Farms

At the beginning of subchapter 4.2 it was noted, that the reliability figures and thus the availability evaluations are only valid for onshore wind farms. In order to get a better understanding between the differences of reliability figures of onshore and offshore wind farms some significant points will be discussed below.

The failure rates of offshore and onshore components in general can be assumed to be similar. Mainly because literally the same components are used and since there don't exist verifiable historical reliability data from offshore operation those from onshore components have to be taken into account for availability evaluations. The main difference between onshore and offshore wind farms is the mean time to maintain (MTTM) of components. It is obvious, that offshore maintenance actions take a lot more economical and time dependent effort than maintenance actions carried out onshore. Thus the time to maintain certain offshore components can be assumed to be ten too twenty times longer. In order to prevent a high number of maintenance actions the layout of offshore wind farms normally focus on redundancy. (E.g. redundant MV collector system)

5.3 Active Power Losses

5.3.1 Calculation Process for Wind Farms

Active power losses are generally divided into load losses (P_{LL}) and no load losses (P_{NL}). The no load losses are voltage dependent and therefore present practically all of the time. The no load losses on the other hand are load dependent and primarily resistive losses. They are proportional to the square of the current. The first step to estimating load losses is the calculation of the loss factor (*lf*). The loss factor is the ratio of average losses divided by the losses at rated generation [42]. It is important to note, that the loss factor (*lf*) is not equal to the capacity factor (*cf*) of the wind farm because ohmic losses are proportional to the square of the load. The loss factor can be obtained by the following equation:

$$T_{lf} = \frac{E_L}{P_{L\max}} = \frac{\int_0^{T_c} I(t)^2 \, dt}{I(t)^2_{\max}} \tag{5.7}$$

$$lf = \frac{T_{lf}}{T_c} = \frac{1}{T_c} \cdot \int_0^{T_c} P(t)^2 \, dt \tag{5.8}$$

E_L	*loss energy [kWh]*	T_{lf}	*equivalent loss hours*
P_{Lmax}	*max. active power losses [kW]*	T_c	*calculation period*
$P(t)$	*transmitted power output at time t*		

The above equations show that the loss factor is equal to the integral of the square of the transmitted active power at time t. The capacity factor is always higher than the loss factor. For utility applications the loss factor may be evaluated by use of the capacity factor only and with a highly approximately approach. This particular approach is only valid for systems that capacity factor exceeds 50%. Thus this approach is only applicable for utility applications and not for wind farms. The estimation of active power losses is based on the generation duration curve of a wind farm at shore site. Figure 5.14 presents a pie chart of the different generation modes and their time shares of the wind farm location.

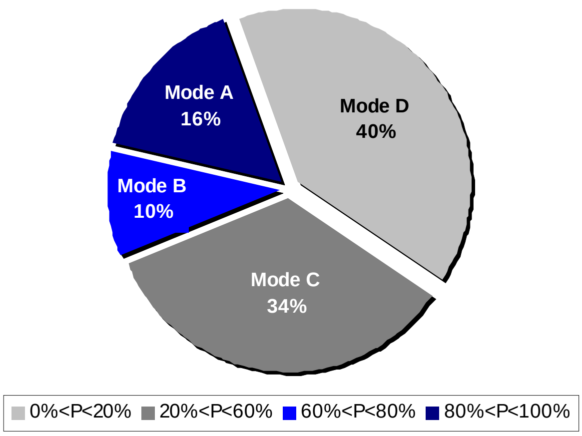


Figure 5.14 Generation modes, shore site

Component	Info	P_{NL} [kW]	P_{LL} [kW]
LV Cable	per WEC	n.q	13
MV Cable	33 km	n.q	150
HV Cable	10 km	n.q	190
MV Trafo	per unit	2,5	13
HV Trafo	per unit	50	400

Table 5.12 Active power loss of components

Figure 5.15 shows the generation duration curve and the related loss duration curve. In addition, the loss factor as well as the capacity factor is displayed in order to provide a better understanding of the relationship between these parameters.

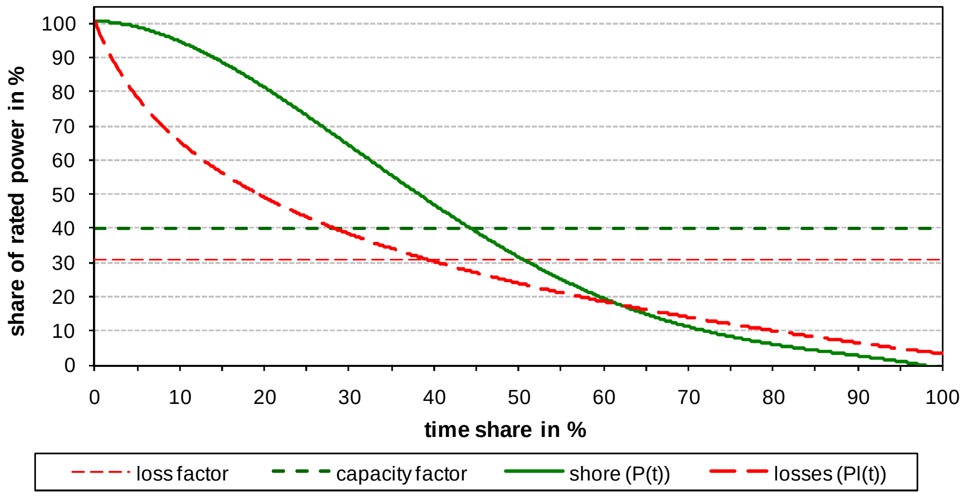


Figure 5.15 Generation-duration curve vs. loss duration curve

The loss duration curve is based on figures from Table 5.12. The exact calculation of the active power loss of several components will not be carried out in detail and further explained. A detailed graphical illustration of active power losses within a wind farm according to the relevant generation mode is provided in Figure 5.16 below.

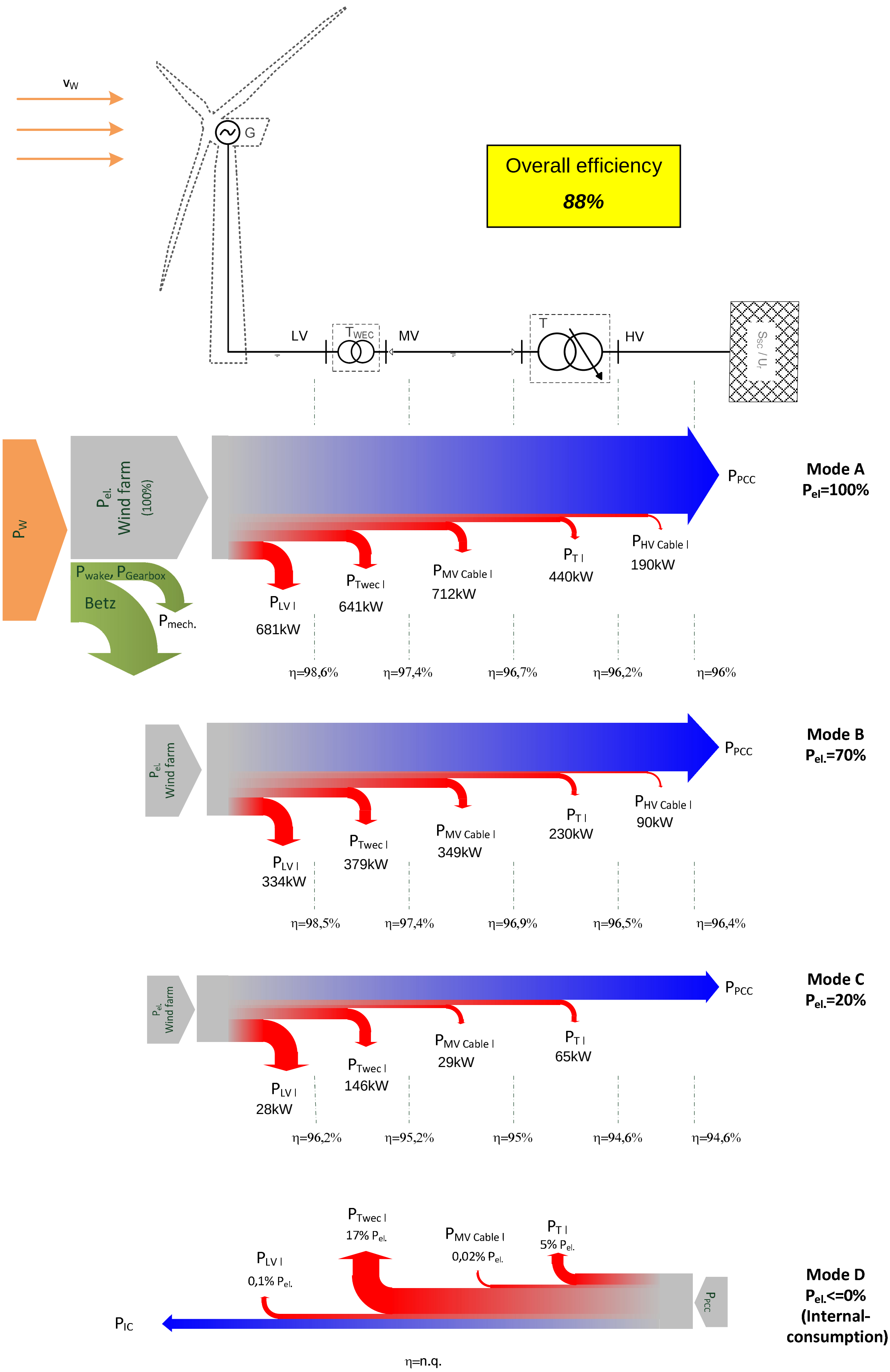


Figure 5.16 Sankey Diagram

This figure also displays the level of efficiency and its decrease due to active power losses. Although the level of efficiency of the generation modes A, B and C is not less than 94% the overall level of efficiency of the wind farm over a period of one year is 88%, due to the no load hours. (Generation mode D - internal consumption)

The lumped active power losses are presented in Table 5.13.

System	Info	P_L [kW]	E_L [MWh/yr]	LR [k€/yr]	LCLR [k€]
Wind farm w/o. LV cable		2.000	5.400	536.	6.086
Wind farm w LV cable		2.680	6.822	682.	7.733

Table 5.13 Active power loss of components

The active power losses are 2,6% of the installed capacity of the wind farm and the related lost energy is about 2% of the total annual energy production of the wind farm. For this particular wind farm, the capacity factor is 40% and the load factor is 31% (shore, site). The causes of active power losses and their overall share are presented as pie chart in Figure 5.17.

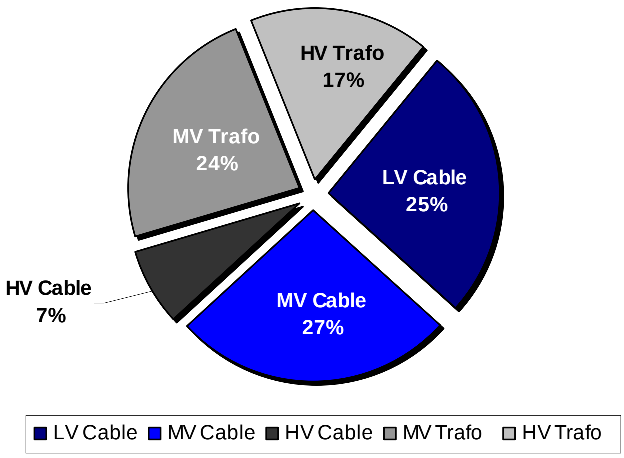


Figure 5.17 Causes of active power losses, generation mode A

Figure 5.17 is only valid for generation mode A where the wind farm operates at rated power. The LV cable of WEC is one of the major causes of reduced active power output due to the high amount of active power transmitted at low voltage levels. The second largest contribution to active power losses are from MV components. This is because of their large number. The MV cable in general and the MV collector system may be optimised with regards to active power losses by means of alternative cross sections, redundancy and alternative layout configurations. Transformers for wind power applications in general should be optimised with regards to their load and no load losses, because of the low capacity factor of wind power systems. Therefore especially the no load losses should be reconsidered and improved by means of different core materials of the transformer.

5.3.2 Economic Evaluation of Active Power Losses

No Load Losses:

No-load losses are present at all times. When the wind farm is not in production mode, such as when the wind is calm, energy must be purchased to supply the no-load losses of the wind farm. Normally, the price and terms of purchased power are different than the prices for fed-in energy, and can include a demand charge [42].

$$PV_{NL} = \left[\frac{P_{NL}}{q^n}\right] \cdot \left[T_0 \cdot C_p + (T_c - T_0) \cdot p + C_{demand}\right] \cdot (1-s) + \left(\frac{P_{NL}}{q^n}\right) \cdot (T_c - T_0) \cdot C_{ptc} \qquad (5.9)$$

$$PV_{NL} = LCLR_{NL} \qquad (5.10)$$

PV_{LR}	*present value of lost revenue [€]*
P_{NL}	*no load losses [kW]*
q^n	*present value factor (n…lifetime)*
T_0	*no load hours (mode D)*
C_p	*Cost of purchased energy [€/kWh]*
C_{dem}	*demand charge per kW peak per year*
s	*income tax rate*
C_{ptc}	*production tax credit per kWh*
p	*€ per kWh wind generation (subsidies)*
$LCLR$	*life cycle lost revenue [€]*

Load losses:

$$PV_{LL} = \left[\frac{P_{LL}}{q^n}\right] \cdot T_C \cdot lf \cdot p \cdot (1-s) + \left(\frac{P_{LL}}{q^n}\right) \cdot T_c \cdot lf \cdot C_{ptc} \qquad (5.11)$$

$$PV_{LL} = LCLR_{LL} \qquad (5.12)$$

Redundancy and its Influence on Active Power Losses

It is obvious that the load losses may be reduced by redundant components because their resistance gets divided into half. However, this concept is not applicable for every component or subsystems due to economical restrictions. It can be shown, that fully redundant power transformers would result in a 30% decrease of load losses (P_{ll}) This 30% decrease is only valid if the capacity factor of the wind farm location above 40% and the installed capacity is larger than 80MW. The same concept can be applied for MV components, although a redundancy there is not always practical, e.g. MV transformer. The no load losses cannot be reduced through redundancies, only by design changes. It should be noted, that for the above evaluation only active power losses were considered. Furthermore, reactive power compensations were not taken into account, but they generally have active power losses that cannot be neglected. In order to estimate the losses accurately the technical availability of WECs as well as for the grid connections should be used to get the precise time of operation.

Certain improvement measures in order to mitigate the active power losses could be

- Just one step up transformer for several WECs
- A higher voltage level at the low voltage side
- Transformer layout variations and optimisations regarding P_0

5.4 Neutral-Point Treatment

The protection concept has a major impact on the availability of the wind farm (see subchapter 4.3.4, p.94) To ensure a safe and correct operation of the wind farm, it is essential that electrical failures get detected and isolated immediately. In order to meet these requirements a thorough design of the systems neutral-point concept is needed. Figure 5.18 presents the most common neutral point arrangements for electrical power systems. Note that arrangement A,B and D require an additional investment, thus arrangement C (low resistance grounding) serves as reference for this evaluation.

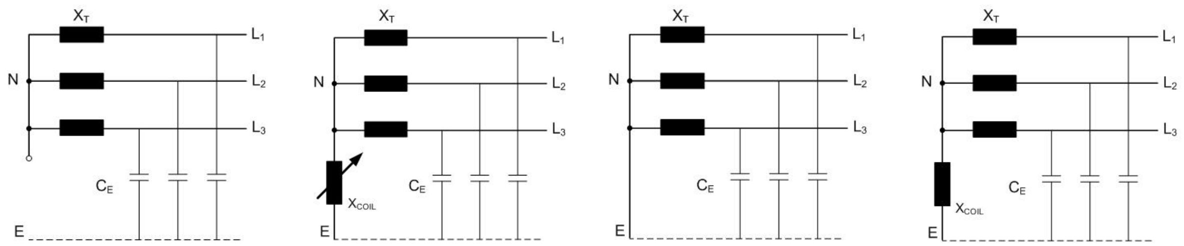


Figure 5.18 Neutral point arrangements

The isolated network in Figure 5.18 is only used for special applications, for example small networks with high continuous supply requirements. Hence, this type is not reasonable for wind farm applications and won't be discussed any further. The properties of the individual arrangements will not be discussed in this investigation. For further information see [17],[47] and [48]. The objective here is to determine whether a compensated MV collector system (B arc suppressor coil) would be profitable or not.

Rating of arc suppressor coils

$$X_{CE} = \frac{1}{j \cdot \omega \cdot C_E} \qquad X_{CE} \quad \textit{wind farm} \tag{5.13}$$

$$C_E = \frac{\varepsilon}{18 \cdot \ln\left(\frac{d_e}{d_c}\right)} \quad [\mu F / km] \tag{5.14}$$

$$Q_{CE} = \frac{U^2}{3 \cdot X_{CE}} \cdot \tan(\delta) \qquad (5.15)$$

tan(δ)	*loss angle*	d_c	*conductor diameter*
d_e	*external (cable) diameter*	ε	*relative permitivity of the insulation*

A_C [mm²]	C_E [µF/km]	I_E [A/km]	l [km]
120	0,18	2,9	10
240	0,23	3,7	7,5
400	0,28	4,5	5
500	0,31	4,9	10

Table 5.14 Technical cable data [21]

Coil	*1 MVA*	*30. – 60.k €*
30kV	*6,3 MVA*	*75. – 90. k€*
Additional Parts	*Controller*	*6. –10. k€*
	detection for cheap UMZ	*100 € per feeder*
	detection incl. control for 10 feeders +current	*15. – 20. k€*

$$C_E = 24{,}075\,[\mu F] \rightarrow X_{CE} = 132{,}2\,[\Omega] \rightarrow Q_{CE} = 6{,}80\,[MVar]$$

$$X_{NP} = X_{CE}$$ *lumped values (tan(δ)=1)*

Arc suppressor coil – life cycle costs pertaining to failure on the collector system

Earth fault frequency: λ_{EF}=1,851 [f/100km], due to the high amount of medium voltage overhead lines in the German distribution system the average earth fault rate is too high. In order to estimate the damage costs (loss of revenue) in an accurate way the failure rate of earth faults only takes external causes, switching causes, environmental causes and reaction causes into account. Hence the failure rate can be assumed to be 50% less of the actual value.

$$S_{NP} = 6{,}8\,[MVA] \quad C_0 = 70\,[k€]$$

$$LCC = \sum_{n=1}^{20} EENS \cdot p \cdot \frac{1}{(1+i)^n} [€]$$ *p=Subsidies(€] , n=MTBF*

$$LCC = C_0 \rightarrow MOFT_{opt.} = 9{,}5\,[h] \ldots.$$ ...*mean operating fault time*

Table 5.15 presents the results of the economic impact of earth fault induced outages of the compensated MV collector system.

Scenario	λ_{EF} [1/yr]	MTBF [yr]	MOFT [h]	E_F [kWh/fault]	LCR [€]	NPV
Most likely case	0,244	4,09	2,5	98.880	23.574	<0
Worst case	0,601	1,66	2,5	98.880	50.565	<0

Table 5.15 EENS and NPV of compensated collector system

λ_{EF} wind farm earth failure rate

The additional energy production during the fault (mean operating fault time MOFT) is financially estimated over the lifetime of the wind farm. This is shown by the life cycle revenue (LCR) in the above table. In both cases (Most likely and worst case), the life cycle revenues are significantly lower than the additional investment costs. Thus the overall NPV is less than zero and the investment is not profitable. Under this assumptions the additional time the wind farm has to be connected in order to obtain a positive NPV would be 4,5 hours.

The additional energy produced during an earth fault was calculated with the assumption that the whole wind farm would be out of service with a different neutral point treatment. Therefore the estimated value of E_F is too high. Assuming the earth fault would only effect the production of one feeder, the life cycle revenue for the worst case scenario reduces to 8 k€. It should also be noted, that additional investments for this arrangement, for example insulation strength or various control, detection and switching devices were not taken into account.

Compared to the other two arrangements (current limiting and low resistance grounding) this configuration has the highest investment costs. The whole protection concept and the additional effort for fault detection, fault clearing and therefore maintaining system stability cannot be neglected. Furthermore, during the fault time, the risk of the occurrence of a multiple failure or an additional failure is higher, due to the high earth fault factor ($\varepsilon_{max}=1,73$)

General

Low resistance grounding result in high earth fault currents, hence a selective, fast and simple protection concept can be implemented. The actual phase to earth short circuit current is directly related to the zero sequence of the transformer. Therefore the high short circuit currents can be adjusted by changing the zero sequence of the transformer. The arrangement with additional impedance at the neutral point is therefore known as current limiting neutral point treatment. In general the earth fault factor should be less than 1,4 and the short circuit current for earth faults should be as low as necessary [73].

Power plants in general and for wind farms in particular usually need an additional starpoint builder (starpoint transformer), depending on the power transformers vector group and the neutral point treatment of the upstream network. In order to fulfill the requirements regarding earth fault factor and short circuit current, the starpoint transformer can either be implemented with a higher impedance or with a neutral point impedance. However, it should be pointed out that in case the starpoint transformer is out of service, the effective operation of the wind farms grounding and protection concept can’t be ensured. Thus a second neutral point builder or a switching option (e.g. spare zero sequence impedance) is recommended.

5.5 Maintenance

Maintenance is the combination of all technical and administrative actions, including supervision actions intended to keep an item up to, or restore it to a state in which it can perform its required function [28]. Maintenance actions can be classified according to their cause, in preventive and corrective maintenance. Basically corrective maintenance is event based, thus is only performed in case a failure occurs. Whereas preventive maintenance is based on predetermined conditions and intend to reduce the probability of ageing induced failures. The concept of maintenance is graphically illustrated in the following figure.

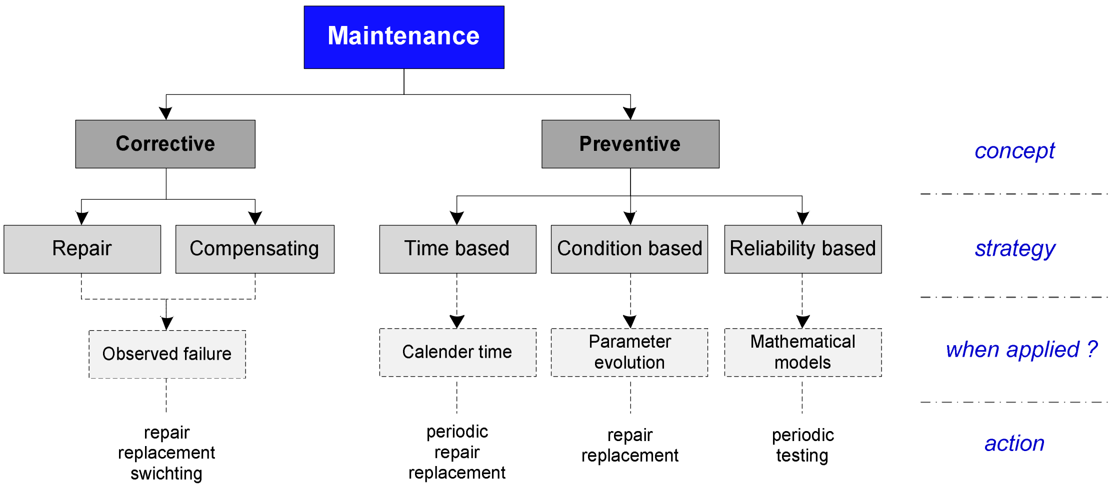


Figure 5.19 The concept of maintenance

5.5.1 Preventive Maintenance

Preventive maintenance is carried out at predetermined intervals or according to the condition of the item and focuses on the improvement of the degradation of the functioning of the item and the reduction of the probability of failure. The major benefits of an effective preventive maintenance strategy are that life cycle costs are low due to the minimising of component down times and the improved safety and performance of the system. The efficiency of preventive maintenance procedures can be classified into the following three levels:

- A General inspection and routine maintenance
- B Inspection, general tests and preventive maintenance
- C Inspection, specific tests and predictive maintenance

Tests would usually include insulation tests, protective device tests, analytical tests as well as grounding tests and functional tests [28].

Figure 5.20 shows the failure rate function with and without maintenance measures. The time frame for this figure was chosen to be from the 10th to the 20th year of operation of the wind farm, because the ageing effects are more visuable.

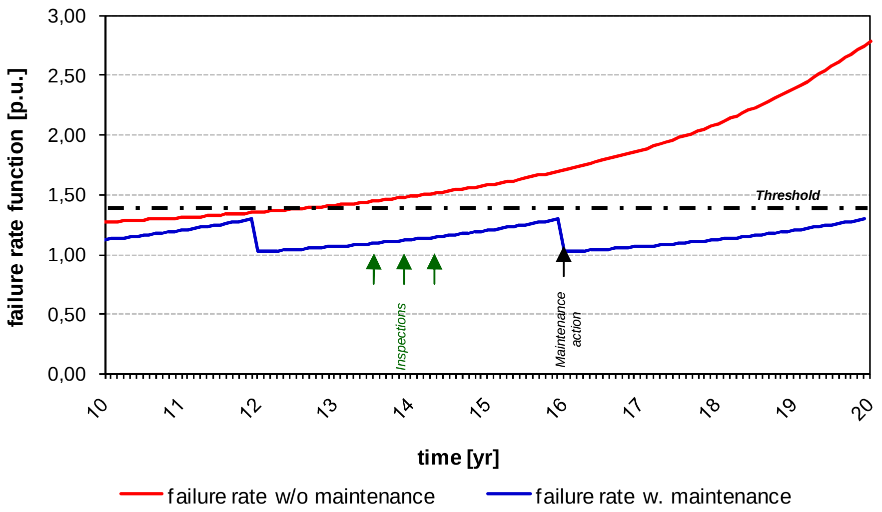


Figure 5.20 Failure rate function with preventive maintenance

Preventive Maintenance Strategies:

- Time based Maintenance (TBM)

TBM is characterised by fixed time intervals between maintenance actions. This concept doesn't take the actual condition of the component into account. It is essential to find the optimum time interval, which can only be achieved through experience. The relationship between costs and benefits of this maintenance strategy is rather low.

- Condition based maintenance (CBM)

This approach takes the actual condition of the component into account which can be evaluated during inspections. Experience and technological knowhow are a necessity to estimate the condition of electrical components. Nowadays monitoring and diagnostic systems are widely used to assess the condition online. Before a certain threshold is reached, the particular maintenance action may be carried out. In order to determine the threshold mathematical models of ageing effects and their influence on degradation of different components need to be established.

- Reliability centred maintenance (RCM)

The reliability centred maintenance strategy is based on the probability of occurrence of certain fault events on components. Thus a thorough understanding of failure mechanisms and

even more important exact reliability models and evaluations of financial failure consequences are needed. For components with an high level of reliability, but low financial failure consequences a corrective maintenance approach is reasonable. Whereas for components with a low level of reliability and high related failure consequences a condition based maintenance strategy is more practical.

Other maintenance strategies, like risk based or forecast based...etc. will not be discussed within this investigation. For more information see [50],[56],[57] and [28].

Influences on Maintenance Strategies

The following measures are essential for deciding which maintenance strategies to apply and for life cycle cost analysis.

- Personnel safety

Faults in electrical power systems must not affect personnel safety

- Failure induced financial damage

The financial damage of the customer has to be as low as possible. In case the risk of component outages is to high the maintenance strategy is intend to mitigate these risks.

- Relevance of the component

Those components that have high failure related energy losses should be maintained in a way that reduces the probability of failures. A condition based maintenance strategy is recommended, if monitoring and diagnostic systems are applicable. Otherwise a time based approach should be considered.

- Number of Components

For high amounts of components condition as well as time based maintenance strategies are usually not applicable due to economical restrictions. Thus, MV components should be designed with low maintenance requirements. Since a corrective maintenance approach seems to be the most effective in case of many components, a certain amount of spare parts is needed in order to keep the repair time low.

- Operational experience with disturbances

Disturbance statistics and the evaluation of failure causes and mechanisms are the basis for maintenance adjustments and lifetime estimations.

- Legal requirements and standards

In almost every country there are some legal standards regarding the maintenance of electrical components and systems. For example the German government regulate the MTBM of step-up transformer systems (ITS/ETS) by law. Thus maintenance actions have to be carried out every four years.

System Availability according to its Maintenance Time:

The following figure presents the availability with respect to maintenance related down time. The dashed line represents the reference level of availability (97%)

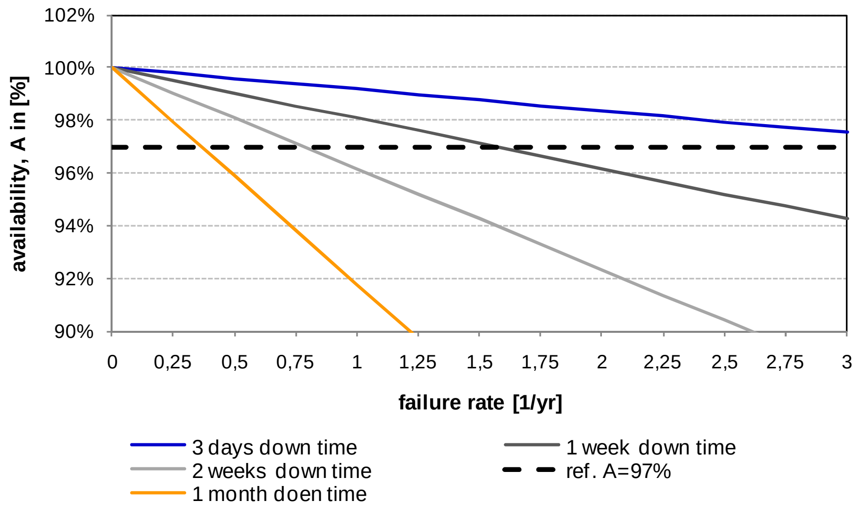


Figure 5.21 Availability with respect to MTTR and number of failures

In subchapter 5.2 (Grid Architecture) different layout alternatives were evaluated regarding their availability and profitability. In the first place merely the failure induced consequences were taken into account, but the second step also considered the influence of maintenance related down time on the level of availability. It was shown, that under certain restrictions (installed capacity, capacity factor) redundant configurations pay for their own additional investment costs. In other words if the lost energy due to maintenance actions is taken into account the life cycle lost revenue of certain components are at least equal to their investment. This concept was proved valid for redundant power transformers. Some customer claim the time to maintain as system down time. It is obvious that this has a major impact on the systems availability. For example, a guaranteed availability of 97% indicates a down time of 260hours. The worst case would now be if all components getting maintained within the same year. This would result in a maintenance induced down time of approximately 220 hours. Hence there would be 40 hours left for corrective maintenance, which implies a high risk that the mean availability is below 97%. This concept is graphically illustrated in figure 5.21 and is also valid for repair times (corrective maintenance)

It should also be noted, that human factors during maintenance actions cannot be neglected. The relationship between human failures and system availability was shown in subchapter 4.4.2. However, the IEEE reliability subcommittee provided factors to quantify the influence of maintenance quality on component failure rates. These factors are presented for some components in the table below.

Maintenance quality	Transformers	Circuit breakers	Motors
Excellent	0,95	0,91	0,89
fair	1,05	1,06	1,07
Poor	1,51	1,28	1,97
All	1	1	1
perfect	0,89	0,79	0,84

Table 5.16 Equipment failure rate multipliers vs. maintenance quality [29]

5.5.2 Maintenance Actions and Intervals of Electrical Components

The next subchapter provides a detailed overview of maintenance related figures of significant electrical components in wind farms. It will be distinguished between maintenance activity, the task that has to be carried out and the intervals between the same activities.

5.5.2.1 HV Components

- Switchgear

Activity	Task	strategy	interval	Info
inspection	Condition assessment	Time based	2 month	
maintenance	Cleaning Functional check adjustments	Time based Condition based	6 yr.	Depends on the condition
	fault	incident based	n.q.	

Table 5.17 Maintenance of HV switchgear

- Power Transformer

Activity	Task	strategy	interval	Info
inspection	Condition assessment	Time based	2 month	
	Protection control	Time based	3 yr.	
	Oil analysis	Time based	3 yr.	Depends on the condition
maintenance	against corrosion	Condition based	10 yr.	
	OLTC	time based	6 yr.	
	foundation	Condition based	>20 yr.	

Table 5.18 Maintenance of power transformers (ABB)

5.5.2.2 MV Components

- ITS/ETS

Activity	Task	strategy	interval	Info
MV Switchgear secondary				
inspection	Condition assessment	Time based	4 yr.	
maintenance	Cleaning Painting Replacement Functional control Fault clearing Grounding check	Condition based (Incident based)	4 yr.	
MV Transformer				
inspection	Condition assessment	Time based	4 yr.	
maintenance	Cleaning painting	Condition based	5-10 yr.	
	faults	Incident based	n.q.	repair

Table 5.19 Maintenance of ITS/ETS

- MV Collector System

Activity	Task	strategy	interval	Info
inspection	Control of terminations	Time based	5-10 yr.	Commissioning Retrofit, fault
	Measure	Incident based	n.q.	
maintenance	Cleaning Painting	Condition based		
	Replacement of terminations and junction boxes	Incident based	1 yr.	
	Fault clearing	Incident based	n.q.	

Table 5.20 Maintenance of MV cable systems

- Substation MV primary switchgear

Activity	Task	strategy	interval	Info
inspection	Control of terminations	Time based	2 month	
	Protection check	Time based	4 yr.	Type dependent
maintenance	Switchgear bays	Time based	10 yr.	Type dependent (Switching cycles)
	fault	Incident based	n.q.	

Table 5.21 Maintenance of MV switchgear primary

WEC

Time based, if an additional service package has been signed (ISP,WSV), twice a year.

Maintenance Costs

For the sake of completeness it should be noted that the maintenance related costs were already introduced in subchapter 2.4.2, p.38

5.6 Alternative Electrical Parameters

5.6.1 Voltage Level Variation of the MV-Collector System

Since the rated power of wind turbine generators and therefore of entire wind farms became larger over the past years the voltage level of the collector system also increases. Commonly the collector systems operate at rated voltages of 10kV, 20kV or 30kV with slight deviation. However, nowadays large wind farms are normally designed with a 30kV (-36kV) MV collector system.

The benefits of a higher voltage level are e.g. the lower active power losses, the additional WECs that can be installed per feeder and of course the bigger areas that can be reach by just one feeder. On the other hand there are also some obvious cons that speak against a higher voltage level. First of all there is the increase of isolation necessary to maintain the electrical strength. This leads directly to an additional effort not only in the investment costs, but also in the number of accessories like joints.

Secondly there is the higher EENS due to more WECs on just one feeder, therefore a thorough design of feeder-disconnectors to separate the collector system in several parts is necessary, in order to improve and control the protection zones as well as the short circuit power. Another con can be the increase of reactive power at PCC delivered from the MV cable and thus the need for high performance facts which would result in significantly higher investment costs. However, the last point can also be an advantage, depending on the external conditions (Grid Code, the country, condition of the upstream transmission system...etc.)

5.6.2 Variation of the Rated Power of Transformers

Through variation of the transformers rated power the level of redundancy and therefore the reliability will vary as well. For example in case of an 100MVA power transformer the additional investment for a redundant layout with two 50MVA transformers is approximately 50%, which easily pays off during the wind farms useful lifetime.

The transformers cooling system is another way to slightly change the rated power and thus the overall investment costs. Transformers especially oil transformers have a great overload factor. Therefore, if the cooling system would be changed from ONAN to ONAF this would result in an drop of approximately 10% regarding the rated power of the transformer.

6 Contract and Insurance Possibilities

The previous chapters focused on the availability evaluation of grid connection concepts for wind farms and the related outage costs. It was shown, that although the level of availability of the grid connection is very high, there are certain inherent risks related to each individual layout that can't always be mitigated in a technological way. This chapter is intended to provide a overview of risks regarding the grid connection of wind farms and how to mitigate them. As mentioned in the previous chapter, the main focus during the design phase of electrical power systems is that they are as reliable as possible (from a technological point of view) and as expensive as necessary (from an economical point of view). Since there is usually a certain level of risk related to this compromise, the second half of this chapter includes insurance possibilities for wind farms. The last part of this chapter shall give an overview of different contractual definitions that can be applied.

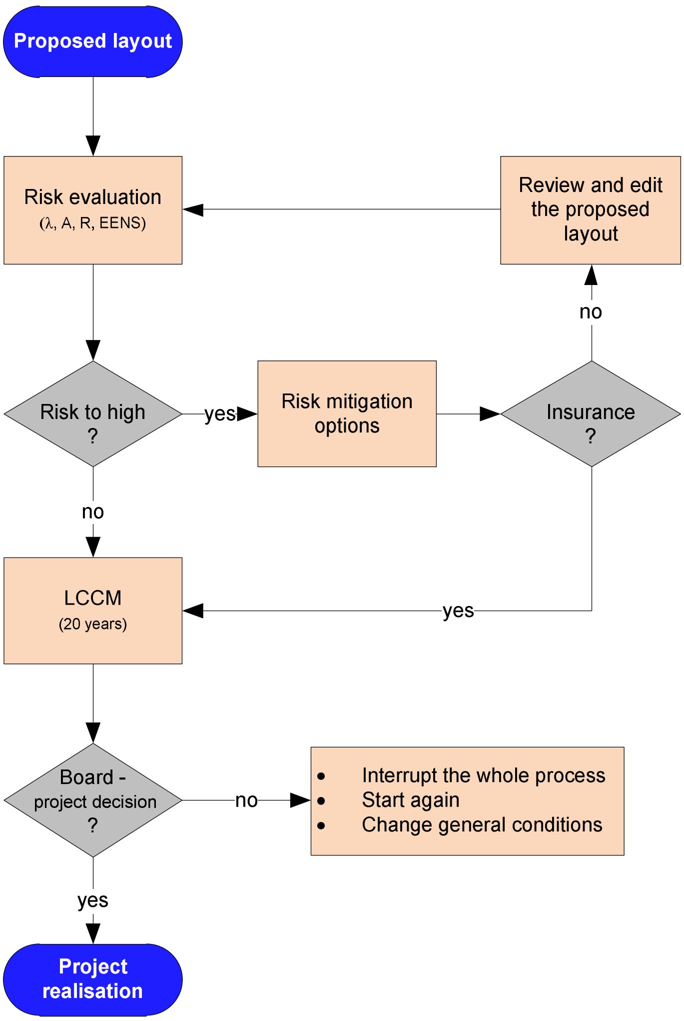


Figure 6.1 Decision process for risk and insurance possibilities of electrical BOP projects

The decision process, whether a proposed wind farm layout and its related risks are reasonable, is shown in Figure 6.1 in a simplified way.

6.1 REpower Standard Contract

The mechanisms of the technical availability guarantee for the WECs as well as for the grid connection are contractually defined within the integrated service package (ISP). Hence the guarantee is only valid if the service and maintenance works are done by REpower itself. The liability costs for general maintenance and repair actions are caped with five hundred thousand Euros. Small repair or replacements of components that don't exceed an investment of 1.500€ can immediately take place without the customers permission. Furthermore the maintenance periods are defined by REpower and must take place within a time frame of plus, minus four weeks based on the stated time. This should give the company the opportunity to shift the maintenance actions in a low production period, usually during the summer month. In case the maintenance of individual components is not done satisfactorily, or in a worst case scenario even lead to a fault, the customer has the opportunity to claim warranty within a period of twenty four month.

REpower guarantees an average technical availability level of ninety-seven percent (97%) in respect of the Wind Farm, which shall be calculated by the customer using equation 6.1 and 6.2 as follows.

$$A_{WEC} = \frac{T_A}{T_c} \cdot 100\,\% \tag{6.1}$$

$$A_{WF} = \frac{\sum_{i=1}^{n} A_{WECi}}{n} \tag{6.2}$$

A_{WEC}	*availability of the WEC*
A_{WF}	*availability of the windfarm*
T_A	*Time the WEC is available*
T_c	*calculation period (time interval)*
n	*number of WECs*

The technical availability of the wind farm (A_{WF}) is calculated as the sum of the average technical availability of the individual WECs within the wind farm (A_{WEC}) in percent, divided by the total number of WECs. The technical availability guarantee applies on the day falling three month after the commissioning date of the last WEC of the wind farm and normally lasts five years. However, the precise time interval for the availability guarantee has to be negotiated; nowadays a common period is 10 years. The bonus-penalty concept, where the customer gets the liquid damages compensated if the availability doesn't meet the guaranteed level and REpower gets an bonus if the availability is beyond the guaranteed level was introduced in subchapter 0.

Important aspects of operation and maintenance contracts that apply with respect to the system availability (e.g. warranty liability product quality...etc.) are presented on the next page.

- Warranty

The warranty period for performed service or maintenance actions is twenty four month. Within this period the customer is entitled to claim warranty of defected performances. REpower is responsible to take all necessary measures to mitigate the defects immediately. Furthermore, the customer is entitled to act on its own responsibility to mitigate the defects if REpower doesn't respond after the customer has informed the company tree times.

- Liability

REpower is liable for any damages exclusively for any physical damage to the property of third parties or injury to persons. In case that any damage or injury is caused by both parties, the customer and REpower, the damage shall be compensated by each party in proportion to its degree of fault.

- Final inspection assurance

At the end of the contract period (ISP) the nominal condition of the WECs and the whole windfarm has to be verified. Therefore all necessary service and maintenance measures to ensure that the components are able to perform their required function adequately shall be applied. The customer may carry out an inspection of the WECs or the whole windfarm on their own costs within three month before the ISP contract expires. If REpower has not fulfilled its contractual obligations, the customer may notify REpower of any services required to be remedied the latest until one month after the ISP contract period expired.

- *Guarantee of quality*

Power curve

REpower guarantees that the relevant power curve is one hundred percent valid during the warranty period for each WEC according to IEC standard 61400-121:2005, whereas the measurements uncertainties are not taken into account. The power curve guarantee shall commence on the date of commissioning of the WEC and end no later than twenty four month after that date.

Sound emission

For the warranty period, an emission related sound level is guaranteed. If the customer can prove, that the actual sound level exceeds the guaranteed level, REpower shall be entitled to take mitigation measures three times. Any further claims for damage compensation of the customer shall be excluded.

Electrical characteristics

REpower guarantees the electrical characteristics of the components as specified in the relevant product descriptions and technical documents.

6.2 Warranty and Guarantee

Warranty is the general liability of the debtor for defects, which the product (e.g. electrical component, service) shows during its delivery (performance). The concept of warranty is regulated by law, thus it has not to be contractually stipulated [64]. It has to be considered that a charge for the delivery (component) is required; otherwise the legally bounded warranty is not valid. It is possible to claim the warranty regardless of who caused or indebted the defect. However, the warranty-defect has to be existent on delivery of the product (component, service) Furthermore, the creditor is not obliged to accept the product regardless of the kind of defect. If the creditor takes a defect product, because he didn't see the defect, warranty can be claimed as well, since it was a defectively delivery.

Type of defect

- *Material defects*
  Material defects are defects which are physically connected to the property, also known as defects of quality.
- *Defects of title*
  These defects usually occur when the ownership or transfer of ownership is not properly recorded. Legal claim or circumstance, that hinders the identification of the true owner of a property.

Primary warranty remedies

- *Improvement* (rework, supplement)
- *Replacement* (reasonable period of time, as less inconvenience for the customer as possible)

If the defects can be corrected, the customer has the right to claim an improvement or a replacement. Improvements in form of reworks or supplements have to take place onsite and without any additional financial efforts. (Additional payments) Furthermore, the transferee can choose between improvement and replacement. The seller (transferor), on the other hand, has the option to claim that the replacement is either impossible or connected to an unreasonable high effort. If both primary warranty remedies (improvement and replacement) are impossible to fulfil, the seller can refer to the secondary warranty remedies.

Secondary warranty remedies:

- Price reduction *if the defect is not negligible*
- Conversion

Compensation for the damage can only be claimed if the primary warranty remedies are impossible. The legal consequences of warranty don't start automatically with the occurrence of a defect, but have to be claimed by the customer within the respective warranty-period. The warranty-period for movable properties is two years and for immovable properties three years. According to warranty, companies can be seen as immovable.

Guarantee

The terms of guarantee normally exceeds the warranty conditions, but are only valid for a short period of time (depends on the contract). However, guarantee is an additional service that sellers or the manufacturers provide and is not legally bounded.

- Guarantee of the seller
- Guarantee of the manufacturer (producer

When speaking of guarantee the guarantee of the manufacturer is meant, in which a third party (normally the manufacturer) covers all defects and therefore assures the property has no defects, what so ever. Type, content and period of time of the guarantee has to be negotiated and set up contractually. Guarantee and warranty are coexistent, in other words both can be valid during the same period of time (normally the warranty-period is much longer) and therefore can be claimed by the customer.

Application to Wind Power Systems

The warranty and guarantee periods for individual components should be outlined taking the failure rate function of the relevant component into account. Due to the higher failure rate at the beginning (teething period) it is recommended, that the first month the component is in operation are excluded from the guarantee period. On the other hand the inverse can be applied to subcontractors of REpower. For example the teething period of components should be covered by the additional guarantee of the subcontractor. Especially HV components should be considered separately because of their significance to the proper operation of the windfarm and their high investment costs. Whereas the failure of MV components in general and the related financial damage should be considered in the selling price, since these components have lower investment costs, but mainly because of the high amount of components.

6.3 Risk Assessment and Mitigation

Risk (R) is defined as the loss (C) that can occur with a given probability (P). The loss can either be financial, personal, energy based...etc. Figure 6.2 shows the concept of risk, its characterisation and furthermore, its influences. It is important to note, that loss can only be determined and evaluated in reference to predefined goals or expectations.

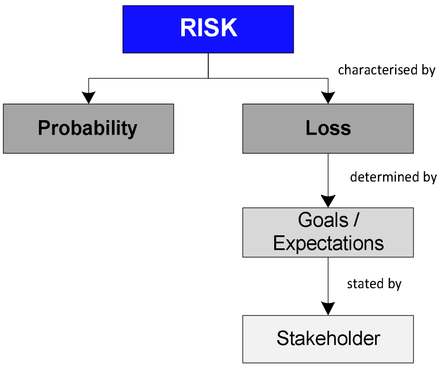


Figure 6.2 Definition of risk [18]

The risk (R_i) associated with one particular event (i) is assessed through the product between the probability (P_i) that the event takes place and the consequences (C_i) associated with the event.

$$R_i = P_i \cdot C_i \tag{6.3}$$

Risks must be related to a time frame (T), such as for example one year. Therefore the risks associated with the number of a specific type of events ($n(T)$) within the defined time frame (T) shall be considered. In that case Equation 6.1 is written as

$$R(T) = \sum_{i=0}^{\infty} P(n(T) = i) \cdot C \cdot i \tag{6.4}$$

$P(n(T)=i)$ is the probability of i events of the actual considered type within the time T and C is the consequence associated with the occurrence of one event. However, equation 6.5 may also conveniently be written as:

$$R(t) = E[n(T)] \cdot C \tag{6.5}$$

where $E[n(t)]$ is the expected number of events of the considered type during the period T. The expected number of events may be established by integration over the occurrences (f) as

$$E[n(T)] = \int f(t)dt \tag{6.6}$$

For different applications either of the two different formulations of risk may be convenient i.e., Equation (6.4) or (6.4).

It is obvious that financial failure consequences also vary over time ($C(t)$) since they are proportional to the failure rate. Thus the failure induced damage costs increase with respect to time and have their peak during the wear-out period. Since the failure rate as well as the financial failure consequences are statistically distributed, the related risk may be presented as an distribution as well. The two figures below show the failure related risk during the burn-in period and during the wear-out period of components. The inherent risk slightly decreases after the component was put into operation and can assumed to be almost constant during the components useful life period. During the wear-out period were certain aging effects occur, the risk will increase again due to the increasing probability of failures.

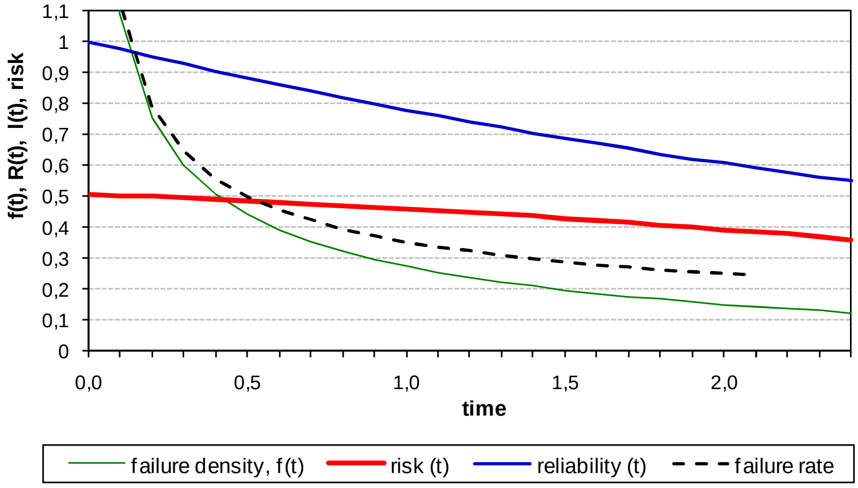


Figure 6.3 Reliability and related risk for the burn-in period

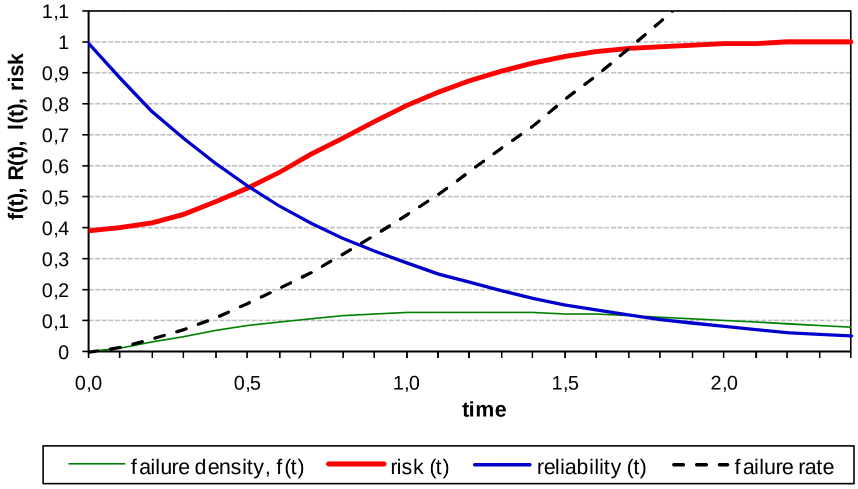


Figure 6.4 Reliability and related risk for the wear-out period

The risk distributions (Γ(t)) in Figure 6.4 and Figure 6.3 were calculated using the following equation:

$$\Gamma(t,\Delta t) = \frac{R(t) - R(t+\Delta t)}{R(t)} \quad (6.7)$$

In general, the risk shall be passed to the customer with the commissioning of the WEC. Where Delivery, Installation and commissioning are not possible for reasons beyond the control of REpower, the risk shall be passed to the customer not later than two months after the notification of readiness for delivery.

In order to quantify the risk in an adequate way, the concept of risk analysis is divided into two parts:

- Determination of the probability of an undesirable event. (generated from detailed analysis of past experience and historical data)
- Evaluation of the consequences, C_i of the undesirable event.

The exact steps to perform a risk analysis are known as the risk triplet and exist of the following stages:

- Selection of a undesirable reference event or scenario
- Estimation of the probability of occurrence, P_i
- Estimation of the consequences of these events, C_i

6.3.1 EPC Project related Risks

The acronym EPC stands for engineering, procurement and construction and can also be summarised by the term turnkey solutions. In other words when speaking of EPC projects the company (contractor) is responsible for the whole project and thus barriers most of the related risks. Regarding the risk of electrical components in particular figure 6.5 provides an overview of different events, their probability and their related severity and how to mitigate the risk in general.

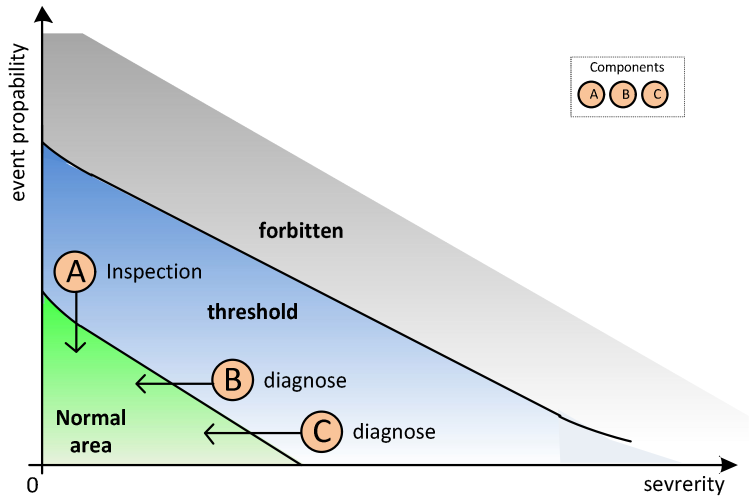


Figure 6.5 Risk of component damage

The probability of occurrence of certain undesired events on electrical components has been discussed in detail in previous subchapters. The severity on the other hand can basically be categorised into following fields:

- People
- Assets
- Environment
- Image/Reputation

Within the next few pages, the related risk of important grid connection components will be elaborated. Basically it is distinguished between high voltage and medium voltage components. It should be pointed out, that only components that are relevant for the proper function of the system are discussed, because of the vast amount of electrical components.

HV Components

It is obvious that the HV components are essential for the functioning of the wind farm, since in case of a failure the whole wind farm would be unavailable, depending on the layout. The risk of HV lines as well as for power transformer is presented in the following tables.

- HV connection

Component	Risk	Consequences	Preventive measures	Probability of occurrence
HV line	fault	Outage of the whole wind farm	Double the HV connection	Project related (see appendix)
Measuring equipment	Failure on the HV/LV side Temporary HV fault	Protection of the hv line disabled	Spare parts Preventive maintenance	
Disconnector	Fail to operate	Outage of the whole wind farm	Spare disconnector	
Circuit breaker	Fail to operate	Outage of the wind farm	Spare circuit breaker	
Protection devices	Failure of the relay, power supply, current transformer, ...etc.		Spare parts	

Table 6.1 Risk evaluation of HV components

- Power Transformer

Component	Risk	Consequences	Preventive measures	Probability of occurrence
HV line	fault	Outage of the whole wind farm	Double the HV connection	Project related (see appendix)
Measuring equipment	Failure on the HV/LV side Temporary HV fault	Protection of the hv line disabled	Spare parts Preventive maintenance	
Disconnector	Fail to operate	Outage of the whole wind farm	Spare disconnector	
Circuit breaker	Fail to operate	Outage of the wind farm	Spare circuit breaker	
Protection devices	Failure of the relay, power supply, current transformer, ...etc.		Spare parts	
Windings and core	Internal failure	Wind farm out of service	Redundancy	
OLTC	Mechanical or electrical failure	Wind farm out of service	Reliable type of OLTC (e.g. vacuum type)	
bushings	Electrical or mechanical failure	Wind farm out of service	Spare parts	

Table 6.2 Risk evaluation of power transformers

MV Components

Because of the vast amount of MV components, for this investigation only important components with a significant impact on the systems performance will be considered. As previously mentioned, the risk for the MV components are rather low due to the overall maintenance support structure. (E.g. spare parts…etc.) However, the MV connection of the power transformer is the exception.

- Substation MV part

Component	Risk	Consequences	Preventive measures	Probability of occurrence
Power transformer cable	Failure on the MV cable	Outage of the whole wind farm	Single phase spare cable	Project related (see appendix)
	Failure of the termination or joint	Outage of the whole wind farm	Spare parts Preventive maintenance	
Switchgear primary	Failure on the main bus	Outage of the whole wind farm	Sectionalised bus, tie breakers	
	Trafo protection device fails	Outage of the wind farm	Spare parts, or installation of a spare bay	
	Feeder protection device fails	Outage of the whole feeder	Spare parts, or installation of a spare bay	
	Aux. Power supply fails	Wind farm out of service	Redundant emergency power concept	

Table 6.3 Risk evaluation of MV substation

- Collector system

Component	Risk	Consequences	Preventive measures	Probability of occurrence
feeder	Failure on the MV cable	Outage of the whole feeder	Interconnections, redundancies	Project related (see appendix)
ITS/ETS	Transformer failure	Outage of the whole feeder	Spare parts Preventive maintenance	
Switchgear secondary	Failure on the busbar	Outage of the downstream WECs	Sectionalised bus, tie breakers	
	Trafo protection device fails	Outage of the WEC	Spare parts, or installation of a spare bay	
	WEC protection device fails	Outage of the WEC	Spare parts, or installation of a spare bay	
	Aux. Power supply fails	WEC out of service	Redundant emergency power concept	

Table 6.4 Risk evaluation of MV collector systems

- Logistics and Infrastructure

The risk related to general logistics, service and infrastructure issues includes topics like transportation, site accessibility, installation and commissioning, service contracts with subcontractors, accuracy of wind reports, legal and market risks….etc..

6.3.2 Risk-Matrix for Grid Connection Components

The probability of occurrence and the related impact (severity) of certain events on grid connection components is presented in the risk-matrix below.

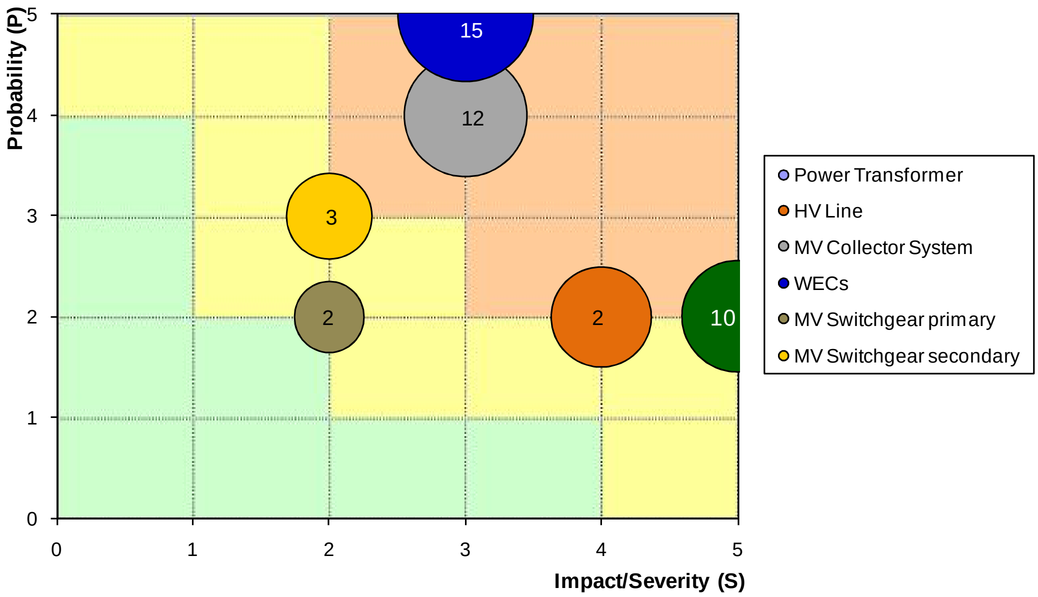


Figure 6.6 Risk matrix of grid connection components

It can be seen, that the WECs and the MV collector system are still the subsystems with the highest risk factors. This is because of the total number of WECs and the total cable length of the collector system. The failure and availability evaluation in subchapter 4.3 has shown similar results. In order to mitigate the high risk of these components certain preventive measures are needed. In case of the MV collector system, preventive maintenance strategies but more important spare parts of joints, terminations...etc. shall be applied. In order to mitigated the risk of WECs a precise quality management of the components is necessary as well as preventive maintenance works and a good support structure.

Interpretation

- MV Collector system **low risk**
  (Incl. trafo and secondary switchgear)
- Substation (MV Part) **low risk**
  (Unattended maintenance)
- Substation (HV Part) **high risk**
  (Insurance possibilities /
  Exclude trafo from availability guarantee?)
- Maintenance **need to be discussed**
  (WEC incl. ITS/ETS
  substation – strategy required)

6.4 Insurance Possibilities

Nowadays almost every renewable energy project is insured in some way. For example the machinery business interruption insurance applies to every power generation system and is valid not only for the operation phase but also during erection (erection business interruption insurance). There are various kinds of insurances that apply during the life cycle of wind power systems. An overview of the most common ones is graphically illustrated in Figure 6.7.

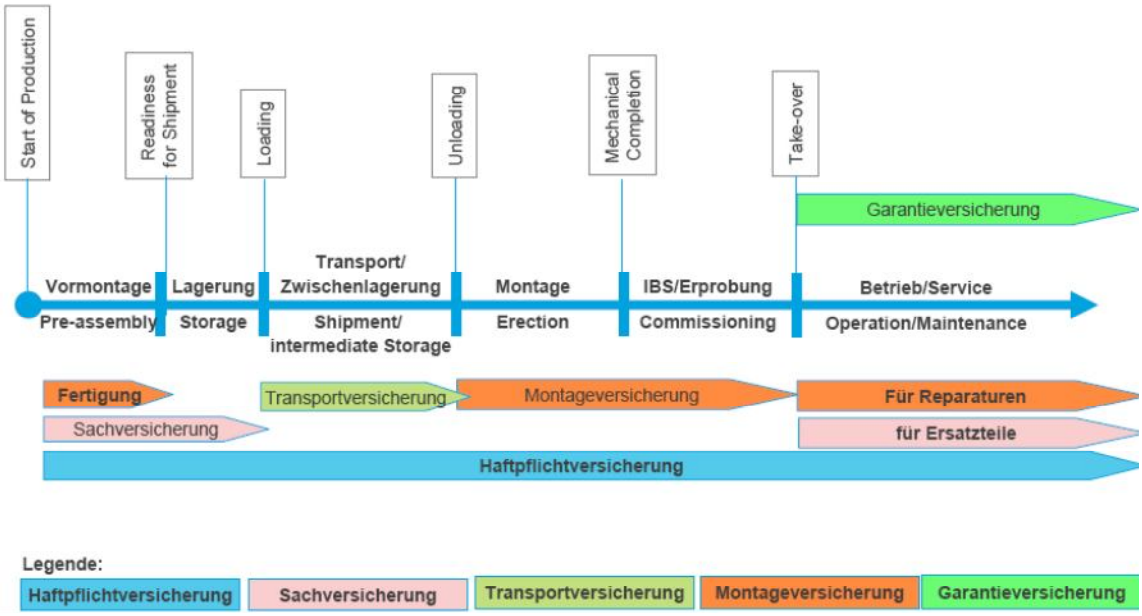


Figure 6.7 Insurances over the life cycle of electrical components [75]

As shown in previous subchapter, the financial damage of customers caused by certain undesired events (e.g. failure of components) is calculated using the capacity factor, which can be interpreted as the fluctuating wind speed. However, in case of insurance premium rates this concept has limited significance, for example the correlation between high wind speeds and the higher damage potential must be taken into account when evaluating whole wind farms. The major influences on insurance rates are the building design and the redundancy of components. The building design is relevant for example in case of fire, which can be seen as a common cause failure. Thus if components are spatially divided in a way that a failure of one component cannot effect the other component, the insurance rate can be assumed to be the half. (E.g. Substations: fire protection, solid building design, various accesses, ventilation...etc.) The second important influence on insurance rates is the level of redundancy. The grid connection layout should be designed in a way that certain bottlenecks (e.g. HV connection) don't occur. Actuarial speaking, significant components should be n-1 redundant, also known as 50% components. In case of redundant power transformers this means, that if one transformer trips only half of the wind farms installed capacity is still connected to the upstream grid. The application of this concept is only valid for individual significant components, due to economical aspects. (E.g. full redundancy of MV collector system)

Furthermore the insurance premium rates are also related to the reputation of the components manufacturers. In other words, the insurance rates for a premium component produced from a well established company are much lower than those of a low-quality product. Therefore it can be assumed that a fifty percent redundancy layout designed with two low-quality products have lower lifecycle costs than the layout alternative with one premium-product and an additional insurance policy beyond a certain installed capacity. In general it is important to note, that the insurance taxes are different for individual countries. Furthermore, cash flows to foreign insurance companies are prohibited by law in order to keep the cash flows local. For example the insurance taxes for Germany are currently nineteen percent, whereas those for the Australian market are thirty percent which represent the highest insurance taxes worldwide. It is important to check the country specific insurance taxes in order to keep the overall costs low, since the insurance premium rates normally don’t include taxes.

In addition it is always possible to get fired from the insurance company; hence in case the insurance company covers for a significant damage or loss they cancel the insurance policy. It is common practice that insurance companies just cover the occurrence of just one major damage event. What should be also taken into account are the various kinds of deductibles concerning individual components. Deductibles represent the own risk and normally are time based. For example a typical deductable period for substations (power transformers) is two to four weeks. Hence if the repair or replace time is less than the deductable period the insurance doesn’t cover the loss. Therefore components which have low MTTRs can be left out of the insurance policy. (E.g. MV collector system)

For wind farms the level of availability cannot be insured in general only the business interruption resulting from insured property damage to the plant can be insured. During the operation period the operator exchanges machinery breakdown and business interruption insurance covering external hazards such as natural catastrophes or terrorism. If REpower is liable for the property damage based on its supply contract, coverage is not provided under this policy but the warrantee of REpower has priority - irrespective of whether REpower has taken out warrantee insurance to cover this risk or not. If REpower is also liable for the availability of the plant based on a service agreement, this warrantee has also priority to the machinery business interruption insurance.

Components

The next section is intended to provide a basic overview of insurance possibilities for individual electrical components and subsystems within a wind farm. It should be noted, that the insurance premium rates are expressed as the percentage of the overall annual turnover of the wind farm. In addition the overall costs for insurance and the concept of binding offers is going to be discussed.

Wind Energy Converter

REpower is responsible for the insurance which covers the transportation and assembly risks. Furthermore, REpower has to provide a relevant insurance of the machinery of the WEC that covers external risks. In case the customer already has such insurance this concept doesn't apply under the restriction that the customer informs Repower four weeks prior to the passage of risk. In addition to the transportation and erection insurance a so called guarantee and business interruption (BU) insurance should be closed up, which basically covers the lost revenue caused by any damage to the insured property. The insured property can be every product of Repowers scope of supply, regardless whether it's new or not. The insurance period starts subsequently to the insurance for erection after the commissioning of the product. The liability of the insurance company typically ends at the end of the ISP contract. The deductibles for WECs with an rated power up to 3,5 MW are 750.000 Euros. Thus all financial damages less than 750.000 Euros are compensated by Repower. In case of financial damages beyond 750.000 Euros the deductibles thereby incurred just three times. The deductibles for facilities with an rated power beyond 3,5 MW are one million Euros and the deductibles for serial damages are one and a half million Euros. It should be noted; that the highest amount of compensation related to the BU insurance is twenty five million Euros within one year. The evaluation of the insurance premium rate is based on the total installed capacity of the wind farm and the annual turnover. Additionally a stop-loss-agreement of 2.250.000 Euros (WECs up to 3,5 MW) or 2.000000 Euros (WECs above 3,5 MW) per year applies. Furthermore, individual components within one WEC may be covered by an additional machinery business interruption insurance (MBU), usually from a different insurance company.

HV Components

Usually in Germany the premium rate of a business interruption insurance for a substation amounts to 1 % of the annual turnover of the wind farm for a maximum period of one year which is likely to happen in case of large substations. Since transformer claims are usually not caused by external events, REpower might be liable for most of the claims based on the service agreement. For this reason the premium rate for the limitation of REpower's liability can only be reduced to a marginal extent and will be at least 0.8 % of the annual turnover subject to a normal time excess of one or two weeks per claim.

MV Collector System

The risk of a failure to the MV cable system is much lower than that of the substations. Therefore the premium rate should be reduced to 0.2 %. However, final clarifications can only be done after detailed review of the grid connection layout. Due to the relatively low impact of failures on the MV collector system an additional insurance is usually not reasonable. It is recommended, that these failures are covered by maintenance support structures.

Availability Insurance

In case of a claim insured or to be insured under a warrantee policy of REpower, the availability can be insured under a warrantee business interruption policy. The costs of risk in form of an insurance premium and the deductible of REpower have to be agreed. This is only possible after a detailed risk assessment and clarification of the interdependencies of all components of the wind farm. As a first calculation for an offer the following estimated values can be taken into consideration:

Overall Insurance Premium

Based on the items mentioned above there will be a premium for the availability of BoP - of course only in respect of insurable losses - totaling to 1.5 to 2 % of the annual turnover of the wind farm plus insurance tax. In addition REpower has to consider for its calculation the uninsured availability claims arising from a business interruption without property damage as well as the deductible. Business disruptions are not that important because long term interruptions exceeding the deductible rather result from property damage. This risk should be evaluated by REpower from a technical point of view. A deductible of 14 days accounts for 4 % of availability. This should be evaluated with the probability of occurrence. As the premium rate shows the insurers expect one long term total failure in 50 years. Failures of one or two months for parts of the plant however are possible more often. This should also be taken into account by REpower when evaluating the calculation of an offer.

Binding Insurance

A binding insurance offer can only be made by means of a submission in the insurance market after a detailed risk analysis and evaluation of all supply and service contracts as well as the location of risk.

<u>Example: Lifecycle Insurance Costs for Power Transformers</u>

The insurance premium for a wind farm power transformer (P_r=100MVA) of high quality, which is located in an ordinary accessible area can vary between seventy thousand and one hundred and fifty thousand Euros per year. At a common interest rate of six percent, an insurance period of ten years (equal to the maintenance period) and a premium of one hundred thousand Euros this would result in an overall paid insurance premium of seven hundred thousand Euros. This is about the same as the total investment costs of the power transformer.

7 Results and increase of Knowledge

General

This thesis presents the level of availability of single, significant electrical grid connection components as well as the availability of whole wind farms according to their installed capacity, layout and applied maintenance strategy.

The objective was to estimate the level of availability of the grid connection concept used by Repower Systems AG, to find significant influences on the systems availability and the optimum between technological and economical design requirements. Furthermore contractual obligations should be derived, taking insurance possibilities into account.

Based on mathematical concept, introduced in the first chapter and by the use of reliability and outage statistics from subcontractors and electric utilities the availability of individual components was calculated. During the next steps the availability of a whole wind farm with an installed capacity of 100MW was calculated which served as reference for the optimisation process in chapter six.

It is important to mention that the results are based on theoretical, analytical methods. Major availability and reliability figures, like mean time to failure (MTTF) or mean time to repair (MTTR) present long term arithmetic averages.

The results show that the wind energy converter itself is the major cause of reduced power output at the point of common coupling. The level of availability of the grid connection is beyond the target value of 97% and can be assumed to be above 99%. The bottle neck of the grid connection is still the high voltage part, not because of the high failure rate but because of the high impact of failures and the maintenance related energy not supplied. The investigation shows, that a redundant layout of the HV connection is reasonable for wind farms with an installed capacity larger than 100MW and a capacity factor above 40%.

Grid Connection Layout

The incremental levels of availability of different grid connection configurations are summarised in Table 7.1. It should be mentioned that the radial network configuration serves as reference for this evaluation. This table shows the relative as well as the absolute increase of availability over a period of one year. Additionally the incremental availability with respect to preventive maintenance actions is taken into account which is represented within the last two columns. The first three columns describe the grid connection configuration. (‘d’ stands for double, redundant layout; ‘s’ stands for single, radial layout)

Layout				ΔA [%]	ΔA [h]	ΔA* [%]	ΔA* [h]
#	substation		feeder				
	HV	MV					
B	*d*	*s*	*s*	0,04%	4	0,37%	33
C	*s*	*d*	*s*	0,00%	0	0,03%	3
D	*d*	*d*	*s*	0,04%	4	0,38%	33
E	*s*	*s*	*d*	0,12%	11	0,31%	27
F	*d*	*s*	*d*	0,16%	14	0,67%	59
G	*s*	*d*	*d*	0,12%	11	0,14%	12
H	*d*	*d*	*d*	0,17%	15	0,69%	60

Table 7.1 Increase of availability

Table 7.1 presents only the technical availability of different system configurations and doesn't consider the financial impact at all. Since technical availability is directly related to lost revenue and investment costs and therefore essential for the decision which layout alternative should be applied, or whether a certain wind farm is profitable or not, the following figure shows the financial side of different grid connection configuration.

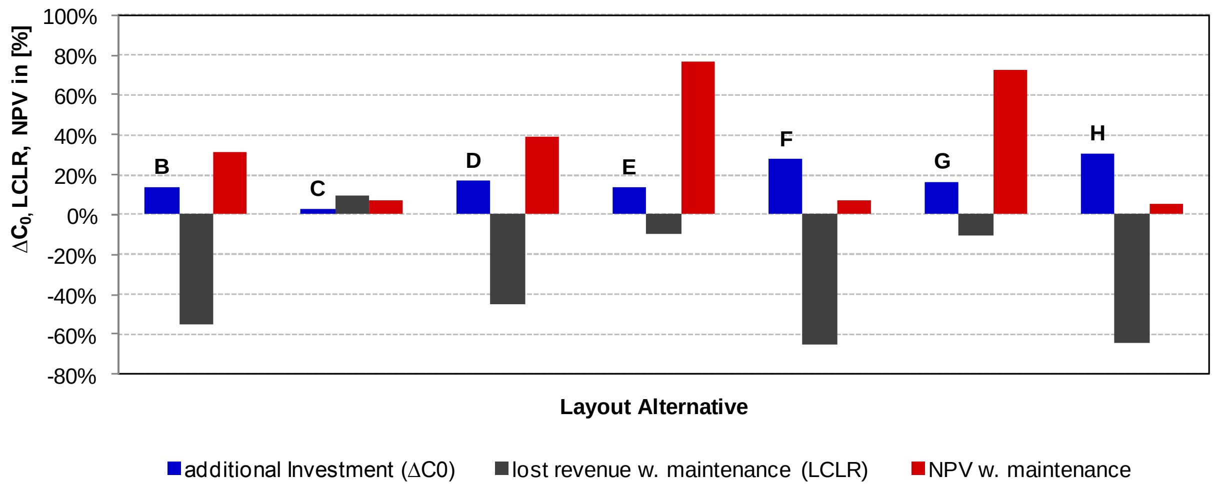


Figure 7.1 Additional investment, lost revenue and NPV of layout alternatives

The lost revenue, taking preventive maintenance actions into account (LCLR) as well as the net present value (NPV) are estimated over the wind farms useful lifetime (twenty years). It can be seen, that a redundant configuration for the collector system and the medium voltage part of the substation for onshore wind farms with an installed capacity of less than 100MW is not reasonable. Whereas a redundant high voltage connection for such wind farms seems to be profitable, due to the maintenance related lost revenue of single power transformers. On the other hand it should be noted that the additional investment for this configuration is fifteen percent higher compared to single, radial layout.

Maintenance methods

Besides corrective maintenance actions the main influencing factor regarding the wind farms availability are preventive maintenance actions. In particular preventive maintenance actions on primary MV switchgear, as well as on high voltage components. It was shown, that over a period of ten years a redundant high voltage connection is profitable for wind farms with an installed capacity not less than 100MW. In other words the additional investment meets the lost revenue due to preventive maintenance actions over a period of ten years.

Risk and Insurance Possibilities

The related risk of different electrical sections within a wind farm can be summarised as follows.

- Medium Voltage_Collector system **low risk**
  (Including transformer and secondary switchgear)
- Substation (Medium Voltage Part) **low risk**
  (Unattended maintenance)
- Substation (High Voltage Part) **high risk**
  (Insurance possibilities / Transformer excluded from the availability guarantee?)
- Maintenance **not quantifiable**
  (WEC including Kiosk/Substation) – Strategy required

8 Conclusion and Outlook

Over the next years the market requirements will certainly get even tougher for availability and performance guarantees for wind farms. Therefore it is necessary for companies to pay more attention to disturbance and failure mechanisms. A specific quality management process to improve the long term performance is recommended with the special focus on failure data acquisition and evaluation as well as maintenance strategies and support.

International Classification

For this investigation reliability figures from subcontractors and from the german network were used. Compared to figures from other countries in which REpower operates, e.g. north America, Australia ect. In general one can assume similar figures. Of course influencing factors like local network configuration, regional standards, geographical aspects have to be taken into account and should be approached according to the specific wind farm project.

Recommended Procedures

The results of this investigation are based on analytical evaluation methods. Thus numerical methods as well as simulation methods are recommended in order to verify the analytical results and evaluate the availability parameters in a more accurate way.

The accuracy of reliability related failure data and statistics from single components are a crucial part of availability calculations. Hence a special data acquisition process is recommended for wind farms installed by REpower in order to obtain a better understanding of wind farm failure mechanisms.

Further Investigations

Maintenance strategies in general have a high impact on the rate of energy not supplied and therefore the wind farms life cycle revenue. Especially preventive maintenance actions including maintenance support should be investigated further.

Within this thesis the failure rates or in other words the occurrence of different undesired events were assumed to be exponentially distributed. Hence different failures occur at random. The correlation between high wind speeds and the frequency of different faults as well as their seasonal variations were not taken into account and should be investigated further.

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Appendix

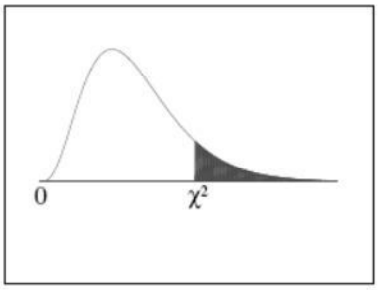
A. Statistical Tables

- <u>Chi-Square Percentage Points</u>

n \ α	99.0%	97.5%	95.0%	90.0%	10.0%	5.0%	2.5%	1.0%
1	0.000	0.001	0.004	0.016	2.706	3.841	5.024	6.635
2	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210
3	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345
4	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277
5	0.554	0.831	1.145	1.610	9.236	11.070	12.833	15.086
6	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812
7	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475
8	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090
9	2.088	2.700	3.325	4.168	14.684	16.919	19.023	21.666
10	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209
11	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.725
12	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217
13	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688
14	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141
15	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578
16	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000
17	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409
18	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805
19	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191
20	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566
21	8.897	10.283	11.591	13.240	29.615	32.671	35.479	38.932
22	9.542	10.982	12.338	14.041	30.813	33.924	36.781	40.289
23	10.196	11.689	13.091	14.848	32.007	35.172	38.076	41.638
24	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980
25	11.524	13.120	14.611	16.473	34.382	37.652	40.646	44.314
26	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642
27	12.879	14.573	16.151	18.114	36.741	40.113	43.195	46.963
28	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278
29	14.256	16.047	17.708	19.768	39.087	42.557	45.722	49.588
30	14.953	16.791	18.493	20.599	40.256	43.773	46.979	50.892
35	18.509	20.569	22.465	24.797	46.059	49.802	53.203	57.342
40	22.164	24.433	26.509	29.051	51.805	55.758	59.342	63.691
45	25.901	28.366	30.612	33.350	57.505	61.656	65.410	69.957

Table A.1 Percentage Points of the Chi-Square (χ2) Distribution

$$P(Z > z_{\alpha,n}) = \alpha$$



The shaded area is equal to α for $\chi^2 = \chi^2_\alpha$.

B. Reliability Figures

The table below show some significant reliability figures from the German electrical power system. For further information regarding the evaluation methods used to obtain this figures and the exact boundaries between adjacent components (e.g. Transformer and related switchgear) see [5] [21]

Fault Location	Reference	Fault Category MV			Fault Category HV			Fault Category EHV		
		Disturbances w interruptions	switch off w/o interruptions	Lumped interruptions	Disturbances w interruptions	switch off w/o interruptions	Lumped interruptions	Disturbances w interruptions	switch off w/o interruptions	Lumped interruptions
Nicht bekannt	100 km SCL	0,33	0,029	1,354	0,018	0,037	1,322	0,003		0,145
Overhead Lines	100km OHLL	3,271	0,215	6,326	0,166	0,296	4,321			1,086
Cable	100 km SCL	1,831	0,348	2,259	0,099	0,861	0,96			2,306
Paper	100km p	2,839	0,61	3,541		1,399	1,399			
PE	100km pe	4,588	0,746	5,43	4,673	9,346	14,019			
XLPE	100km xlpe	0,468	0,138	0,627		0,139	0,139			6,098
Miscellaneous Synthetic Cable	100km sk	1,771	0,59	2,362						
Oil	100km ök	2,197	0,879	3,808	0,124	1,119	1,243			
Gasaußendruckkabel	100km ga				0,132	1,32	1,452			
Gasinnendruckkabel	100km gi					0,737	0,737			
Miscellaneous Cable	100km sk	2,812	0,35	3,346		0,391	0,391			
Substations	100 Felder ges	0,227	0,084	0,331	0,198	0,78	1,144			4,285
Freiluft-SA	100 Felder fsa	3,67	0,229	3,899	0,196	0,934	1,392			4,406
Innenraum-SA luftisoliert offen	100 Felder isa	0,458	0,117	0,627	0,107	0,403	0,537			
Innenraum-SA luftisoliert gekapse	100 Felder gsa	0,164	0,108	0,272	0,33	0,33	0,99			7,317
Gasisolierte SA	100 Felder gis	0,165	0,09	0,27	0,206	1,371	1,714			1,613
Sonstige SA	100 Felder ssa	0,049	0,033	0,095	0,296	0,46	0,756			
Ortsnetzstationen Gesamt	100 ONS gesamt	0,424	0,064	0,512						
Maststation	100 ONS m	1,36	0,007	1,409						
Kompaktstation luftisoliert	100 ONS kl	0,307	0,042	0,354						
Kompaktstation gasisoliert	100 ONS kg	0,191	0,005	0,196						
Gebäudestation luftisoliert	100 ONS gl	0,344	0,103	0,466						
Gebäudestation gasisoliert	100 ONS gg	0,211	0,032	0,242						
Einbaustation luftisoliert	100 ONS el	0,242	0,228	0,493						
Einbaustation gasisoliert	100 ONS eg	0,1	0,025	0,125						
Sonstige ONS	100 ONS sonst	0,412	0,036	0,496						
Transformers	100 Trafos	0,202	0,029	0,238	0,7		1,838			3,934
More Fault Locations	100km SKL	0,246	0,069	0,433	0,176		0,517			0,332
Protection System	100km SKL	0,022	0,004	0,027	0,021		0,058			0,053
Rückwirkung	100km SKL	0,199	0,049	0,36	0,142		0,327			0,162
Übrige Fehlerorte	100km SKL	0,026	0,016	0,046	0,013		0,132			0,117
Lumped	100km SKL	3,472	0,5	6,118	0,469		6,487			2,016
Lumped w/o force majeure	100km SKL	3,443	0,497	6,077	0,462		6,479			2,016
Anteil in MS, HS, HöS		56,80%	8,20%	100%	7,20%		100,00%			100%
Mittlere Anzahl Fehlerorte/Störung		1,139	1,034	1,086	1,386		1,079			1,084
Absolute Anzahl		11.146	2	19.640	291		4.027			722

Table B.1 Disturbance and Availability Statistics – VDN [53]

Reliability figures from other countries e.g. the US, Canada, Switzerland or Austria can be obtained through [53], [29] and [72].

Due to the specific confidential agreement the reliability figures from subcontractors will not be presented in this thesis.

C. Average Prices

In this section the average prices of electrical components and the related logistic costs are presented. Furthermore the average costs for manpower are shown in Table C.3, which were used to evaluate the preventive and corrective maintenance costs.

- <u>Component Prices</u>

	Source		Component	Infos	Price	unit	Comments
Trafo			HV Trafo	>50 MVA	15	€/kVA	Incl. Logistics
			MV Trafo 1	> 1 MVA	20,00	€/kVA	excl. Logistics
			MV Trafo 2	< 1 MVA	200,00	€/kVA	
	jules		logistics	up to 20MVA	1.500,00	€/unit	5*
				2,5 MVA	51.500,00	€	
MV Cable	nkt	150	MV Cable	system lengh (SL)	45.000,00	€/km	incl. Excavation & laying
			Term	per system (6)	1.620,00	€/set	270
			Joints	3 per km SL		€/km	
	nkt		service	excavation & install	25.000,00	€/km	
			logistics	per project	0,00	€	
					26.620,00		
	südkabel	500	MV Cable	SL	65.000,00	€/km	incl. Excavation & laying
			Term	per system (6)	2.070,00	€/set	345
			Joints	3 per km SL		€/km	
			service	excavation & install	25.000,00	€/km	
			logistics	per project	2.000,00	€	
					29.070,00	€	
HV Cable	Nexans	1600 mm	HV Cable	system lengh (SL)	346.000,00	€/km	excl. Excavation & Installation
			Term	per system (6)	26.600,00	€/set	
			Joints	4,15 per km SL	13.000,00	€/km	
			service	install, manhours…	22.000,00	k€/km	
			logistics	per project	0,00	€	
		1600			407.600,00		
	Nexans	800 mm	HV Cable	system lengh (SL)	210.000,00	€/km	excl. Excavation & Installation
	Areva		Term	per system (6)	26.100,00	€/set	
			Joints	2,25 per km SL	6.007,50	€/km	7000€ südwind
			service	install, manhours…	22.000,00	k€/km	66000 nkt
			logistics	per project	0,00	€	
		800		SL	264.107,50	€/km	

Table C.1 Average component prices and the additional costs for logistics and installation

MV Switchgear		FEU secondary	MV Switchgear double busbar	per bay, with 2 dc, gis cb	20.000,00	€/bay	incl. SCADA & measurement
		RMU secondary	MV Switchgear single busbar	per bay, with 1 dc, gis cb	25.000,00	€/bay	incl. SCADA & measurement
			logistics	transp+instalation	15.000,00	€/wec	
				RMU	90.000,00	€/wec	
		AIS aux. p.supply	MV Switchgear xxx busbar	1LTS, 1ES, HH fuse, SCADA	15.000,00	€/bay	incl. SCADA & measurement
	Areva	AIS primary entry	MV Switchgear xxx busbar	1CB,1ES,je3Wandler, UMZ	30.000,00	€/bay	incl. SCADA & measurement
		AIS primary outgoing	MV Switchgear xxx busbar	1CB, 1ES, je3Wandler, UMZ	30.000,00	€/bay	incl. SCADA & measurement
		GIS primary	MV Switchgear xxx busbar	per bay, with 2 dc, gis cb	50.000,00	€/bay	incl. SCADA & measurement
		GIS primary	MV Switchgear xxx busbar	per bay, with 2 dc, gis cb	50.000,00	€/bay	incl. SCADA & measurement
			logistics	transp+instalation	30.000,00	€/10bays	
HV Switchgear		AIS	HV Switchgear single busbar		60.000,00	€/bay	
	Areva	GIS	HV Switchgear single busbar	per bay, with 2dc & gis cb	70.000,00	€/bay	incl. Scada & protection
			SF6 CB 3~	1600A, 40kA	27.000,00	€/unit	
			DC	with 1 earthing switch	9.000,00	€/unit	x2
			Measurement	current&voltage trafo	30.000,00	€/unit	
			overvoltage protection		2.000,00	€/unit	x3
			logistics		15.000,00	€	15-20 kE
					83.000,00		
External Equipment	trench	MV	arc suppressor coil	MV	60.000,00	€/unit	
			additional earth flault protection			€/unit	
	Areva		MV NOSPE Resistor	24kV	8.000,00	€/unit	
	Areva	DC aux. P.supply	UPS	1 converter, 1 inverter, 30A 400V, 36 Cells	80.000,00	€/unit	
	domin it	static	Compensation	Capacitance	8.000	€/Mvar	
			Compensation	Inductance	5.000	€/Mvar	

Table C.2 Average component prices and the additional costs for logistic and installation

- <u>Costs for Manpower</u>

Profession	Hourly wages in €
Service technician	50.-
Electrical engineer	80.-
…working after 18 o'clock	+20%
Working on saturdays	+40%
Working on Sundays and holidays	+50%

Table C.3 Average manpower costs

D. Risk and Severity Ratings

Table D.1 presents the probability of occurrence of certain events and their risk related ratings.

Probability of occurence (P)	P in [%]
1 = Low probability - unlikely to happen	P < 10 %
2 = Lower Medium probability - might happen	10 % < P < 40 %
3 = Medium probability - quite possible	40 % < P < 60 %
4 = Higher Medium Probability - likely to happen	60 % < P < 75 %
5 = High probability - very likely to happen	P > 75 %

Table D.1 Probability of occurrence

The following table shows the severity ratings for different areas of interest.

Severity Rating	People	Asset	Environment	Reputation
1	No health effect/injury	No damage	No effect	No impact
2	Slight health effect/injury	Slight damage	Slight effect	Slight impact
3	Minor health effect/injury	Minor damage	Minor effect	Limited impact
4	Major health effect/injury	Localised damage	Localised effect	Considerable impact
5	Multiple fatalities	Major damage	Major effect	National impact

Table D.2 Severity ratings for different areas

The concept of the risk matrix is shown in Figure D.1. The different colored arrays and their meaning are discussed below.

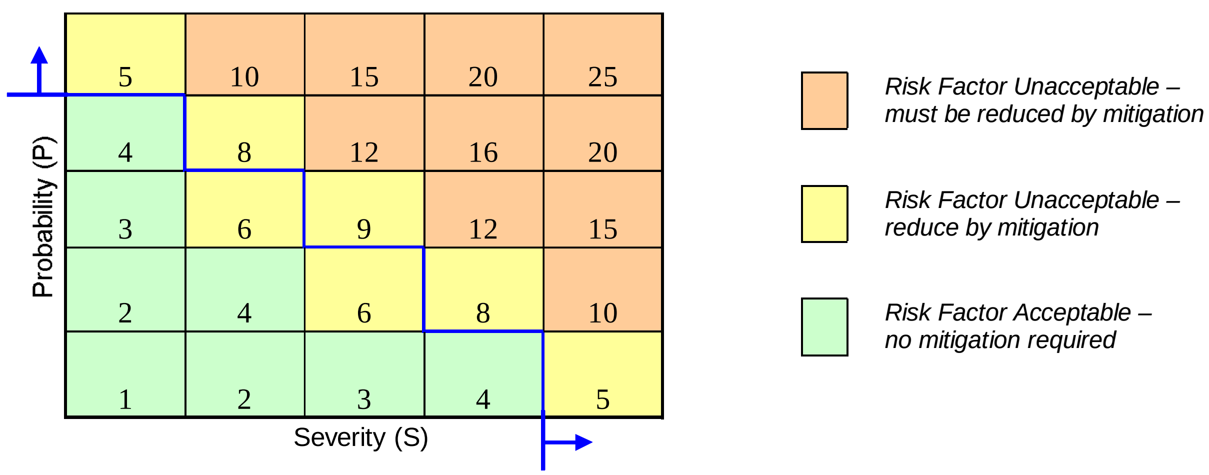


Figure D.1 Riskmatrix example

The introduced risk and severity ratings are commonly used nowadays. However, there exist different rating concepts. For Example, a six step rating is presented below.

Probability

Level	Descriptor	Description
1	Almost impossible	Has never happened anywhere, impossible sequence
2	Conceivable, but very unlikely	Has never happened after many years, but is possible
3	Remotely possible	Remotely possible coincidence, say 1 in 100-1000 chance
4	Unusual, but possible	Unusual, but possible sequence of coincidence, say 1 in 10-100 chance
5	Quite possible	Not unusual, say a 1 in 10 chance
6	Almost certain	The most likely and expected result if the chosen sequence or scenario takes place

Table D.3 Probability of occurrence

Impact (Severity)

Level	Descriptor	Description
1	Insignificant	No loss of any output power
2	Minor	Loss of … % of generation for … time
3	Serious	Loss of … % of generation for … time
4	Very serious	Loss of … % of generation for … time
5	Disaster	Loss of … % of generation for … time
6	Catastrophe	Permanent loss of all generation for … time

Table D.4 The impact of certain events and their risk rating

From Table D.5 it can be seen, that this rating concept is more precisely than the one before, due to the additional rating step.

Risk Score	Risk Rating	Required actions
1 to 5	Low risk	No inmediate action required
6 to 11	Moderate risk	Analyse cost effectiveness of implementing preventive measurement
12 to 23	Substantial risk	Analyse cost effectiveness of implementing preventive measurement
24 to 29	High risk	Implement preventive measurement
30 to 36	Very high risk	Implement preventive measurement

Table D.5 sections oft he risk matrix

E. Types of Faults

- Symmetrical Faults

Three phase fault

Fault condition: $U_{ph1}=U_{ph2}=U_{ph3}$, $I_1+I_2+I_3=0$

- Asymmetrical Faults

Three phase to earth fault

Fault condition: $U_{ph1}=U_{ph2}=U_{ph3}=0$

Two phase fault

Fault condition: $U_{ph2}=U_{ph3}$ $I_1=0, I_2=-I_3,$

Two phase to earth fault

Fault condition: $U_{ph2}=U_{ph3}=0$ $I_1=0$

Phase to earth fault

Fault condition: $U_{ph1}=0$ $I_2=I_3=0,$

Earth Fault

Fault condition: $U_{ph1}= U_{ph2}=\varepsilon \cdot U_{ph} \sim U_{verk}$

- Over Load

Currents that permanently exceeds their rated value under normal operating conditions, lead to overload of components. Due to the high current items have to be protected against thermal stress which can lead to a shorter lifetime (see ageing) or disordered function. The load of wind energy converter highly varies within one year, the load factor for example normally lays between 0,2-0,4[1]. Furthermore, wind energy projects are calculated with a useful lifetime of 20 years, hence the single components can also be designed for 20 years which is much less compared with the utility sector or the industry. But with the focus on repowering[2] this process has to be reconsidered.

- Over Voltage (control disorder)
- Unsymmetrical Load
- Unbalance of Active Power

Voltage Dip

Is a sudden reduction of the voltage (90%-1% U_r) at a point in an electrical system followed by voltage recovery after a short period of time from a few cycles to a few seconds (10ms-1min).

[1] Estimated from REpower Wind farms operating in different countries.

[2] Repowering denotes the replacement of old inefficient WECs with new powerful WECs.

Interruption of Supply

A state, were the voltage is less than 1% of the rated voltage on the pcc. Interruption of supply can be classified in:

- <u>Planed Interruption</u>
- <u>Random Interruption (Stochastic Events)</u>

Sustained interruption – duration >3min, through a permanent fault

Momentary interruption – duration =<3min, through a temporary fault

Voltage Characteristics	Values		Measure parameters			
	LV	MV	Reference	Interval	Period	%
frequency	49,5Hz – 50,5 Hz		Mean value	10s	1 week	95
Dips (<1min)	Several 10th-1000th per year (U<90%)		rms	10ms	1 yr	100
Momentary Interruptions (≤3min)	Several 10 – 1000th per year (U<1%)		rms	10ms	1 yr	100
Random Sustained Interruption (<3min)	Several 10 – 50 per year (U<1%)		rms	10ms	1 yr	100
Temporary over voltages (grid frequency)	<1,5kV	1,7-2 U_r	rms	10ms	---	100

Table E.1 Voltage characteristics according to EN50160

Characteristics of voltage dips and interruptions are the remaining voltage and the duration. These two parameters basically determine a fault within an electric power system.

F. Availability Evaluation Project Mt.Mercer

Grid Connection Availability and Risk Evaluation

Project Mt.Mercer

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Contents

Abbreviations

LV	Low Voltage (U<1kV)
MV	Medium Voltage (1kV<U<72,5kV)
HV	High Voltage (72,5kV<U<125kV)
VDN	German Utility Association
CEA	Canadian Electricity Association
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTM	Mean Time to Maintain
km SL	Cable km System Length (L_1+L_2+L_3)
R(20)	Reliability / Probability that the component survive 20 years w/o a failure.
LCMC	Life Cycle Maintenance Cost (20 years)
A	Mean (Asymptotic) Availability over one year in %
U	Unavailability
r	(MTTR) Mean Time To Repair
μ	Repair Rate
λ_M	Maintenance Rate
λ_F	Failure Rate (frequency)

1 General

The frequency of failures that occur during the lifetime of an electrical component varies with time and can be described with a bathtub shaped curve which can be divided into 3 parts. During the first month the failure rate is slightly higher due to damage during transportation, carless handle during installation or due to production failures …etc. After this so called teething-period has passed the component is in its useful-life-period where failures occur at random (const. failure rate, hence exponential life distribution). Table 0 shows some useful equations to evaluate the availability of components in this particular period [2]. The wear-out-period where failures occur mostly because of ageing effects of the isolation is the last part of the curve. When exactly the ageing effects will appear depends on several influences. (Thermal-, electrical- and mechanical stress)

Calculated Data	Equation
Availability	$A = \frac{MTBF}{MTBF + MTTR} = \frac{T_U}{T_U + T_D}$ [1]
Failure Rate	$\lambda = \frac{N}{T} = \frac{1}{MTBF}$ [2]
MTBF	$MTBF = \frac{T}{n} \approx \frac{1}{\lambda}$
Repair Rate	$\mu = \frac{1}{MTTR}$
Reliability	$R(t) = e^{-(\lambda \cdot t)}$
	$R(20) \rightarrow t = 20\ [yr]$

Series System
$\lambda_S = \sum_{i=1}^{n} \lambda_i$
$r_S = \frac{\sum_{i=1}^{n} \lambda_i \cdot r_i}{\lambda_S}$
$U_S = \sum_{i=1}^{n} \lambda_i \cdot r_i$
Parallel System
$\lambda_P = U_P \sum_{i=1}^{n} \mu_i$
$U_P = \prod_{i=1}^{n} \frac{\lambda_i}{\lambda_i + \mu_i}$
$r_S = \frac{U_P}{\lambda_P}$

table 0 Some useful equations [2]

[1] Mean or asymptotic Availability. Evaluated over a period of 1 year.

[2] Assumed the failure rate and the repair rate are exponentially distributed. Hence only the useful life period, were failures occur at random are considered.

2 Reliability Figures

2.1 Worst Case

The figures in the tables presented below are based on the disturbance and availability statistics from the German power system.[1] The mean time to repair or to maintain are related to the project location, the contractor and their experience and other influences, hence they can vary within a broad range. The repair and maintenance rates in this report were derived from phone calls with ABB's and AREVA's service department.

The figures presented in table 2-1 illustrate a worst case scenario, whereas the figures in table 2-2 can be seen as a most likely case scenario.

Component		MTBF [yr]	λ_F [1/yr]	MTTR [h]	R(20) [%]	A [%]	ref.
MV Cable XLPE	per km SL	159	0,00627	72	88%	99,995%	vdn
MV Transformer	Unit	420	0,00238	96	95%	99,997%	vdn
MV secondary Switchg. GIS	Unit	510	0,002	72	96%	99,998%	vdn
MV primary Switchg. GIS	per bay	368	0,00272	72	95%	99,998%	vdn
HV Cable XLPE	per km SL	719	0,00139	96	97%	99,998%	vdn
HV Transformer	Unit	54	0,01838	168	69%	99,965%	vdn
HV switchgear GIS	per bay	58	0,01714	72	71%	99,986%	vdn
Protection System	per 100km SL	77	0,013	12	77%	99,998%	vdn

table 2-1 Reliability figures based on all occurred events [1]

In Table 2-1 all failures that occurred over a period of one year are taken into account, whether the particular event had led to an interruption of supply or not.

2.2 Most Likely Case

For the most likely case scenario only the events that had led to an interruption of supply or to damage are taken into account.

Component		MTBF [yr]	λ_F [1/yr]	MTTR [h]	R(20) [%]	A [%]	ref.
MV Cable XLPE	per km SL	217	0,00461	24	91%	99,999%	vdn
MV Transformer	Unit	1010	0,00099	48	98%	99,999%	vdn
MV secondary Switchg. GIS	Unit	1000	0,00025	24	98%	100,00%	vdn
MV primary Switchg. GIS	per bay	952	0,00105	24	98%	100,00%	vdn
HV Cable XLPE	per km SL	719	0,00139	48	97%	99,999%	vdn
HV Transformer	Unit	176	0,00569	168	89%	99,989%	vdn
HV switchgear GIS	per bay	73	0,01371	24	76%	99,992%	vdn
Protection System	per 100kmSL	200	0,005	6	90%	100,00%	vdn

table 2-2 Reliability figures based on events that had led to damage [1]

2.3 The WEC (MM Series)

The reliability figures of the turbine were provided by the service department and can be seen in table 2-3. For further questions on the calculation method please call Anton Kupper.

The failure rates of the turbine extremely vary over time and they are related to several influences (season, country,…etc) hence they are extremely unstable. With this background and due to the evaluation methods that were used to estimate this figures these data need to be discussed and furthermore used very carefully.

Component		MTBF [yr]	λ_F [1/yr]	MTTR [h]	R(120h) [%]	A [%]
MM Total	ISP/ISK	0,057	17,5	10	62 %	98,04%
MM Indoor	ISP/ISK	0,086	11,6	4	73 %	99,47%
MM Outdoor	ISP/ISK	0,097	10,3	17	75 %	98,04%
MM Total	w/o ISP/ISK	0,046	21,9	11	55 %	97,34%
MM Indoor	w/o ISP/ISK	0,063	15,9	4	65 %	99,28%
MM Outdoor	w/o ISP/ISK	0,086	11,6	15	73 %	98,05%

table 2-3 WEC reliability figures

Now since the guaranteed availability over a period of one year is 97% and the reliability figures from table 2-3 exactly meet this value for this evaluation an average availability of 96% is assumed. According to this the failure rate of the WEC is assumed to be 0,5-1 failure per year with an mean down time of approximately 85 hours.

Figure 3.1-2 shows the share of failures on single components that lead to a reduced power output at PCC. ~97% of all failures that occur are caused by the turbine itself.

Due to the fact that the assumptions for this scenario (λ_{WEC}=0,5, MTTR=85h) are very rough the WECs will not be taken into account in further calculations.

3 Charts

3.1 Reliability of Components

Figure 3-1-1 shows the failure rates from the worst case and most likely case scenario, based on table 2-1 and table 2-2.

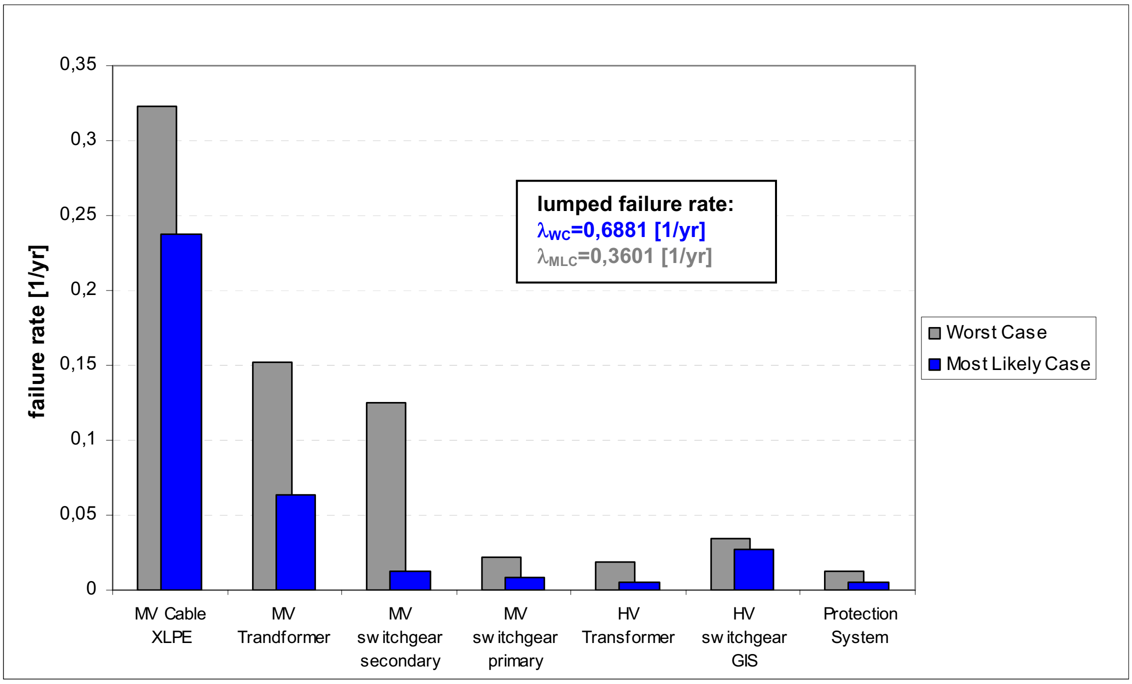


figure 3.1-1 Failure rate of single items

How many failures that lead to a reduced power output at PCC are caused by individual components can be seen in figure 3.1-2 taken the WECs into account and in figure 3.1-3 without the WECS. Evidently 97,4% of the failures that occur are caused by the wind energy converters.

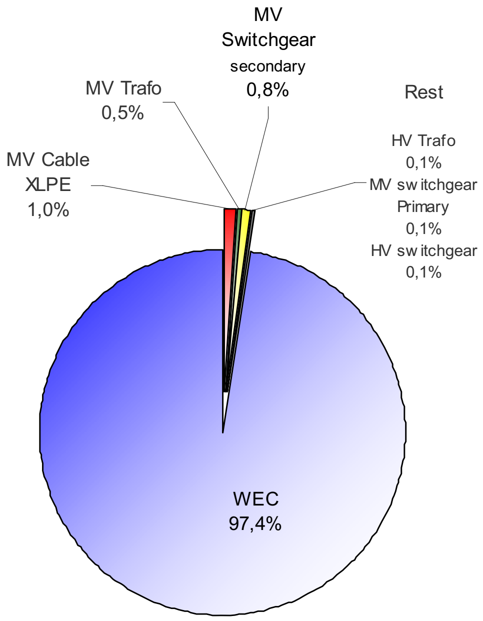


figure 3.1-2 Wind farm failure causes

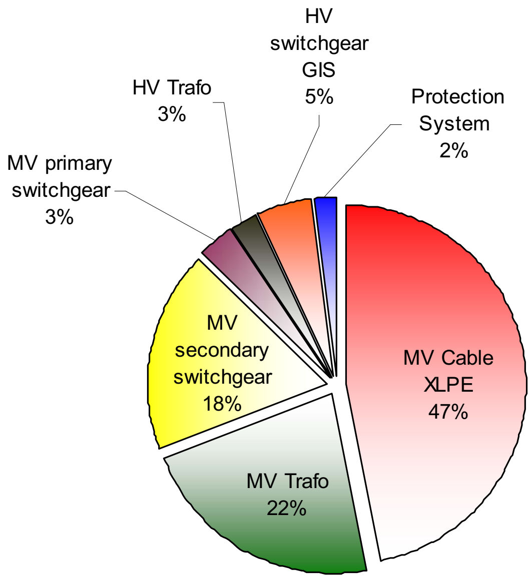


figure 3.1-3 Failure rate of grid connection components

3.2 Availability of Subsystems

feeder	A [%]	λ [1/yr]F	MTTR [h]
1	99,900%	0,128	68,3
2	99,930%	0,090	67,9
3	99,922%	0,101	68,0
4	99,937%	0,081	67,5
5	99,930%	0,090	67,9
6	99,936%	0,083	67,6
hv	99,919%	0,071	81,6

System	A [%]	λ [1/yr]	MTTR [h]
WF	99,47%	0,6881	~73

table 3-1 Availability of the grid connection

(Worst Case w/o WEC)

feeder	A [%]	λ [1/yr]	MTTR [h]
1	99,974%	0,077	29,3
2	99,985%	0,039	33,0
3	99,985%	0,032	40,4
4	99,992%	0,025	28,6
5	99,983%	0,041	36,8
6	99,969%	0,068	39,8
hv	99,981%	0,020	78,9

System	A_{wf}	λ_{wf} [1/yr]	MTTR [h]
WF	99,87%	0,3601	~40

table 3-2 Availability of the grid connection

(Most likely Case w/o WEC)

The technical availability of each feeder as well as of the HV connection can be seen in the table 3-1 and 3-2, presented above.

These values were calculated using the equations from table 0 (page1). In order that the whole subsystem (e.g. feeder1) is in an up state (functioning) it is assumed that each component is in an up state (functioning) as well. Hence a series structure can be used to calculate the availability.

4 Expected Energy Not Supplied [EENS]

Installed Capacity: 64 x 2050 [kW]
Capacity factor: 36,9 %[3]
Theoretical Production w/o electrical losses: E_{TP}=~483 [GWh]
Theoretical Production with electrical losses: E_{TP}=~425 [GWh]

4.1 Capacity Outage Probability

The different capacity levels and the associated probabilities of nonexistence can be seen in figure 4.1-1. The capacity outage probability can be easily obtained using the binomial distribution.

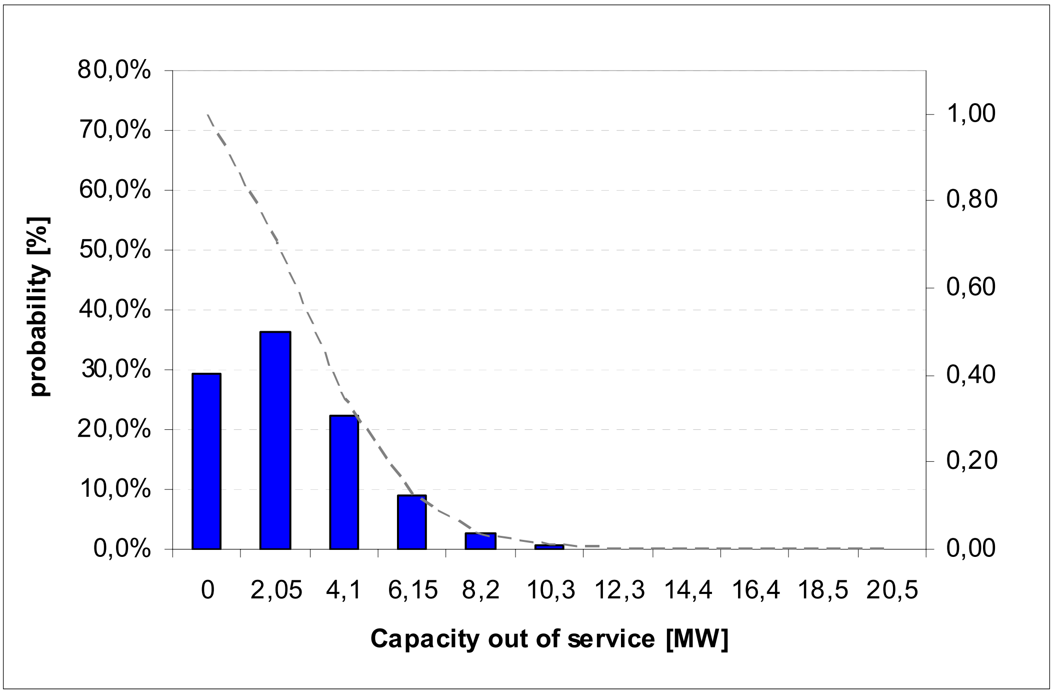


figure 4.1-1 Capacity outage probability

The probability that all turbines are in an up state (functioning) is according to figure 4.1-1 ~30%. Considering one unit can be out of service the probability that all the other turbines are functioning is round about 66%, or in other words 66% of the time more than 98,5% of the installed capacity is available.

4.2 EENS (Worst Case)

Wind farm failure rate [w/o WECs]:	0,688 [1/yr]
EENS [w/o Wecs]	~ 603,2 [MWh]
Energy availability [w/o Wecs]	~ 99,6 [%]
EENS [w WECs]	~3,1 [GWh]
Energy availability [w WECs]	~98 [%]

[3] The capacity factor was calculated based on the measured wind data from the document 'site suitable wind assessment MT Mercer'.

4.3 Interpretation

- *Worst Case*

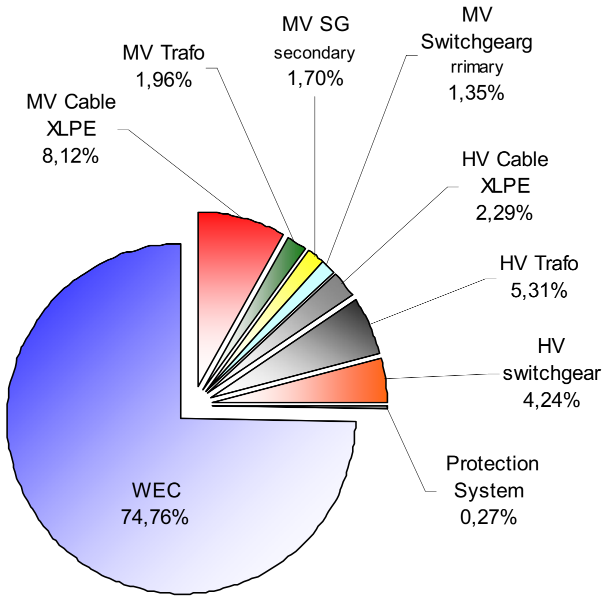


figure 3-4.3-1 EENS at PCC causes

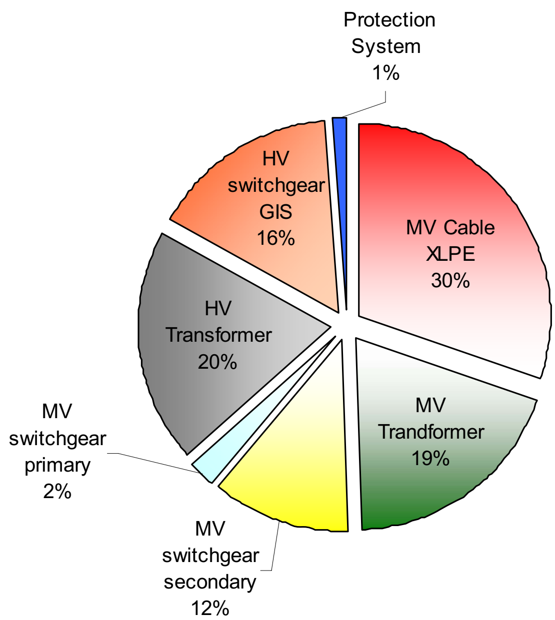


figure 3-4.3-2 EENS at PCC causes w/o WECs

The causes of the expected energy not supplied at PCC can be seen in the pie charts above. Unlike in figure 2.1-3 where only the failure rates were considered in figure 3-2/-3 also the related not supplied energy was taken into account. More than 45% of the EENS are caused by faults on the hv connection.

- *Most Likely Case*

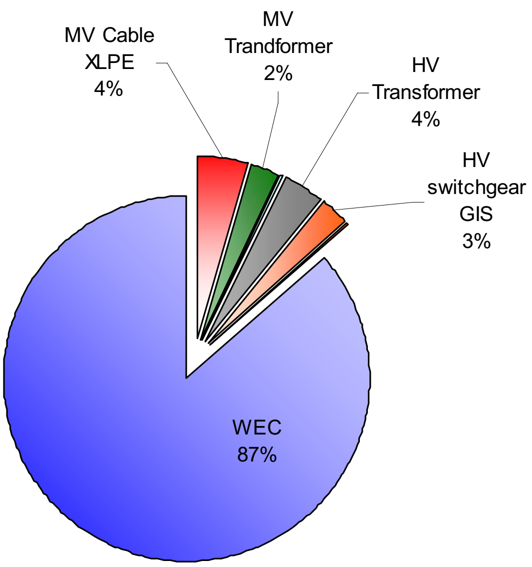


figure 3-4.3-3 EENS at PCC causes

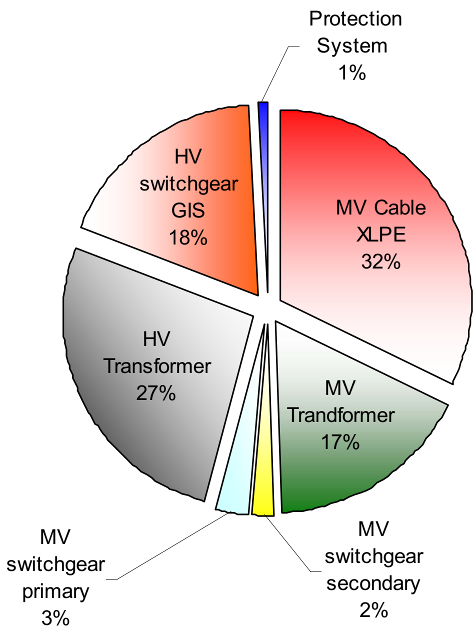


figure 3-4.3-4 EENS at PCC causes w/o WECs

5 HV Connection

5.1 Power Transformer

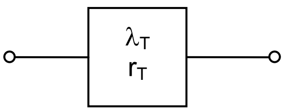
Component		MTBF [yr]	λ_F [1/yr]	MTTR [h]	R(20) [%]	A [%]	A* [%][4]	ref.
HV Trafo (110-149kV)	Unit	16	0,0612	250	29%	99,826%	97,908%	Canada
HV Trafo (72,5-125kV)	Unit	54	0,01838	168	69%	99,965%	98,047%	Germany
HV Trafo	Unit	65	0,0153	168	74%	99,971%	98,053%	USA

table 5-1 Transformer Reliability Figures (Most likely case)

Table 5-1 shows the failure rate of high voltage transformers from different countries. The statistical values from the German network and those from the US vary in the same range. The figures from the Canadian electricity association are a little bit higher because in this case the subcomponents (Joints, ground wire…etc.) were taken into account.

Bushing, winding and tap changer related failures contribute to the largest percentage of the failures recorded. Most transformer failures occur on the mechanical parts (~40% OLTC).

- *Scenario 1:* Worst case (λ_1/r_1) / Most likely case ((λ_1/r_1))



The worst case is of course if a failure occurs within a transformer for example on the windings. Due to the fact that approximately 40% of all transformer failures occur on the tap changer the probability of a failure within a transformer is very low (table 5-1). Table 5-2 gives an overview of mean times to repair and mean times to replace times regarding different fault locations.

Fault location	Strategy	MTTR [h]	Replace	ref.
OLTC	Onsite	168	1-4 weeks	ABB, Areva
Bushings	Onsite	--	1-4 weeks	ABB, Areva
Core (Windings…etc)	Onsite	4-6 month	--	ABB, Areva
Core (Windings…etc)	Offsite	1 yr	1 yr	ABB, Areva

table 5-2 Fault location and mean repair/replace time

If, for example the OLTC experience a failure that lead to damage and assumed it can be repaired within one week (MTTR/MTTM) the technical availability of the transformer would be 98,1%.

Figure 5.1-1 shows a sensitivity analysis with different repair rates.

[4] A* denotes the technical availability considering the time to maintain as unavailability.

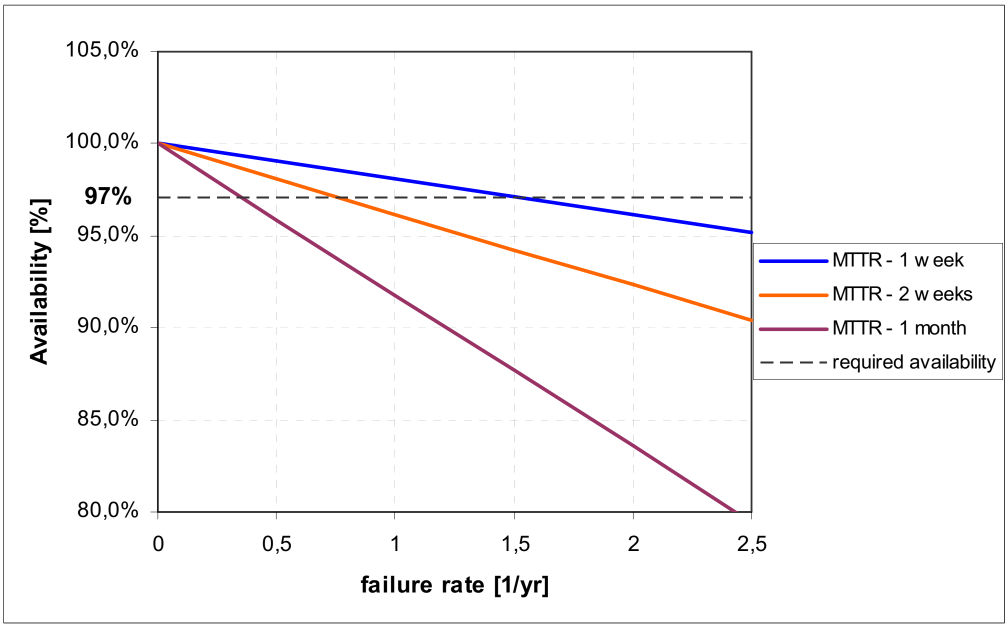


figure 5.1-1 Transformer Availability with different repair times

- *Scenario 2:* Transformer Redundancy

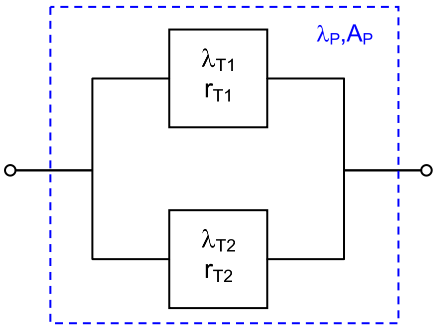


figure 5.1-2 Two parallel Transformers

A_P [%]	λ_P [1/yr]	MTTR [yr]
99,999988%	0,0000123	84

table 5-3 Availability of Scen.2

The availability of a redundant transformer layout can be assumed to be 100%. (table 4-3)

- *Scenario 3:* Transformer life cycle maintenance costs (LCMC)

Different maintenance strategies (λ_M/MTTM)
The OLTC is the part of an hv transformer that has to be maintained continuously [3],[4]. Table 4-4 shows two different maintenance strategies for the OLTC. The first one with 7 years between maintenance and the second one with just 5 years between maintenance. Furthermore the energy not supplied and the related lost revenue due to maintenance can be seen.

	Component		λ_M [1/yr]	MTBM [yr]	MTTM [h]	ENS [kWh]	lost revenue [$]	LCMC [$]
Strategy 1	OLTC	Offline	0,14286	7	168	8.155.392	815.539	1.284.223
Strategy 2	OLTC	Offline	0,2	5	168	8.155.392	815.539	1.839.323
	General (Oil,…etc)	Online	1	1	8			

table 5-4 Transformer Maintenance[5]

[5] Data source: ABB, Areva TD

The lifecycle maintenance costs (LCMC) are the present values of the lost revenue over a period of 20 years due to maintenance.

It can be seen (table 5-4) that the life cycle maintenance costs of one transformer are almost as high as the investment of a second transformer.

The LCMC in table 5-4 are based on an interest rate of 5%.

5.2 Transformer Ageing

This sub chapter is based on [4] [5] [6] and [7].

The risk evaluation of electrical components is based on two variables. The first one is the outage risk estimated by data like age, time in operation, rated power, application, load history as and availability of spare parts. The second variable is the location within the power system. Different maintenance strategies can be derived from these two variables. It has to be taken into account, that maintenance strategies like condition based, time based, reliability based….etc. are only visible after 15-20 years when the wear out period already had begun.

Ageing effects due to thermal, electrical, ambient and mechanical influences (TEAM-factors) can be described with an increasing failure rate after a particular time in operation.
On which parts the ageing effects start and when can be seen in [7]. The bushings and the tap changer are the first parts that experience a higher failure rate mainly due to ambient and mechanical effects. The higher risk of these items can be covered with spare parts due to the low investment costs (bushings).

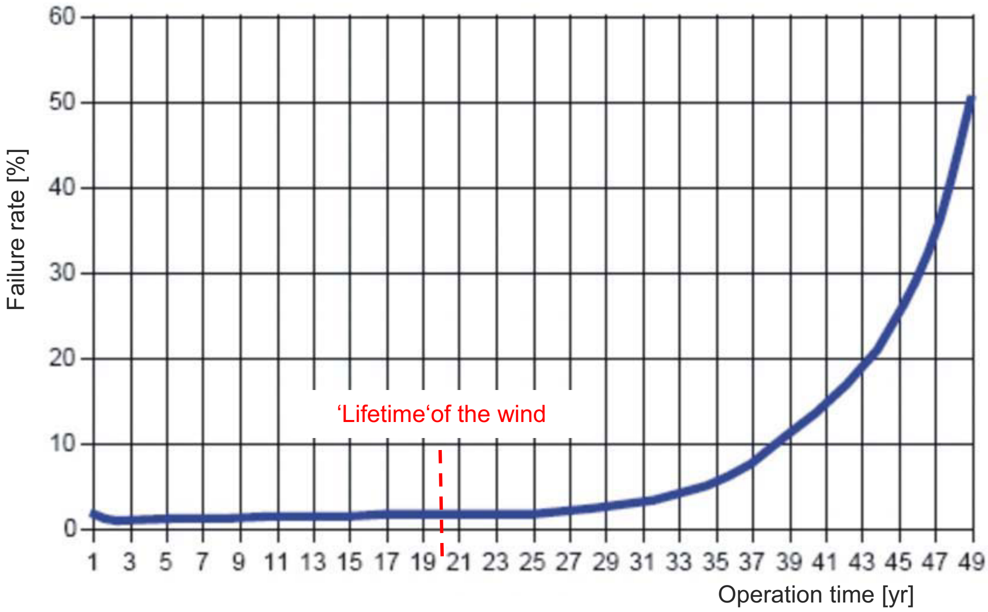


figure 5.2-1 Transformer bath tube curve [5]

Figure 6.2-1 shows the relative failure rate over the lifetime of HV transformers. It can be seen, that ageing effects can be expected after 25 years in operation. Compared with the lifetime of the whole wind farm the ageing effects of HV transformers can be neglected.

The load factor (0,2-0,4) as well as the power flow of wind farms and their influence on the ageing effects of HV transformers need to be discussed and further investigated.

6 Conclusion

- Collector system — **low risk**
  (Incl. trafo and secondary switchgear)

- Substation (MV Part) — **low risk**
  (Unattended maintenance)

- Substation (HV Part) — **high risk**
  (Insurance possibilities / Trafo excluded from the availability guarantee?)

- Maintenance — **need to be discussed**
  (WEC incl. Kiosk / Substation) – Strategy required

7 References

[1] VDN (FNN) "Disturbance and Availability Statistic 2006", VDE-Verl., Berlin, 2006.

[2] R.Billinton: „Reliability Evaluation of Power Systems“, Springer, Berlin 1996

[3] VDN: "Technical Report- Maintenance Management", VDE-Verl. Berlin, 2004.

[4] ABB: ‘Trafo Asset Management-ABB’s Solution for Improved Reliability and Life Extension of Transformers’, ABB Ldt., 2008. (www.abb.com/transformers)

[5] C.Summereder: “Analysis and Estimation of High Voltage Components”, professorial dissertation, TU Graz, 2010

[6] William H. Bartley P.E.: “Investigating Transformer Failures”, Hartford CT.

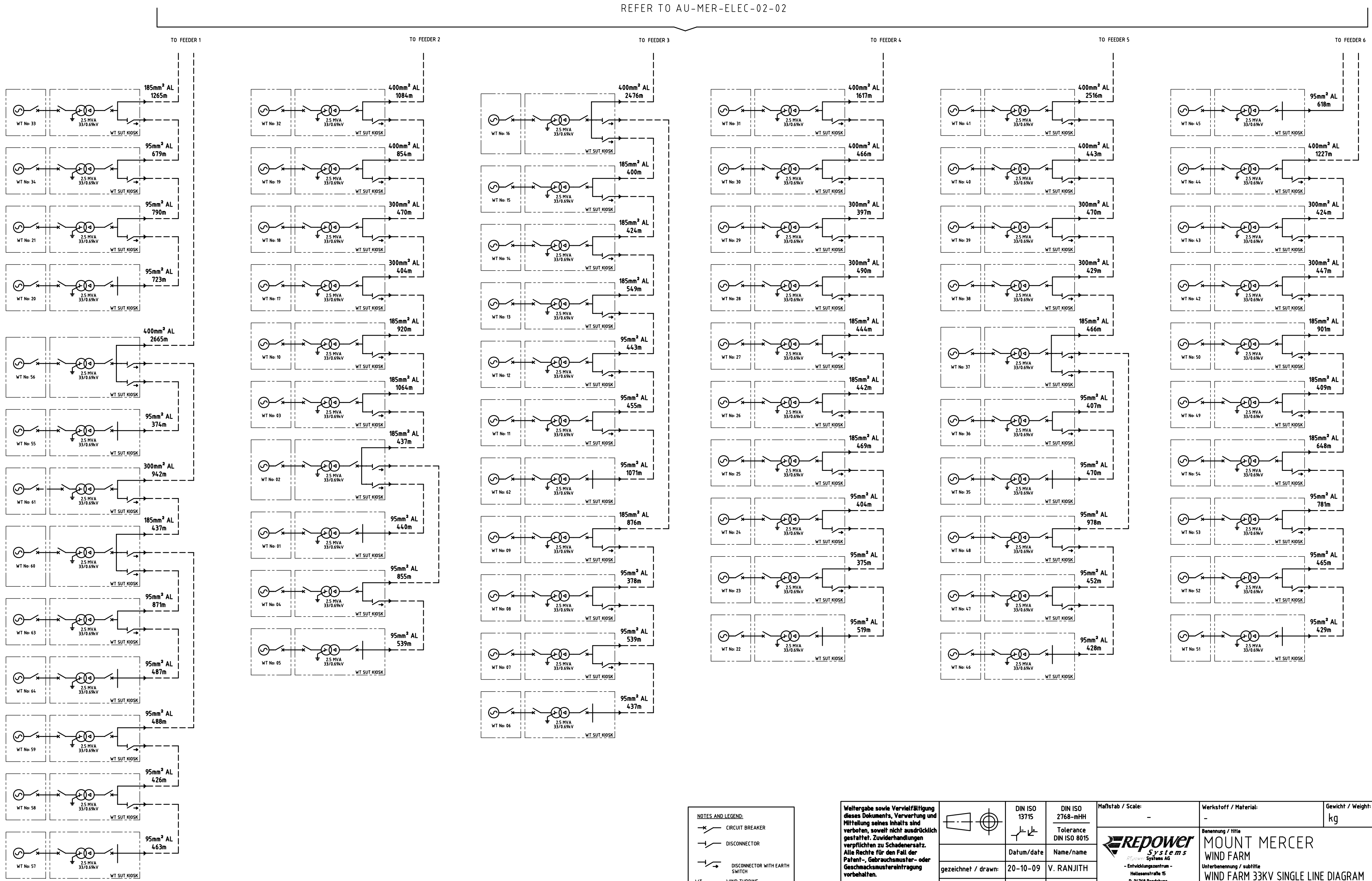
[7] L.Geldenhuis: „Large Power Transformer Reliability Improvement in Eskom Distribution“, Cired 2007

[8] IEEE “Std. 493-2007 – Gold Book”, New York, 2007

8 Appendix

The following single line diagrams (SLD) of the relevant electrical subsystems of the wind farm are attached:

- Wind Turbine SLD
- Wind Farm Substation SLD
- Wind Farm Protection SLD
- Wind Farm Cable Routes SLD



NOTES AND LEGEND:

- CIRCUIT BREAKER
- DISCONNECTOR
- DISCONNECTOR WITH EARTH SWITCH
- WT: WIND TURBINE
- SUT: STEP UP TRANSFORMER

	DIN ISO 13715	DIN ISO 2768-mHH Tolerance DIN ISO 8015
	Datum/date	Name/name
gezeichnet / drawn:	20-10-09	V. RANJITH
geprüft / checked:	20-10-09	C. FARMER
freigegeben/released:	20-10-09	J. WARMAN
Stückzahl pro Anlage / No. of Pieces per Turbine: –	Schutzvermerk DIN ISO 16016	Protection Mark DIN ISO 16016
SAP-No.: –	Pos.-Nr.: –	
EDP NO. F:\MD		

Maßstab / Scale: –

REpower Systems
REpower Systems AG
– Entwicklungszentrum –
Hollesenstraße 15
D-24768 Rendsburg
Phone: +49 – 4331 – 131390
Fax. No: +49 – 4331 – 13139999

Angegebene Spezifikation ist zwingend zu beachten!
Indicated Specification has to be strictly observed!

Werkstoff / Material: –

Gewicht / Weight: kg

Benennung / title
MOUNT MERCER
WIND FARM

Unterbenennung / subtitle
WIND FARM 33KV SINGLE LINE DIAGRAM

Zeichnungsnummer / Drawing Number: AU-MER-ELEC-02-01

Version / revision: A-1

Spezifikationsnummer / Specification Number: –

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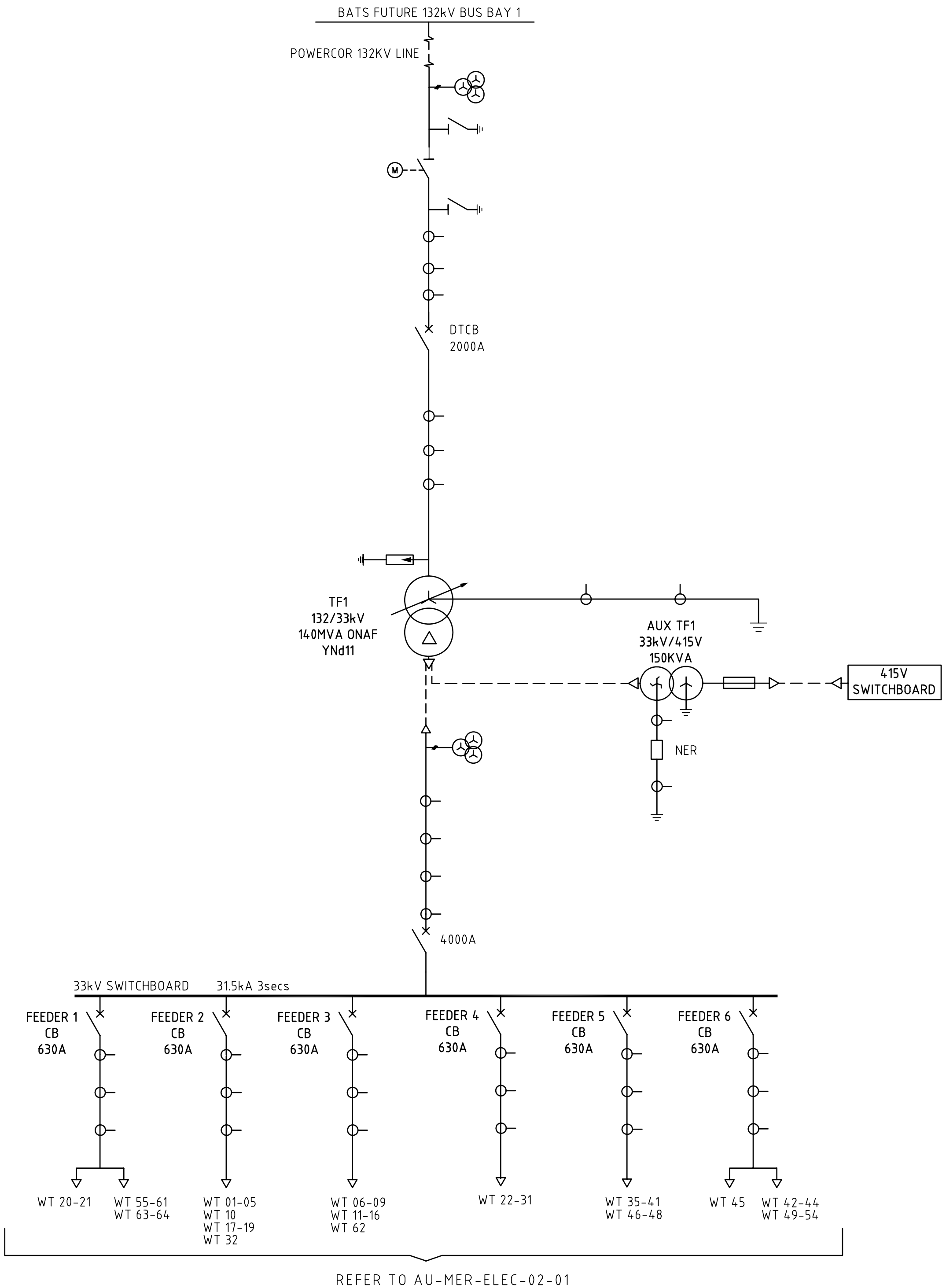
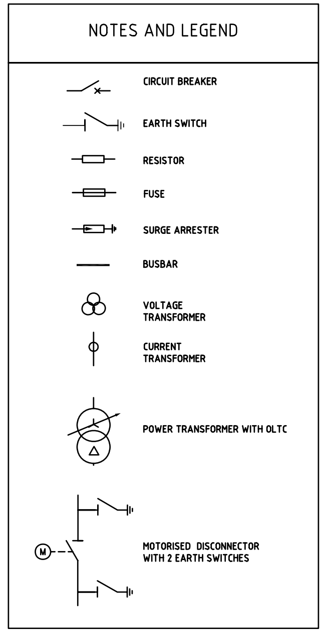
Bl-Blatt/Bl-Sheet: A3

(Ers.f. / repl.for) –

(Ers.d. / repl.by) –

Plot-Datum:





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	Datum/date	Name/name
gezeichnet / drawn:	20-10-09	V. RANJITH
geprüft / checked:	20-10-09	C. FARMER
freigegeben/released:	20-10-09	J. WARMAN

Stückzahl pro Anlage / No. of Pieces per Turbine: –
Schutzvermerk DIN ISO 16016
Protection Mark DIN ISO 16016
SAP-No.: –
Pos.-Nr.: –
EDP NO. F:\MD

Maßstab / Scale: –

REpower Systems
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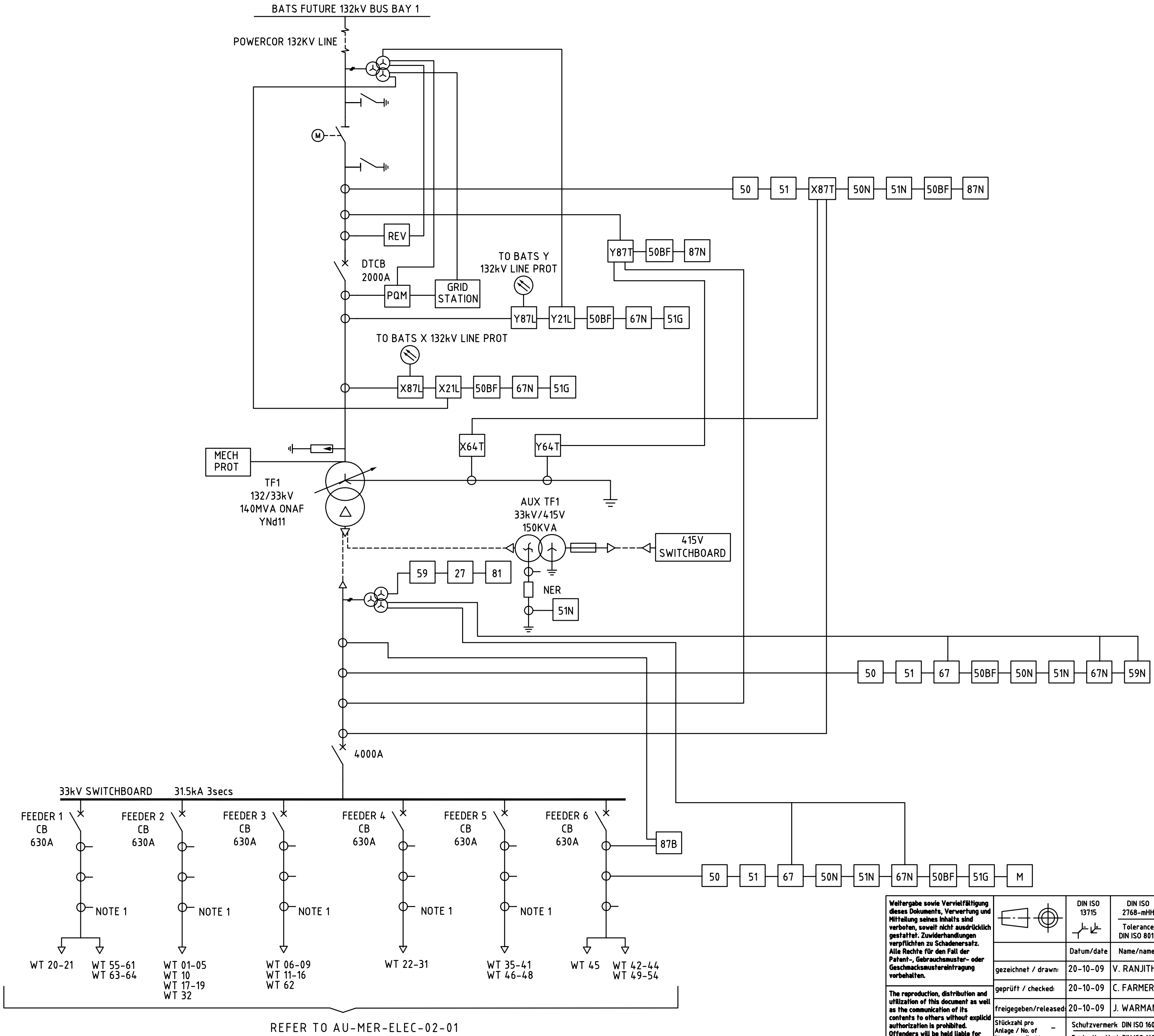
Werkstoff / Material: –
Gewicht / Weight: kg

Benennung / title
MOUNT MERCER
WIND FARM SUBSTATION

Unterbenennung / subtitle
WIND FARM SUBSTATION 33kV SLD

Zeichnungsnummer / Drawing Number: AU-MER-ELEC-02-02
Version / revision: A-1
Spezifikationsnummer / Specification Number: –
Blatt/Sheet: –
DIN-Blatt/DIN-Sheet: A3
(Ers.f. / repl.for:) –
(Ers.d. / repl.by:) –
Plot-Datum:



NOTES AND LEGEND

21L	DISTANCE
27	UNDERVOLTAGE
50	INSTANTANEOUS PHASE OVERCURRENT
50N	INSTANTANEOUS NEUTRAL OVERCURRENT
50BF	CIRCUIT BREAKER FAIL
51	TIME DELAYED PHASE OVERCURRENT
51N	TIME DELAYED NEUTRAL OVERCURRENT
59	OVERVOLTAGE
59N	NEUTRAL VOLTAGE DISPLACEMENT
67	PHASE DIRECTIONAL OVERCURRENT
67N	DIRECTIONAL EARTH FAULT
81	FREQUENCY
87	DIFFERENTIAL
87L	LINE DIFFERENTIAL
87T	TRANSFORMER DIFFERENTIAL PROTECTION
87N	RESTRICTED EARTH FAULT
M	METERING
51G	SENSITIVE EARTH FAULT
REV	REVENUE METER
PQM	POWER QUALITY METER
⦸	FIBRE OPTIC SIGNAL / INTER TRIP

NOTES:
1. SAME AS FEEDER 6

	Datum/date	Name/name
gezeichnet / drawn:	20-10-09	V. RANJITH
geprüft / checked:	20-10-09	C. FARMER
freigegeben/released:	20-10-09	J. WARMAN

DIN ISO 13715 · DIN ISO 2768-mHH · Tolerance DIN ISO 8015

Stückzahl pro Anlage / No. of Pieces per Turbine: –
Schutzvermerk DIN ISO 16016
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Angegebene Spezifikation ist zwingend zu beachten!
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Werkstoff / Material: –
Gewicht / Weight: kg

Benennung / title
MOUNT MERCER
WIND FARM SUBSTATION

Unterbenennung / subtitle
WIND FARM PROTECTION 33kV SLD

Zeichnungsnummer / Drawing Number: AU-MER-ELEC-02-03
Version / revision: A-1
Spezifikationsnummer / Specification Number: –
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DIN-Blatt/DIN-Sheet: A3
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(Ers.d. / repl.by:) –
Plot-Datum: