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Optimization of an Off-shore Wind Farm Collection Grid

Bachelor's Thesis in Renewable Energies

ELENA MALZ

Department of Energy & Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Offshore wind energy has aroused interest in the previous years and the wind power industry is growing constantly. The investment for a wind farm is enormous and therefore maximal revenue is required by reducing any kind of losses. However, since the offshore wind energy technology is still in an early state, there is a lack of an optimal grid design. In this thesis the relationship between reliability and financial losses is studied. It is obvious that the more reliability a wind farm shows, the more a secure power production can be expected. However, there is an upper limit, where adding more reliability implies increasing investment costs without adding more benefit. For an investigation of this limit, a ring layout is chosen, which connects eight 6 MW wind turbines. Six layouts with different reliabilities are considered, from a radial layout up to a full redundancy solution. By calculating power losses and the corresponding losses in revenues, the effect of the influence parameters, wind speed and electricity price is studied. Finally a comparison between the layouts is done, which results in a minimum of financial losses at a redundancy around 70-75%.

Contents

1

Introduction

WIND ENERGY has gained much attention during the last decades [1]. Many researches bring wind energy into focus and new technologies are developed to improve the mechanical, electrical or aerodynamic properties. The focus of this thesis is laid on developing an optimal collection grid layout by comparing reliability with investment and operation costs.

1.1 Offshore Wind Energy

There are two parts of wind energy, onshore and offshore, whereas the onshore technology has been developed first. In the meantime the attention is directed more and more towards offshore wind farms. The good sites onshore will soon be taken, which results in the expansion of wind power offshore [1]. In addition, the wind is also more stable and less turbulent compared to onshore sites [2]. The main reasons of moving wind turbines off shore are obviously the higher energy profit and also the lower visual impact to gain social acceptance [3]. Since the first offshore wind park was established in Denmark in 1991, offshore wind energy production developed extremely [4]. Currently, in October 2012, the world's largest wind farm is Walney in the Irish Sea in the UK. The power capacity is 367.2 MW and might increase to 600 MW [5]. According to the European Wind Energy Association (EWEA), in June 2012, 10% of the total wind energy was produced by 4.3 GW offshore wind parks. In 2020, even 40 GW offshore installations are estimated, which provide 4% of the EU electricity demand [6]. Apparently, the offshore wind energy market is growing and rise discussions about a new foward-looking industry.

Even if energy production offshore has many advantages, the increasing costs of maintenance and installation are a drawback. Before starting a project proposal, exact measurements and planning has to be undertaken to minimize unnecessary costs. Thus, besides several new obstacles, an appropriate grid has to be designed to optimize the electrical system of the wind farm. The main challenge are varying wind speeds, which lead to fluctuating power production. This complicates the power feed to the still underdeveloped grid enormously [2].

Investment costs for an offshore wind farm are rather high, as mentioned before. The costs for the electrical part are about 10-15% of the total amount. It includes the costs for platform with the step-up transformer, switch gears and the submarine cables as well as the cable installation [7]. The latter can be optimized in the topology and the capacity of the cables. Due to the fact that there is a compromise between costs and reliability, the optimal balance should be investigated.

1.2 Problem

An important aspect for a power plant is the availability or respectively its reliability. That means, that outages should effect the supply slightly. Wind energy is disputed, because of the challenge to feed the power into the power grid, which is dependent on wind fluctuation [2]. Additionally, a wind farm is quite capital intensive. That means the purchase outlay is extremely high, more precisely 75% of the whole expenditures and consequently a farm is a risky investment. Under operation, the costs are small, because fuel costs are zero and maintenance costs are rather low [8]. As a result, to avoid loss of money the project has to be planned carefully and should provide a safe income by constant energy production. Redundancy remedies cable defects or other failures to prevent unnecessary loss of energy. They can be extremely high, if a turbine has to be turned off at high wind speeds. However, in some point, more reliability is not beneficial anymore and adding redundancy is worthless [9]. It is hard to set a perfect layout or an optimal design, because the off shore wind power is still not mature and the conditions differ for each project [3, 10].

1.3 Aim of the study

The benefit of a wind farm can be increased, inter alia, by lowering the costs down to a minimum by investigating the most efficient topology. Hereby, the right amount of redundancy has to be installed, to keep a level of reliability. At the same time the installation costs should be as low as possible. The aim of the study is to optimize the relation between redundancy and the financial expense for the cables in a collection grid. The focus is laid on the cable sizes, which affect the losses in a large scale. As mentioned in the previous section, designing a default suitable grid for an offshore wind park is challenging. On the one hand full reliability is desired to avoid high losses during a failure, on the other hand outlay costs are already extremely high and need to be lowered. An additional objective in this thesis is demonstrating the change in losses by different settings and modifications of parameters. That means e.g. the impact of failures and resistance losses at different wind speeds on the financial losses. Starting from a point where highest redundancy is desired, the crucial question of this thesis is, if the total financial losses can being reduced by lowering redundancy. The focus is laid on the losses, therefore revenues are not taken into account. The main aim of the study is to find an optimal ratio between redundancy and the costs during life time.

1.4 Simplifications and Assumptions

- Regarding to the cables, no distinction is made between summer and winter temperatures in the sea bed. During winter, the ground is colder and the current is better conducted, which is an advantage considering the higher power outcome during this time of the year. But dynamic line rating is not considered due to the lack of exact datas.
- It is also important to chose right elements like switches, disconnectors and breakers, because this can also save a lot of money. This study will however focus on the submarine cables, disregarding any power electronic devices.
- Several costs (e.g. transformer and platform costs) and losses caused by turbine failure or transformer breakdown are not taken into account, because they are assumed to be equal for all cases.
- Expecting higher wind speeds in the winter imposes a dependency on the seasons regarding failure losses exists, but since this dependency is valid generally, it is also disregarded.
- The possibility of a simultaneous damage in two cables is rather low and is therefore not taken into the account.
- The fluctuations of voltage between 0.9 - 1.1 of the normal operation voltage are excluded.
- Uneven wind speeds are not considered, thus all wind turbine generators are assumed to produce the same energy.
- Cable heating during higher currents results in even higher resistances. In this thesis this is not considered, but will be discussed in the discussion.

1.5 Outline

In this section, the individual parts of the thesis are introduced.

Chapter 2 - Background
The second chapter gives a general knowledge about wind energy, such as the topology, the wind turbine, the cables, and the wind farm site. Also, the importance of redundancy and losses is mentioned.

Chapter 3 - Theory

In this part, the theory of the thesis is described and the equations are introduced. This section starts with the calculation of the wind energy by means of the Weibull equations and establishing the power curve of the turbine.
Further on, the different kinds of losses, caused by turbine grid, and failures are presented, effecting the annual energy production. Finally the energy price and the investment analysis is introduced.

Chapter 4 - Method

In this chapter, the focus is shifted from theory to practical issues. It begins with the definition for redundancy and introducing 6 different layouts. Afterwards, the method of calculating different losses and the financial outcome is discussed. Finally the layouts are compared.

Chapter 5 - Results

In this chapter, the results of the thesis are presented.

Chapter 6 - Conclusion

The last Chapter includes the discussion, the conclusion and finally the possible future work.

2

Background

In this chapter, the wind farm layout including the topology, cables and the turbines, is introduced. A wind farm could be divided into three parts, the collection system, the transmission system and the interface to the main grid on shore [9]. The collection grid itself consists of the turbines, the power electronic, the transformers on a platform and the connecting submarine cables [7]. Since the study deals only with the collection grid, the other parts will be only mentioned briefly.

2.1 Topology

Wind turbines can be connected in different ways, radial, star or ring layout. Due to its high reliability, the latter is used in the thesis. Generally, there are different kinds of ring solutions, the total ring and the U ring. U rings have two feeder cables instead of only one and can still supply the energy if one feeder cable breaks [3]. This is because the current can flow in both directions, which enables a path even during a failure. It is the most common topology and in several papers, it is showed to be the best layout, but also the most expensive [3]. For the investigations the U ring is chosen, due to the best reliability. It is shown in fig. 2.1. In this thesis a U ring is simply called ring layout. The wind turbine generators (WTGs) in the ring layout will be connected with 9 cables in total. The future idea of distances is around 1 to 1.5 km to avoid shadow effects [7]. In this study, all distances between the individual WTGs are set to 1 km, so the calculations are done with a uniform cable length of 1 km for all nine cables. In a ring layout the WTGs are connected in parallel, which entails one voltage level. The construction voltage is 36 kV (AC), whereas the operation voltage level is 3 kV lower, around 33 kV. The system consists of 8 turbines, which are presented in the following section.

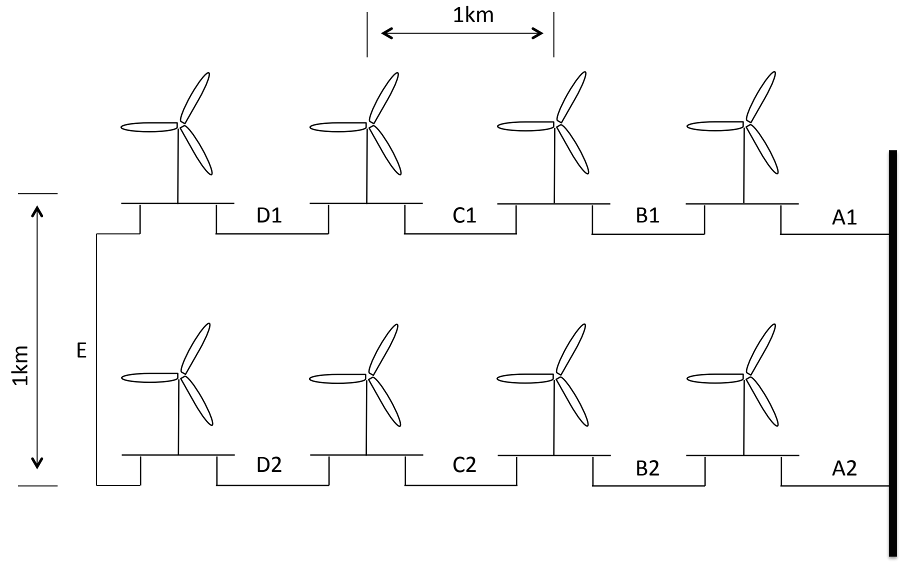


Figure 2.1: Wind farm layout investigated in this study

2.2 Wind Turbine

Offshore WTGs, as well as the rotor diameters, are becoming larger and larger. In June 2011, Siemens' first 6MW direct drive turbine SWT-6.0-120 with a 120m rotor was installed at the Høvsøre site in Denmark [11]. Later in October 2012, the turbine SWT-6.0-154 with the largest rotor started the test mode in Østerlid, Denmark. The size of the generator comes to 6 MW, while the diameter reaches 175m, making the largest wind turbine on the market [12]. Due to the size development and the increase of the offshore market, this turbine is chosen for this thesis. In table 2.1, data used for the calculations are listed.

Each wind turbine has an individual power curve, which illustrates the corresponding power outcome for different wind speeds. For the Siemens wind turbine, no appropriate power curve is available, so a fitting power curve is developed. This is shown later in the thesis in the Method chapter.

Table 2.1: Wind turbine SWT-6.0-154 data ([13])

Rotor	
Diameter	154 m
Swept area	18600 m^2
Tower	
Tower height	116 m
Grid Terminals	
Nominal power	6000 kW
Voltage	690 V
Frequency	50 Hz
Operation data	
Cut-in wind speed	3-5 $^m/_s$
Nominal power at	12-14 $^m/_s$
Cut-out wind speed	25 $^m/_s$

2.3 Wind Farm Site

The investigation of a site is the most important step before planning a wind farm. Wind data for Europe are collected in the European Wind Atlas. It includes all wind speed frequencies from each wind direction, Weibull parameters as well as the roughness parameter. These data are used to plan and design the wind farm with appropriate turbines and their arrangement [14]. No specific Weibull parameters are chosen to generalize the study, but some random example values are taken to show the different cases.

In large wind parks, wind shading is a problem and wind gusts can lead to an unequal energy output of the individual turbines [7]. In the thesis, uneven wind speeds are neglected and all WTG are assumed to produce the same energy.

2.4 Submarine Cables

The submarine cables chosen for this thesis are XLPE (cross linked polyethylene) cables with three aluminum (Al) cores from ABB. The XLPC molecules are extremely resistant against deformation at high temperatures, which is an advantage for underground cables [15]. The main materials used in cables are copper (Cu) or aluminum (Al). Al is lighter than Cu, but the resistance of Cu is lower, which would be more important in sub-sea cables [16]. However the prices for the aluminum cables are around half of the Copper-cables, which is the reason for choosing Al cables [17]. Generally, the cross section of the cables should feature at least the size to manage the normal power flow. To reduce resistance losses in the cable, a larger cross section is useful. This is however discussed later in the Method Chapter.

Losses in cables are mainly caused by ohmic resistances, which increase with the length of the cable. Dielectric losses of the XLPE insulation are negligible [18]. Thus, these losses are disregarded in the calculations. The maximal current a cable can manage, depends on the temperature of its environment, the seabed in this case. Ground temperature changes with laying depth, average sea bed temperature, the amount and the distances of cables [18]. All the external facts have to be taken into account to adjust the cables. They are assumed to be the same in summer and winter, referring to the assumptions in the introduction.

Installation of offshore cables can be carried out by implementing different methods, such as water jetting, pre-excavating and ploughing. Apart from these methods, the simplest way is laying the cable directly on the sea-bed without any protection. In case of a damage, the localization and the access is quite easy, compared to the other methods. However, in some cases the cables are protected afterwards and the method become more expensive. For protecting the cables, materials like soft soil, cement bags, half pipes, or rocks are used for covering. Due to the purchase and processing of the material, this operation costs up to 0.6 - 0.8 M€/km [19]. In soft soil, water-jetting is a cheaper way of burying cables. Hereby, a high pressure jet is used to fluidize the sediment and let the cable fall simultaneously to bury it directly. The necessary vessel is fast to (de)mobilize, which is favorable considering bad weather conditions. Also the possibility to trench directly next to the wind turbine is an advantage, when the distances between the foundations are small. According to the law, spillage of sedimentation has to be avoided. This is a problematic issue, since water-jetting results in a lot water turbidity [20]. However, the cost is around 0.1 M€/km and lower compared to the other methods [19]. If the sea bed is even and soft enough, ploughing is the most common way to bury the cable. This costs around 0.2-0.3 M€/km [19]. If the soil is inhomogeneous, there is a need for equipment change, thus moving into stiffer soil areas delays the procedures and adds up to the expenses. This operation jeopardizes the cables and also hindering boulders or rocks lead to tension and stress exposure during swerving. A permanent stiff soil is handled by pre-excavating, which is time-consuming and need 2 or 3 different steps: Trenching, laying and, depending on the place, covering. The laying of the cable should occur soon after trenching, since the trench is refilled with sand from time to time [20]. In some cases the sea bed has to be cut with special equipment, which leads to expenses from 0.6-0.7 M€/km [19].

The installation is a crucial part for establishing an offshore wind farm. A lot of money flows into this part of a project and should therefore be planned precisely. In this thesis no exact installation method is defined. Costs will be changed later to study the influences on the total financial losses.

2.5 Losses

During operation, losses are expected at different points, distributed across the whole wind farm.

Firstly, losses occur directly at the wind turbine. The most important part of the losses is the physical limit of Betz, c_p. It specifies the percentage of the maximal energy, which can be harvested from the wind energy. In reality, a harvest of 100% of the energy is impossible, because this would lead to a wind speed of zero after the wind turbine. A simple illustrative explanation is, if the air stops behind the blades, it acts like a wall and blocks the wind flow. Since no fresh wind can flow through the rotor area anymore the whole system stops. After passing the rotor, some energy must be left in the wind to continue the air movement. This phenomenon results in the theoretical maximum of $c_{p,betz} = 0.59$. The real value of c_p in wind turbines is around 0.4 - 0.48, because turbulence effects prevent reaching the maximum [21]. For a wind farm also the park effects have to be considered. Due to the comparatively narrow configuration of the wind turbines, a shadow effect influences the power production and leads to losses of generally 5-10% [8]. This value depends on the amount of WTGs and the distances between them. After several months of operation, blade soiling could come into play, resulting in more turbulences. In the case of the open sea, only salt and light dirt can be considered. Another fraction of the production is lost due to the wind hysteresis, which may change rapidly and the wind turbine mechanism is not able to react fast enough. Transforming kinetic energy to electrical energy leads to losses as well, which is dependent on the generator installed. A Sankey diagram for the losses is showed in fig. 2.2. All the losses mentioned above are constant in some way. They happen before the collection grid and thus cannot be changed by improving the layout of the cable system.

The gained power in the individual wind turbines is collected by the collection grid. During power transferring, cable resistances are always reducing the power. All kind of cables have ohmic, dielectric, inductive and capacitive impedances, where these impedances increase with the length of the cable. The main affecting losses are however the ohmic losses, as already discussed in the submarine cable section. Outages happen in all kinds of electrical systems, if no full reliability is given. If a decisive part of the wind farm fails, turbines are disconnected or have to be switched off for up to several weeks. In this time, financial losses occur, because of the unavailability, the repair costs and the spare parts. Despite of higher wind forces, offshore rotors are supposed to last longer due to more stable wind speeds. However, in general, all devices are exposed to harsher weather conditions and offshore repair time is much longer and more costly [10]. Especially in case of an offshore outage during winter, repair work may have to wait then until summer [3]. In the thesis, the repair costs and the spare parts are not investigated. The amount of costs are the same for all layouts and not necessary in times of working out the ratio. The unavailability time is however different for each layout, since the redundancy in the systems varies. This is discussed further in the theory and method chapter.

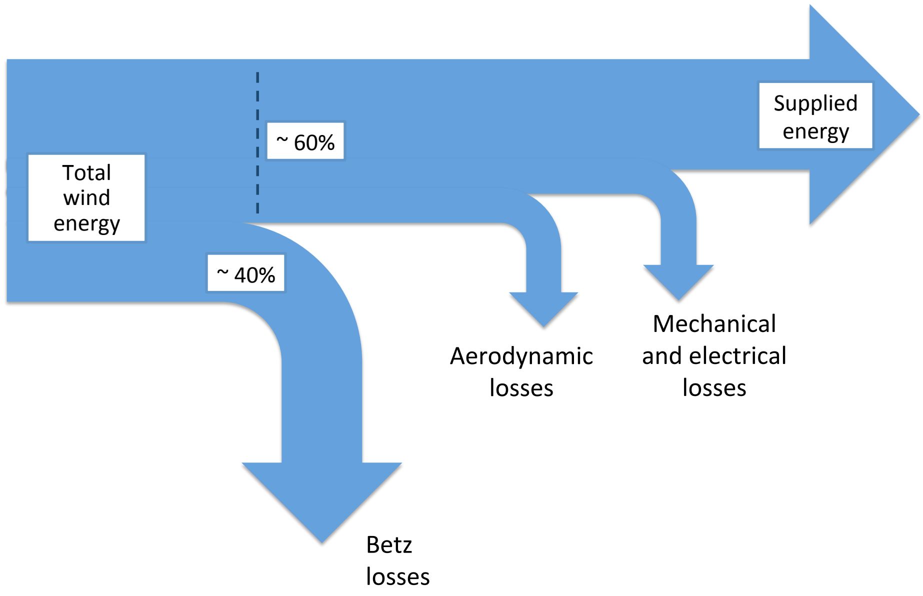


Figure 2.2: Sankey diagramm of the typical losses for a wind turbine

2.6 Redundancy

Each electrical system has outages, which can take a long time to repair and cause losses, if no reliability is given [9]. The definition of redundancy according to the dictionary [22] is the *"duplication of components in electronic or mechanical equipment so that operations can continue following failure of a part"*. The design of the collection grid influences the reliability of the wind farm in a large scale [3]. Generally, a higher redundancy leads to less power losses and therefore higher beneficial outcome. However, at some point, adding redundancy is worthless. Whilst the investment costs rise linearly, the effect of added redundancy becomes less and less pronounced. As soon as the costs of an investment exceed its benefit, adding redundancy is not worth any more [9].
It is suggested to make use of bigger cable sizes to avoid ohmic losses. However, bigger sized cables become heavier and thicker and at some point one cable has to be substituted by two smaller cables. If cables are laid directly next to each other, they are very likely to fail at the same time. Man made damage, like dropping the anchor on a cable, is 3-5 times higher than an internal failure [10, 20]. Therefore, if a failure happens by external influences, it concerns probably both cables at the same time.

2.7 Wind Energy Price

Wind energy is quite different to conventional power plants in regard to the cost distribution. The costs of a wind farm include mainly the capital costs (75%). In contrast, conventional power plants, such as gas and coal, have a comparatively low outlay. The cost emphasis is laid on the operation and maintenance (O&M), because of fuel costs etc.. This is the crucial distinction, which is an advantage for wind energy. O&M costs are lower for wind energy, because the fuel costs are zero over the whole operation time [1]. Although the zero fuel costs are beneficial, the previous project planning is much more important. Since the outlay is quite high, the total financial expense for wind power seems much more expensive and the payback time should be as short as possible. Calculations have to be done 20 years in advance to estimate the benefits. However, the wind forecast can only made in the short term. All together, wind energy projects are more risky but at the same time more reliable in the long run. Since oil and gas prices are unstable and connected to the economical situation, it can be certain that wind blows in the future as well [8]. In this study, the costs are calculated by studying the cases based on different energy prices.

3

Theory

3.1 Energy Calculations

3.1.1 Weibull Wind distribution

Depicting wind data from a site is normally done in a Weibull distribution. The Weibull distribution exists in two different ways. Firstly, the cumulative distribution, which adds up the windspeed frequency and secondly, the distribution density, which represents each frequency density of the windspeed. Following equations are used for the two Weibull curves [23]:

cumulative distribution:

$$F(v) = 1 - exp(-(\frac{v}{A})^k), \tag{3.1}$$

distribution densitiy:

$$f(v) = \frac{k}{A} \cdot (\frac{v}{A})^{k-1} \cdot exp(-(\frac{v}{A})^k), \tag{3.2}$$

where

$$A = Weibull\,factor \quad k = Weibull\,factor \quad v = Wind\ speed$$

The parameters A and k are normally given by the European wind atlas [14]. However in this thesis, these parameters are chosen randomly and are adjustable. Since A and k do not give any clear information, the average wind speed v_m can be used as a more predicating value. By calculating the average wind speed by eq. (3.3) a quick estimation of the economical value of a site can be drawn [24].

$$v_m = A \cdot (0.568 + (\frac{0.434}{k}))^{\frac{1}{k}} \tag{3.3}$$

3.1.2 Power Curve of the Wind Turbine

The installed power of a wind turbine is far more than the real power output. A wind turbine can not be compared with a conventional power plant that operates nearly full time at maximal power outcome. On the contrary, a WTG presents full output power less than 50% of the time full. Unsteady wind speeds are the reason for that. To demonstrate the resulting power production at a specific windspeed, a power curve is necessary. The wind turbine power curve is simulated and depicted based on the following equations [21]:

$$P_{Rotor} = 0 \qquad v < v_{cut-in} \tag{3.4a}$$

$$P_{Rotor} = c_p \cdot \frac{\rho}{2} \cdot \eta \cdot v^3 \cdot \pi \cdot R^2 \qquad v_{cut-in} < v < v_N \tag{3.4b}$$

$$P_{Rotor} = P_N \qquad v_N < v < v_{cut-out} \tag{3.4c}$$

$$P_{Rotor} = 0 \qquad v > v_{cut-out} \tag{3.4d}$$

whereas v_N is the wind speed, where the turbine reaches the nominal power and it is calculated by

$$v_n = \sqrt[3]{\frac{P_n}{c_p \cdot \frac{\rho}{2} \cdot \eta \cdot \pi \cdot R^2}} \tag{3.5}$$

where

c_p = *Betz factor* $\quad$ ρ = *Air density* $\quad$ η = *Losses (mentioned in the next section)*

R = *Rotor radius* $\quad$ P_N = *Power at* v_N

With the help of the cut-in, nominal power and cut-out wind speed the curve can be shaped. At the cut-in windspeed v_{cut-in} the turbine starts to operate, whereas at the cut-out wind speed $v_{cut-out}$ the turbine turns off. Below and above those wind speeds, the power outcome is zero. At the nominal wind speed v_n the power outcome reaches the installed power P_N and keeps this power constant until the wind speed of $v_{cut-off}$. Finally, losses have to be considered to get the real power curve, which are discussed in the next section. The originated graph illustrates the actual power outcome at several wind speeds. For the exact output power over a time slot, the data have to be combined with the Weibull function.

3.2 Losses

In this section different kinds of losses are discussed.

3.2.1 Turbine Losses

Turbine losses have constant values, which cannot be lowered by changing the grid configuration. The Betz value, mentioned in the background, is determined by the physics law as well as the shape and the aerodynamics of the rotor blades. The mechanical and electrical losses depend only on the installed system in the nacelle. Therefore, the wind power has to be multiplied with eq. (3.6) to get the real wind turbine power output [25].

$$\eta = c_p \cdot \eta_m \cdot \eta_{ge} \tag{3.6}$$

where

η_m = *Mechanical losses* η_{ge} = *Generator losses*

3.2.2 Grid Losses

A large part of the losses occur in the cables, because these losses increase with higher currents and the length of the cable. Thus, already in the collection grid a lot of energy can get lost, if the wrong cables are installed. Capacity and inductance will be disregarded in this thesis and only ohmic resistances are considered. They are dependent on the core diameter and differ therefore in each individual cable. As already mentioned earlier, resistances change with temperature, which has to be taken into account during the designing phase. These influences can be considered by multiplying rating factors, taken from the ABB data sheet [15].

The resistance losses P_{losses} are calculated for each cable individually by

$$P_{Losses} = 3 \cdot I^2 \cdot R \tag{3.7}$$

or with regard to the cable lengths

$$P_{Losses} = 3 \cdot I^2 \cdot R' \cdot l \tag{3.8}$$

R = *Resistance* [Ω] I = *Current* [A]

R' = *Resistance per meter* [$\frac{\Omega}{m}$] l = *Length of the cable* [m]

The current in eq. (3.7) and eq. (3.8) varies with the wind speed. With higher wind speeds, the current increases enormously, since the power outcome changes with the cube of the windspeed. Applying the Weibull figures, the amount of losses during a year at a specific windspeed can be calculated as

$$P_{Losses,i} = f(v_i) \cdot P_i \cdot 8760 \tag{3.9}$$

where

P_i = *Power output at* v_i *8760* = *Hours per year*

$f(v_i)$ = *Frequency of* v_i*, described by Weibull*

The individual power losses can be added up to the total losses for all wind speeds by

$$P_{Losses,total} = \sum_{i=1}^{s} P_{Losses,i} \tag{3.10}$$

where

s = *Total number of wind speeds*

3.2.3 Failure Losses

Only cable failures are taken into account, because failures in other parts of the system remain the same in all the cases. The time, where the wind farm is not available over the year, can be calculated by the failure frequency λ and the duration of the outage time μ [9]:

$$U = \frac{\lambda \cdot \mu}{8760} \tag{3.11}$$

where

U = *Unavailability time*

The energy not supported (ENS) over this time period is defined by the unavailability time multiplied by the lost energy E_i [9].

$$ENS_i = \sum E_i \cdot U \tag{3.12}$$

where

ENS_i = *Total energy not supported at* v_i E_i = *Lost energy at* v_i

The value of ENS is much higher in the upper wind speed sections, therefore the total not supported energy ENS_{total} is the sum of the individual losses, correlated to the specific wind speeds by taking the Weibull curve into account. This is shown by

$$ENS_{total} = \sum_{i=1}^{s} ENS_i \cdot f(v_i) \tag{3.13}$$

3.3 Annual Energy Production

Finally by combining the mentioned information, the annual energy production (AEP) can be estimated in three steps.

First, the energy output E_i at different wind speeds during a year is calculated by:

$$E_i = f(v_i) \cdot P_i \cdot 8760 \tag{3.14}$$

Second, the single wind speeds are added up to the total Energy output during a year.

$$E_{ges} = \sum_{i=1}^{s} E_i \tag{3.15}$$

Thirdly, having all the losses, the annual energy production (AEP) of the wind farm is calculated as

$$AEP = E_{ges} - ENS_{total} - P_{Losses,total} \tag{3.16}$$

3.4 Investment Analyses

Finally, the investment analysis can be done, by taking into account the calculated power losses. The expenditures consist of the initial investment and the annual lost revenues due to power losses. The initial investment includes the acquisition costs of the cables and their installation. Annual costs are the summarized power losses multiplied by the electricity price. Considering the annual costs over the whole lifetime, a discount rate has to be considered as well.

Applying these parameters, the net present value (NPV) can be calculated. The NPV converts any cash flows in the future into the present amount and is therefore perfectly applicable for comparing the benefits of different layouts [9].
The NPV is calculated as:

$$NPV = \sum_{i=1}^{n} \frac{S}{(1+k)^t} - I_0 \tag{3.17}$$

where

S = *Expected annual costs* k = *Discount rate*
I_0 = *Initial Investment* t = *Life time*

4

Method

This chapter is about the implementation of the theory, discussed in the previous chapter. Six different designs are investigated, which will be described further down. All calculations in this study are implemented in MATLAB. To clarify the work, the following chapter illustrates the steps of the approach. The individual steps are displayed in a diagram in fig. 4.2.

4.1 Redundancy Definition

The definition of redundancy changes with the type of analysis. Therefore, no general definition exists for redundancy in energy systems [26]. Among several possible emphasizes, this reliability study considers the economic issue. Hereby, different scenarios with various layouts are investigated to compare power production, benefits and outlay costs. Furthermore, the cable redundancy parameter ξ is introduced. The definition is based mainly on the feeder cable, since it has the most load to carry. The layout is seen as two equal rows, connected to a ring layout by an additional cable. Under normal operation the connecting cable is not used. In case of an outage, this cable allows a load flow from one row to the other. The amount of power that can be carried dependent on the redundancy, defined as below.

The redundancy factor ξ indicates how many percent of the power in array 2 can be managed by a cable in array 1, additionally to its normal load. The power output is assumed to be at the upper limit at 6MW per turbine.

In accordance with this definition, redundancy is determined in the event of full power outcome. However, only around 30% of the time, a wind farm is operating in full outcome power. The rest of the time, less power is produced, which implies a higher reliability during these times. Depending on the wind and the redundancy value of the system, full redundancy is given under a relatively long time period. The following list presents the different cases investigated in this thesis. In fig. 4.1 the layouts are shown to clarify the definition.

- **100% Redundancy**
  An ξ of 100% complies full redundancy at any time of the year. The diameter of the cables are sized big enough to carry every possible load in the wind farm during any kind of failure. This means, during a failure in cable A2, the cable A1 is able to carry the full load of 8 turbines, or 48 MW. Thus, no losses are expected by cable failures.
  Cable cross sections have an upper limit due to their diameter and weigh. In this study, the maximal cross section is 1000 mm^2, which implies a current of I = 770.4 A [15]. The original value is around 720 A, but by considering the ambient temperature at 10°C, the maximal cable current increases. Since the failure current is too high in cable A1 or A2, called the A cables, one big cable is divided into two adjacent cables. The distance between those cables is two meters to reduce interactions. The interactions are considered by an additional rating factor [15].

- **75% Redundancy**
  If there is a failure in one of the A cables, the other one can only carry 75% of the full power outcome. Therefore, one of the WTGs will be disconnected until the cable is repaired. During lower wind speeds, more redundancy is possible.

- **50% Redundancy**
  If there is a failure in one of the A cables, the other feeder cable can only carry 50% of the full power outcome. Therefore, two of the WTGs have to be disconnected until the cable is repaired. During lower wind speeds, more redundancy is possible.

- **0% Redundancy**
  The cable layout of $\xi = 0$ is designed to carry the full load only under normal operation. That means, that under full power outcome no redundancy is given, but there exists a connecting cable between the two arrays. Redundancy is given under certain wind speeds, even if the cables are sized only suitable for the nominal load. Consequently, there is some redundancy in the system if a failure occurs and the power output is less than 6 MW. The connecting cable has the appropriate size to transfer as much power as the neighboring cables D1 or D2 can manage.

- **Radial Layout**
  In the radial layout, the connecting cable is not present, therefore the current can only flow in one direction. In case of a failure there is no possibility for an array to take over the power of the other one. Hence, if there is a failure in one of the A cables, the whole row will be out of order.

- **Average Wind Speed Layout (AWS)**
  Since the layouts described above are designed for full power output, nearly all cables are oversized. That means, during most of the time, the flowing current is much less than the maximum possible current. This pushes up the investment costs unnecessarily and can be avoided by adapting the cable cross section to the average current flow. Taking the average windspeed into account, the corresponding power flow is used to calculate the cable sizes. Each cable is therefore dimensioned to provide 100% redundancy up to the average wind speed.

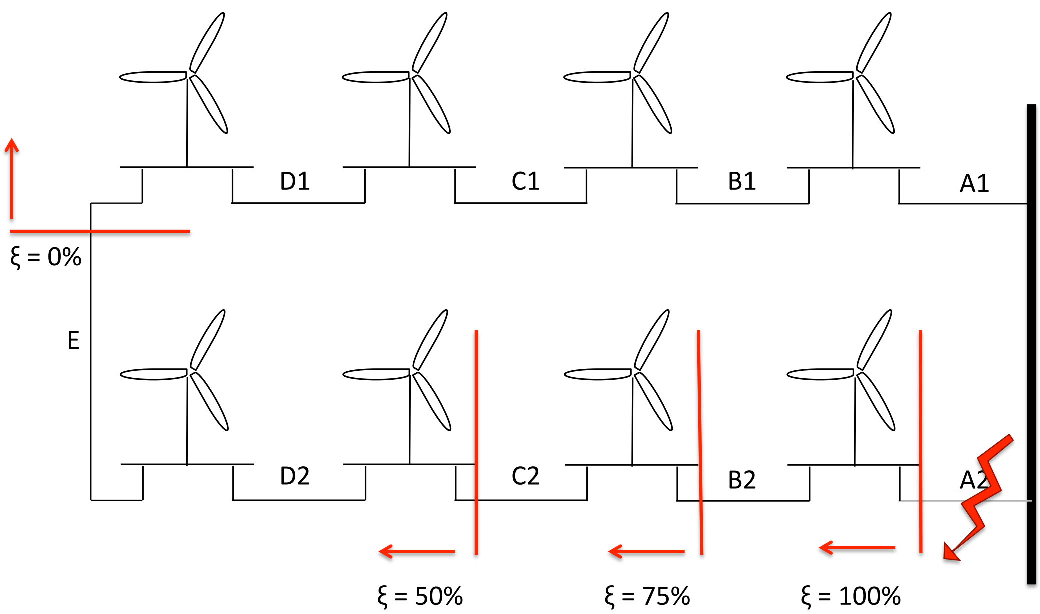


Figure 4.1: Different definitions of redundancies during a failure in cable A2 (corresponding to a failure in cable A1)

4.2 Energy Calculations

First, the kinetic energy has to be investigated by courtesy of the wind values A and k, which give information about the wind distribution. The Weibull curves are easily calculated by eq. (3.2) and eq. (3.1), mentioned in the theory part. For comparisons, default values are set, which are shown in table 4.1.

Table 4.1: Default values

A (Weibull factor)	10.09
k (Weibull factor)	2.05
v_m (mean wind speed)	9.8 m/s
c_p	0.4
η	0.95
Cable installation costs	0.1 M€/km
Electricity price	0.25 €/kWh

Due to the unavailability of the power curve on the wind turbine data sheet, the power curve is calculated. Hereby, the information In - and Off cut wind speeds are used of table 2.1, combined with the Betz limit, aerodynamic, mechanical and electrical losses. By taking all these informations into account the curve can be calculated using eq. (3.4). The power curve is given in the results chapter.

Since the wind information is given, the focus is now put on the resulting power flow and the losses in the different layouts, introduced before. Depending on the selected redundancy, the maximal power flow in each cable is calculated and compiled into a vector. This is done by assuming a failure and defining the maximal possible power in each cable. For example $\xi = 100\%$, the maximum power in cable A1 or A2 would be $8 \cdot 6MW$, whereas for $\xi = 75\%$ the A cables carry only the maximal power of for $7 \cdot 6MW$. Furthermore, the corresponding maximal current in each cable is calculated by eq.

$$I = \frac{P}{V \cdot \sqrt{3}}. \tag{4.1}$$

Knowing the flowing currents, the cable cross sections can be determined with the help of a table from ABB [15]. The right cross section is necessary to provide a permanent power flow without causing overload situations. The data sheet of ABB presents cables from 95 mm^2 till 1000 mm^2, whereas the maximum current in the 1000 mm^2 cable is around 720 A. In case of exceeding the maximum, the current is divided up into two equal cables, instead of using one big sized cable. Knowing the necessary diameters of each cable, the purchase costs can be investigated. Adding up the individual cable prices and the installation costs of the system the capital price can be calculated. For further calculations, for each cable the resistances are determined, by using data from ABB [15].

4.3 Grid Losses

Knowing the resistance of the cables, cable losses can be calculated at any current. For this purpose, the data from the power and Weibull curves are used. For all wind speeds, the appropriate power outcome of the turbine and therefore the correlative currents are

known. Using the determined cable resistances, the losses can be calculated. By applying eq. (3.7), a set of cable losses is provided, which demonstrate the losses as a function of the wind speed.
In order to identify the total losses during a specific time period, the frequency of the wind speeds has to be taken into consideration. Hereby, the available Weibull wind datas are implemented like eq. (3.9). Losses are calculated with the assumption that the wind park is running in normal operation mode all year long. Failures are not subtracted from these losses, because it would be an insignificant amount of energy. Adding up the losses during the different wind speeds, the total losses are calculated by using eq. (3.10).

4.4 Failure losses

Additionally to the grid losses, the cable failure losses have to be calculated. Hereby failure frequency λ and repair duration μ from table 4.2 are taken into the account. These parameters were used to analyze the wind farm Lillegrund in southern Sweden and since the farm is close to the main land, the outage time is assumed as quite short. As mentioned in the background, the outage time can be quite long, but the data are overtaken unmodified by [9] and no sensibility studies are done.

Table 4.2: Failure rate and time parameter

	Failure rate λ [1/year]	Outage time τ [weeks]
Subsea cable	0.004	4

An important aspect while investigating the failure losses, is the dependence of the redundancy on the wind velocity. The default redundancy of the system is not present during the whole operation time. The lower the wind speeds are, the higher the expected redundancy is. Up to a specific wind speed, full redundancy is provided for even a less redundant system.

The present redundancy of the system is defined in the case of full power outcome, thus 6 MW per wind turbine. The lower the wind speeds, the more load can be carried. For this calculation, the key element is the cable E, seen in fig. 4.1. This cable is crucial, because it determines the maximal load flow between the two arrays. During lower wind velocities, more power can flow. Dependent on the maximum current of this cable, the wind speed range can be identified, in which all turbines can be still connected. As an example, consider the layout with ξ=50%. If one of the two A cables breaks at a full power of 6vMW, 6 of 8 turbines are still connected. However at a wind speed of v_1, 75% of the WTGs can be supplied and at v_2, 100% reliability is provided ($v_2 < v_1$). Therefore the redundancy at each wind speed has to be considered individually. If this is done, the unavailability can be calculated by eq. (3.11). Finally, the NSE per wind speed is known by eq. (3.12) and the total ENS during a year by eq. (3.13).

4.5 Different Layouts and Comparison

For comparison, the six different layouts are investigated. These layouts are explained above and are partly demonstrated in fig 4.1. Comparison is made by changing the parameters, like wind speed, electricity price and installation costs. Changes in installation costs is the easiest to implement, because the wind parameters and layout parameters remain the same. This is also true for the electricity price. The changes in wind speed are however more complicated. For each wind speed the Weibull factor A is changed, a new Weibull curve is needed and the losses change accordingly. Especially, the AWS layout is more complicated, because the cross sections change with each loop. Thus, resistances and power losses vary extremely.

Since the main aim is to find out, if reduced redundancy results in lower costs than full redundancy, following central equation can be formulated:

$$\frac{C_{reduced\ redundancy}}{C_{total\ redundancy}} = k, \qquad C \ = \ C_{investment} + C_{grid\ losses} + C_{failure\ losses} \tag{4.2}$$

whereas k>1 means, that full redundancy is the best solution and k<1 presents a more favorable layout with less reliability. The results of the comparison are given in the next chapter.

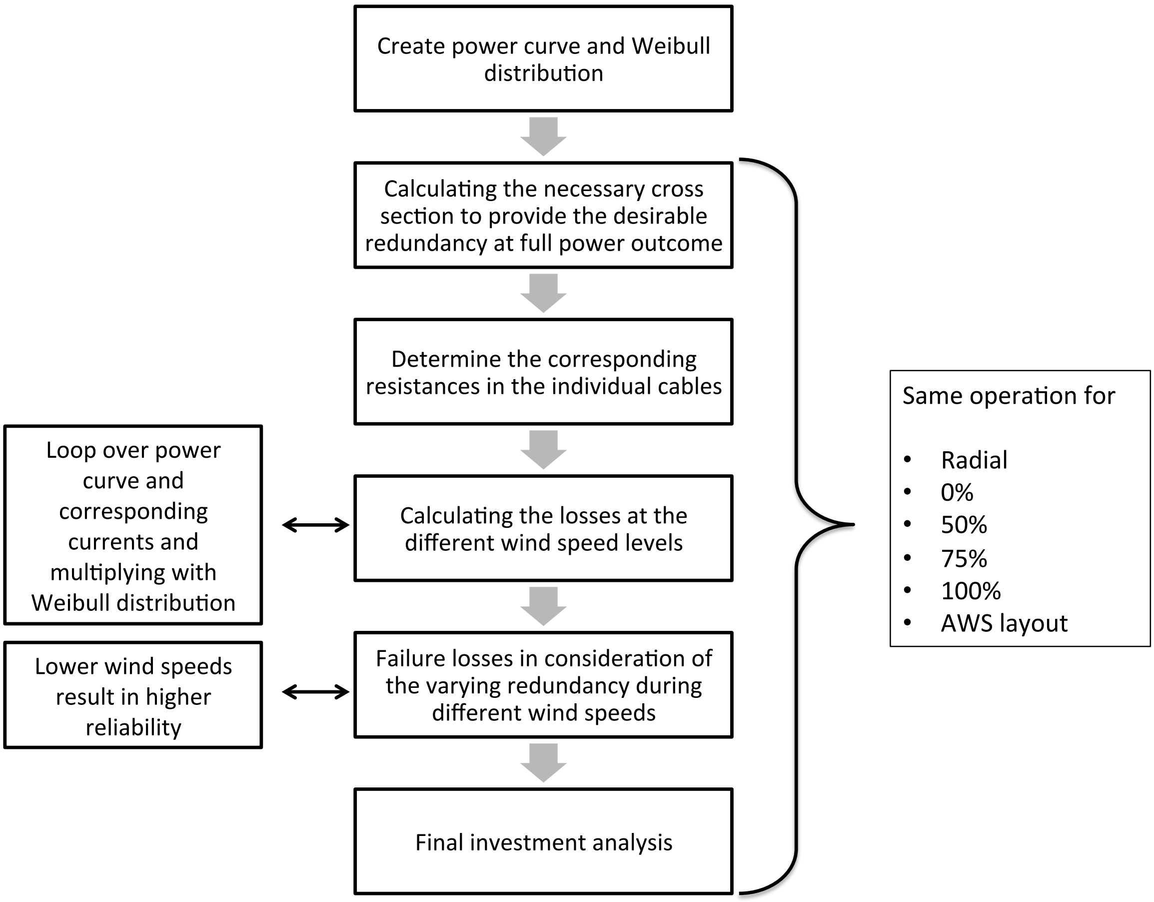


Figure 4.2: A visual demonstration of the calculation procedure to find the most appropriate layout

5

Results

In this thesis, the collection grid of a wind farm has been investigated in terms of reliability, outlay costs and financial losses during 20 years of operation. Financial losses depend on the layout, the electricity price, the windspeed and the investment costs.

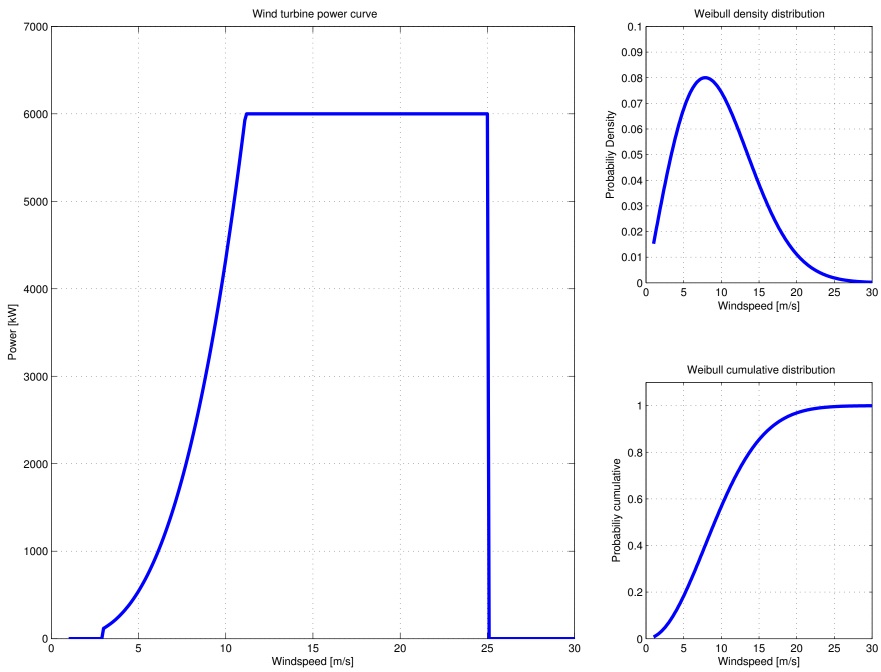


Figure 5.1: Power curve and Weibull distributions

The total financial losses are studied, firstly for different electricity prices, secondly for variable wind speeds and thirdly, for different installation costs. It has to be mentioned, that revenues are not added to the financial losses. Sensibility analyses, for variable repair time of the cables, result in too insignificant changes compared to the other cases and are therefore not taken into account.

Fig. 5.1 shows the power curve of the wind turbine and also the two default weibull curves. Since the ratio between reduced redundancy and full redundancy is investigated, the axes of the following figures are defined per unit and the 100% redundancy layout is set to 1.

5.1 Variable Electricity Price

The benefit of a wind turbine or a wind energy park depends highly on the revenues. Therefore, the electricity price is one of the most significant factors to investigate. Due to laws, subsidies and changes in the economy, wind feed-in revenues change a lot, even during a small time scale. Fig. 5.2 gives an idea of how financial losses change by varying energy prices. To investigate the effect of the electricity price, the other parameters are set to the default values. The installation costs for the cables are 0.1 M€/km and the average windspeed is 9.7 m/s, whereas corresponding Weibull figures can be seen in fig. 5.1.

Fig 5.2 demonstrates the development of the different layouts, as a function of the energy price. At low energy prices, the installation costs have larger weight than the losses during operation time and the system's reliability is not as important. Therefore, the radial solution is the cheapest with a start value at around 1.4 M€until an energy price of 5.1 $\frac{ct}{kWh}$. At this point, there is an intersection between the radial, $\xi = 50\%$ and the average wind speed (AWS) layout. The latter, though, has a greater gradient and is thus not worth further mentioning. At 14.1 ct/kWh the 70% crosses the 50% layout and remains the most appropriate and beneficial solution.

Returning to the basic question, if less redundancy can result in less financial losses, fig. 5.2 gives an answer. It illustrates that 100% of reliability is definitely not the most favorable choice. The investments costs are much higher than probable losses during a failure. Compared to the layout with $\xi = 75\%$, it is obviously not worth spending money to increase redundancy to 100%.

5.2 Variable Windspeed

The second investigation focuses on the average windspeed, which influences the power production in a large scale. The higher the wind speeds during a year are, the higher the revenues become. Also, failures lead to greater losses of benefits. Fig. 5.3 illustrates the development of the losses, depending on the average windspeed. The electricity price is set to the default value of 0.25 €/kWh and the cable installation costs to 0.1 M€/km. The layout with redundancy $\xi = 50\%$ is obviously the most suitable construction, since it is continuous the cheapest layout.

According to the European Energy Portal, in April 2010 the feed-in tariffs in Germany for wind offshore were around 0.13 - 0.15 €/kWh [27]. For a second analysis, the electrical energy price is set to 0.14 €/kWh, apart from the remaining default values. In this case, quite overlapping results appear, which can be seen in fig. 5.4. The radial and the 0% layout surpass the costs for the full redundant system already below a wind speed of v = 8.5 m/s. Since the average wind speeds offshore are higher, these layouts are not suitable. Below an average wind speed of 10 $\frac{m}{s}$ the construction of ξ= 50% is most suitable. At higher wind speeds ξ= 75% becomes lower.

The AWS layout results in a special curve, which totally deviates from the others. The reason for this difference is the definition of the layout design. Apart from the other cases, this design is dependent on the average wind speed. A more precisely layout description can be found in chapter 4. The reason for this serrated curve is that for every wind speed the average power output changes. This change leads to a new calculation of the appropriate cross section every time. Thus, increasing windspeed, increases the current in the cable, resulting in higher resistance losses, due to eq.(3.7). Because of the squared current, the corresponding grid losses increase rapidly. At one point, the flowing current exceed the limit of the maximum current in the actual cable size and a bigger cable is taken, which leads to a step down after the peak. Thus, all the peaks arise out of the changing cross section and the associated changing cable resistance losses. Generally the losses for this layout are incredibly high in the beginning, because at lower wind speeds the cable sizes are at a minimum point and for all cables the smallest cross section is chosen. Thus, compared to the other layouts, the resistances in the cables are immensely high. In fig. 5.3 and 5.4 the curve has a minimum at a wind speed range of 10.2-10.7 m/s and then suddenly rise and remain more or less equal. The abrupt increase is the result of dividing up the current into two cables, which is discussed later.

Like the results before, the figure displays the financial differences between $\xi = 100$ and $\xi = [50, 75]$. Similarly, 75% redundancy gives the most beneficial construction and 100% exceeds the point where adding redundancy becomes more costly.

5.3 Variable Installation Costs

The case of variable installation costs is also implemented with the default values, an electricity price of 0.25 €/kWh and the wind conditions shown in fig 5.1 and table 4.1. The result of changing installation costs are shown in fig. 5.5. Investigations of the installation costs of the cable are worth considering when the way of installation has to be decided. As mentioned in chapter 2, the seabed conditions decides, which method of cable laying can be applied. The cable installation is a fixed initial cost and results therefore in the the same cost increase for all layouts. There are however two exceptions. Firstly, the radial layout costs are decreasing more sharply with rising installation costs, due to one cable less installed. Secondly, the full redundancy layout has two installed A cables instead of one, which causes a faster increase in investment costs. The only intersection occurs between the radial layout and the 100% layout at around 0.62 M€. However, the three most appropriate solutions are not involved in the intersection and remain the cheapest. Therefore, variable installation costs are not further investigated.

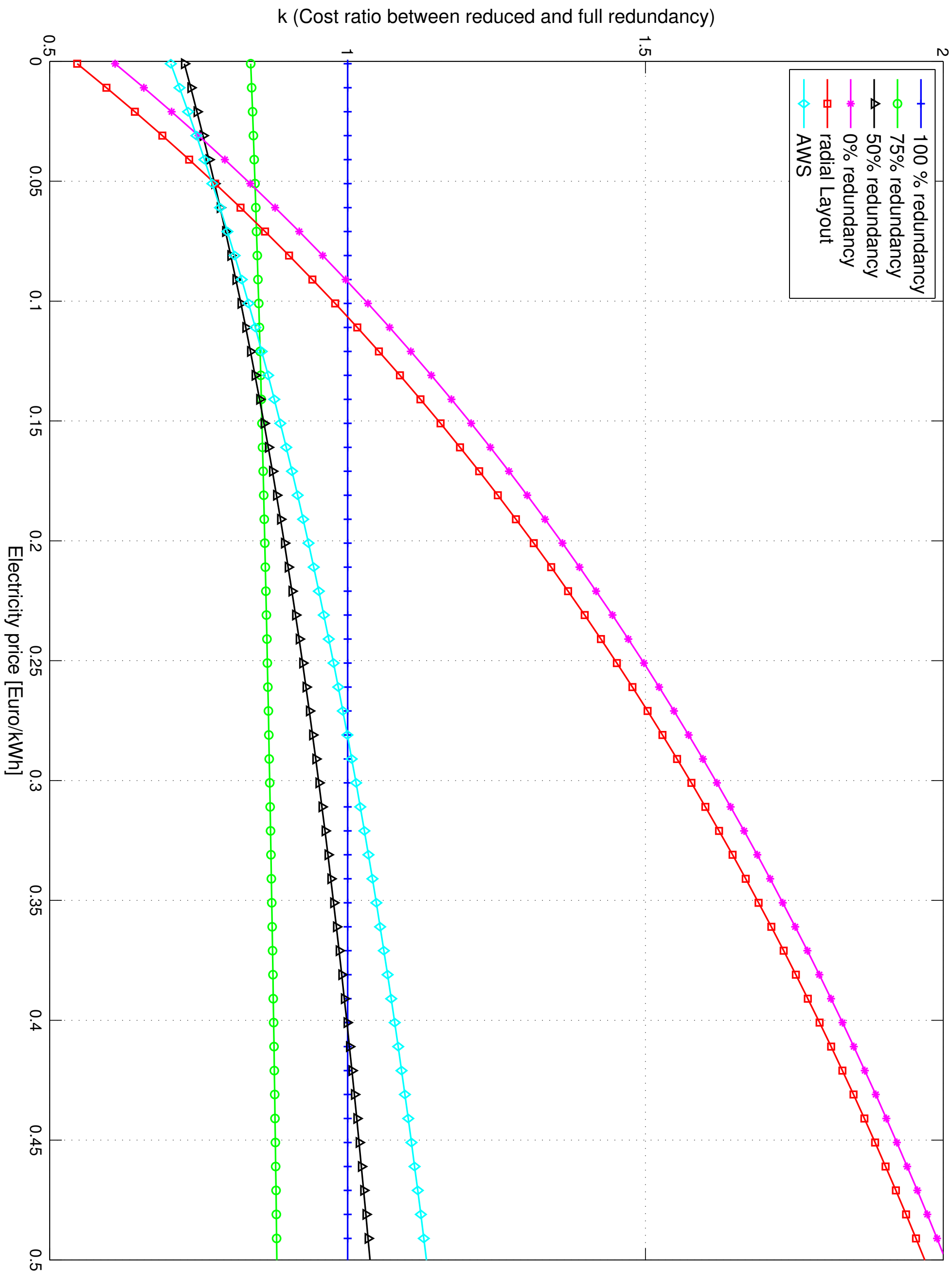


Figure 5.2: k as a function of the energy price with the installation costs of 0.1 M€/km and average wind speed of 9.7 m/s

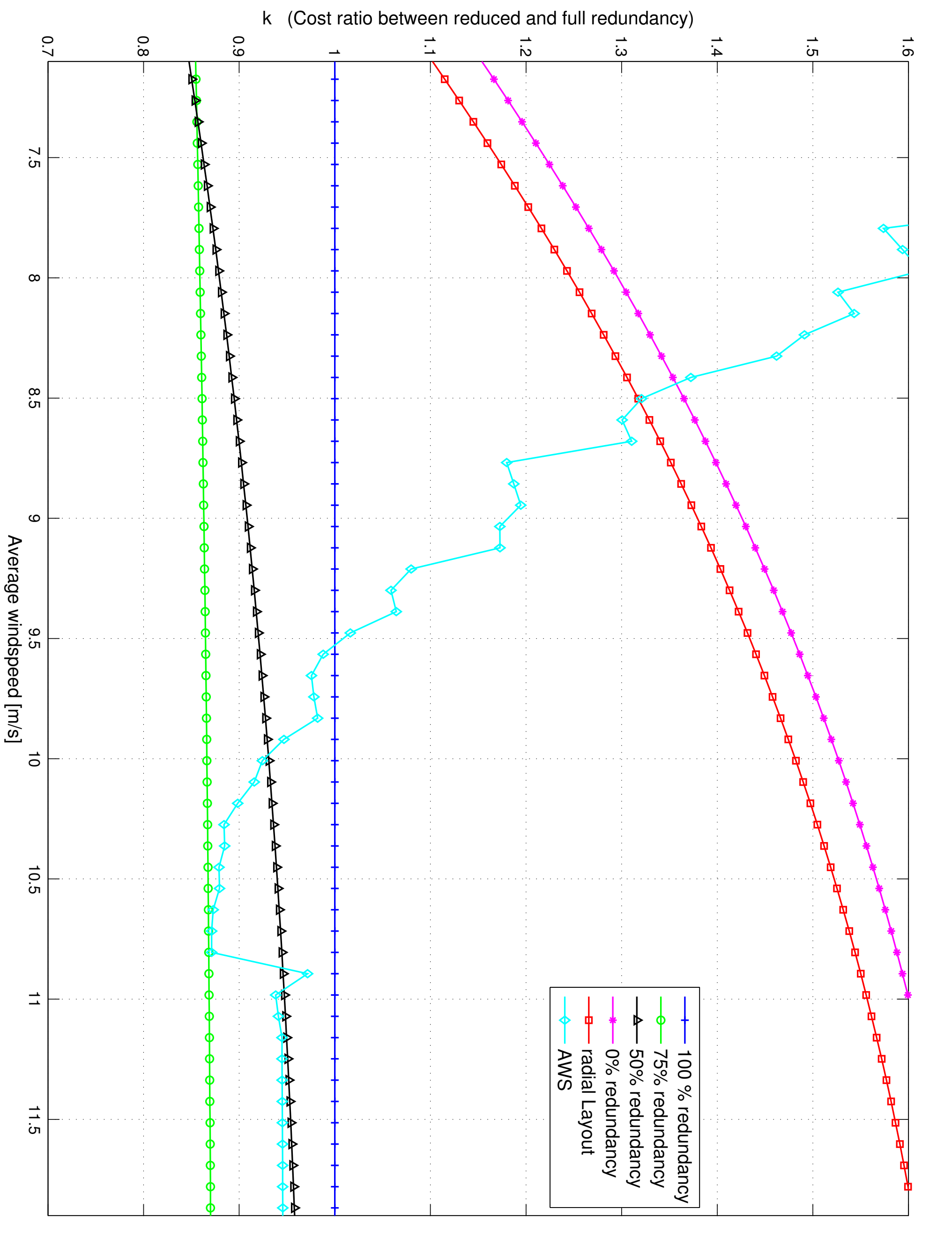


Figure 5.3: k as a function of the average wind speed with the installation costs of 0.1 M€/km and the energy price of 0.25 €/kWh

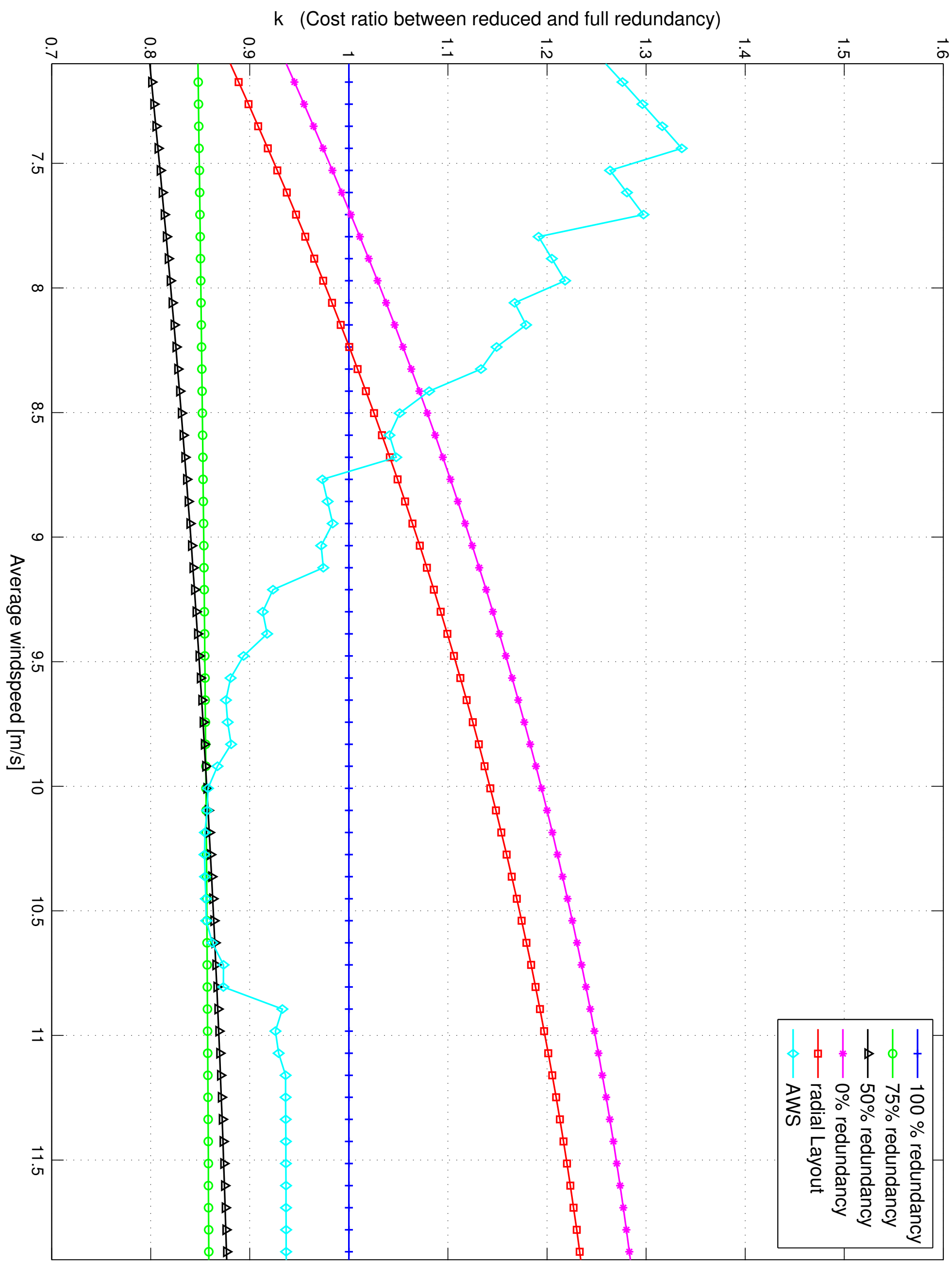


Figure 5.4: k as a function of the average wind speed with the installation costs of 0.1 M€/km and the energy price of 0.14 €/kWh

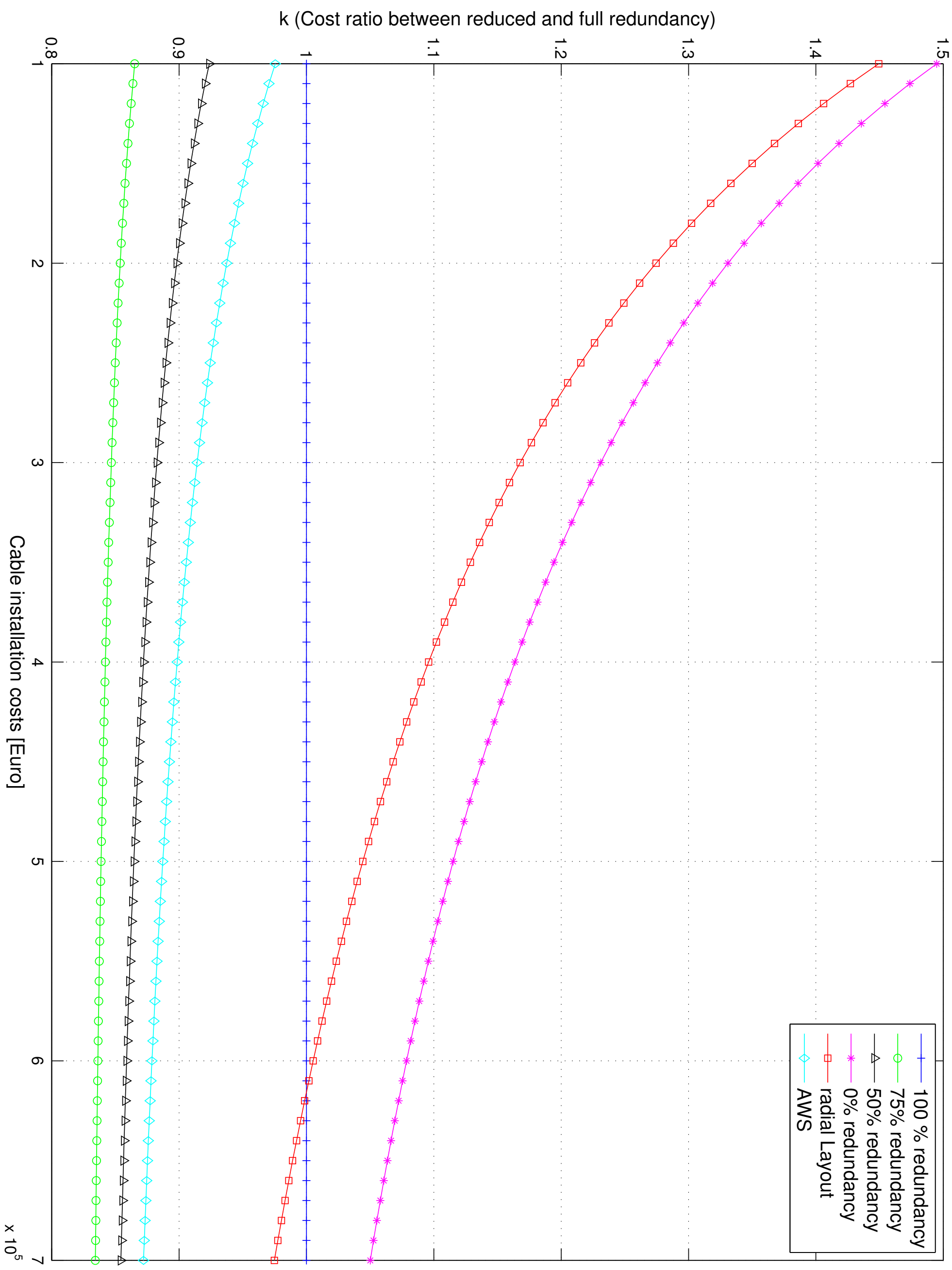


Figure 5.5: k as a function of the cable installation costs with the energy price of 0.25 €/kWh and average wind speed of 9.7 m/s

5.4 Cable Losses

In the following table and figure, the cable cross sections and the respective losses at full power outcome (6 MW/turbine) are compared. These results are obtained regardless of the windspeed. Therefore, the average wind speed layout is not considered in this part, due to its wind speed dependance. Also, the radial layout is disregarded, because of its similarity to the 0% layout. In table 5.1 the individual cross sections of the cables are demonstrated.

Table 5.1: Cable cross sections of the individual cables in each layout

Default windspeed v = 9.7 m/s									
Redundancy ξ	Cable Cross Section [mm^2]								
	A1	B1	C1	D1	E	D2	C2	B2	A2
0%	300	150	95	95	95	95	95	150	300
50%	630	500	300	150	95	150	300	500	630
75%	1000	630	500	300	150	300	500	630	1000
100%	2x300	1000	630	500	300	500	630	1000	2x300

According to eq. (3.7), the resistance constitutes the main part of the differences between the losses, since the individual currents in the different cables are the same for all layouts at normal operation. For the normal operation in fig. 5.6, it is noticeable that the 0% layout has extremely high grid losses, which is caused by the small cross sections, shown in table 5.1. In addition, it is conspicuous that from cable B1 to D1 or B2 to D2 the losses decline with increasing redundancy, due to the bigger cross sections. One exception is the feeder cable A1 or A2, in which the 100% layout surpass suddenly the 75% and the 50%. The reason for this sharp increase of losses is the double cable. As mentioned before, the cable A1 and A2 in $\xi = 100\%$ consists of two cables. The total current is too high and can not be carried by the biggest cable with a cross section 1000 mm^2. Therefore the current is halved and cables with suitable sizes are chosen, which result in two times 300 mm^2. It is noticeable, that the total cross section of the two cables is smaller than 1000 mm^2. The reasons for that are explained more precisely in the discussion.

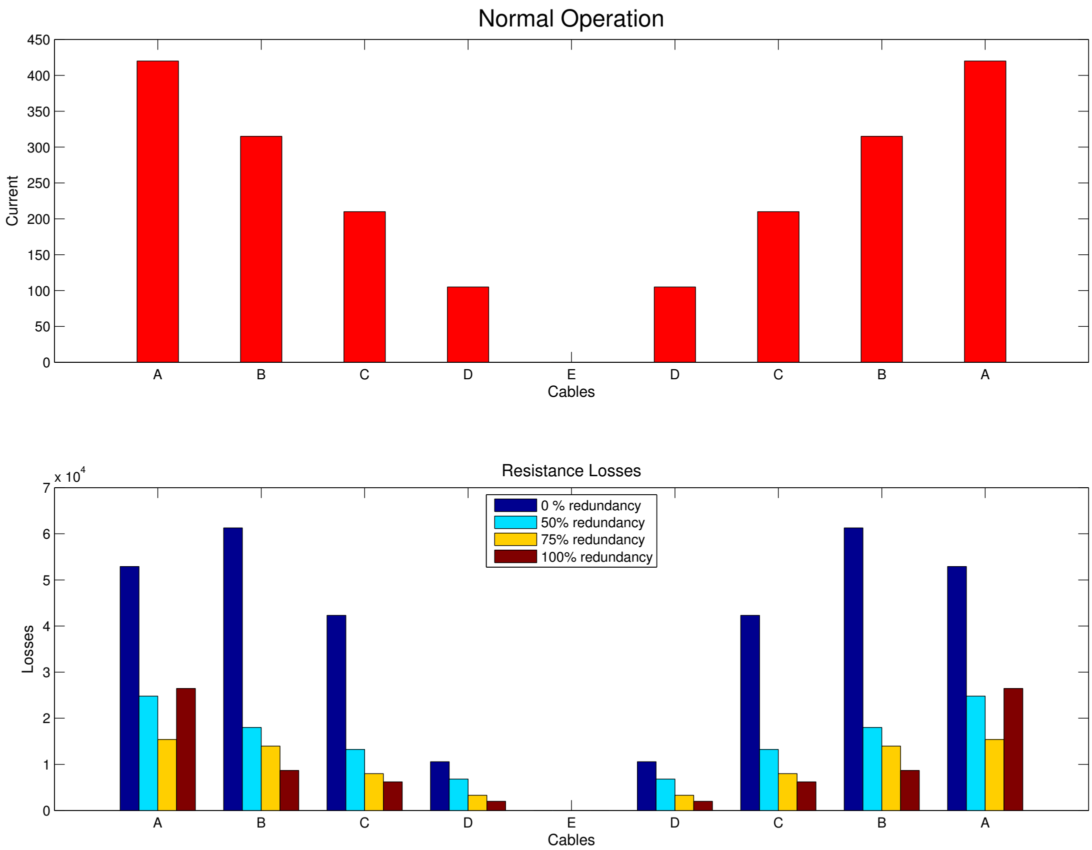


Figure 5.6: Currents and losses in normal operation

6

Discussion

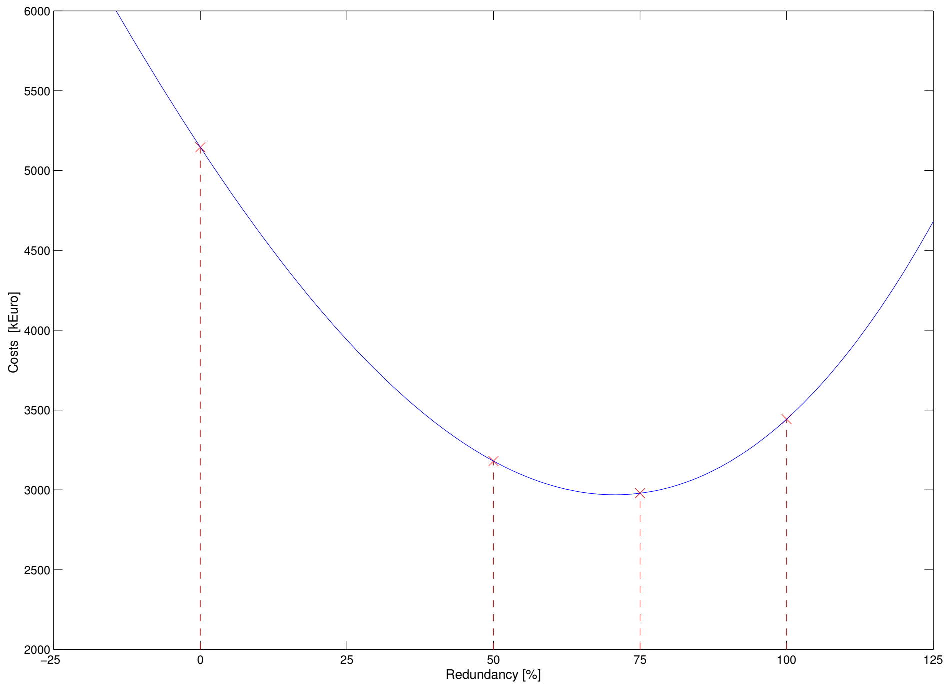
6.1 Discussion

The fig. 5.2, 5.3, 5.4 and 5.5 show six different layouts dependent on three different parameters. For a better comparison, the parameters are fixed to the default values, a wind speed of v = 9.7 m/s, an energy price of 0.25 €/kWh and installation costs of 100000 €/km. In the fig 6.1 the layouts with ξ = 0, 50, 75 and 100 are illustrated to clarify the results. A minimum can be seen around 70-75%. Important to notice is that the curve is only valid for the interval of 0 to 100.

The average wind speed layout is not taken into account, because the curve varies extremely by changing the wind speed. Besides, the reliability definition, compared to the other layouts, is too deviating to make an adequate comparison. A more precise discussion about this curve is made later in this section. Also, the radial layout is left out of consideration, because it is related to the 0% layout. As in fig. 6.1 can be seen, the interpolated curve presents a minimum cost at a redundancy around 70%. But since it is a spline and only four different cases are investigated, the real curve progression can not been defined. A fact to be emphasized, is the definition of redundancy. As mentioned previously, the redundancy has no uniform definition, but the results are extremely dependent on that. The clear meaning of redundancy in this thesis is discussed in the method chapter.

An interesting aspect is also the intersection between the $\xi = 75\%$ and $\xi = 100\%$ in fig 5.2, which denotes the electricity price, where the full redundancy design becomes more beneficial. However, in these results, the costs of ξ=100% increase faster and therefore full redundancy will never be the cheapest layout. Since it has no failure losses it should consequentially become cheaper at a certain energy price. But it has to be considered that the costs, caused by resistance losses carry more weight than outages. It can be

Figure 6.1: Graph of costs of the 0%, 50%, 75% and 100% layouts in the intverval of [0 100]



noted generally, that the higher the redundancy, the larger the cable sizes and therefore the lower the grid losses. However, this is not applicable for the full redundancy layout, since the A cables are divided. The resistances by ABB have no linear behavior and the same thermal resistance ($= 1^{\mathrm{Km}}/\mathrm{W}$) is assumed for all cables [15]. Smaller cables have a better heat dissipation and can therefore manage higher currents per mm^2. For this reason, half the current requires less than half the cross section. The cross sections are smaller and have therefore higher resistances and also higher losses. In this regard, dividing the current and calculating a suitable new cross section is pointless. This problem can be solved in better ways. The installation of two cables with the area of 1000 mm^2 would lower the grid losses but also rise the investment and installation costs immensely. Also a cable with a cross section greater than 1000 mm^2 could be produced to increase the possible maximum current in the cable.

It is important to point out that the thermal dependency influences the cable resistances extremely. In this thesis, the resistances for calculating the grid losses are used from the ABB cable data sheet and are kept constant during the entire calculations [15]. The seabed is assumed to be 10°C, which is beneficial regarding the maximum temperature in the cables. To adapt the parameter, a rating factor is added, which increases the current limit in a cable by 7% [15]. Apart from external impacts the cable heating in itself is also crucial. The electrical resistance is temperature dependent and increases when the current is rising. At high wind speeds, the current is higher and the cable becomes warmer. The changes in resistance can become rather significant, since the temperature difference ΔT in the conductor can rise up to 70 K. That would imply approximately a 27% higher resistance, but most of the times the currents are below the maximal cable current, what keeps the effect within limits. If instead of a constant resistance, a resistance as a function of the temperature is used, the losses at high wind speeds increase even more sharply. When comparing the different layouts, the slope of the curve changes in all cases, but with a different intensity. On the one hand, the current in the smaller cables reaches the limit faster, whereas on the other hand, the heat dissipation of the big cables is worse. For an exact investigation, this facts should be considered.

When taking a closer look at the average layout, it is difficult to draw a clear conclusion. Calculating a new cross section for each wind speed leads to an array of curves. The composition of those by hopping from one curve to another, results in this jagged appearance. Compared to the other graphs, it leaves doubts about its practical usability. However, it is reasonable to observe thoroughly the wind speeds for designing the cable sizes. In figures 5.3 and 5.4, the minimum occurs at around v = 10.5 m/s, which is in the range of average offshore wind speeds. Moreover, the curve shows the dependance of grid losses on cable sizes. Designing cables with suitable sizes for the expected power flow, creates unnecessary high ohmic losses in the most cases. This outcome fits the advice of ABB to avoid losses by using larger cable diameters [15] . Thus, saving in cable outlay costs returns a lower benefit of the produced wind power. This statement is however only valid up to a certain point, the minimum at v = 10.5 m/s. Above the minimum, a sharp increase occur due to the split into two lines. Dividing the current in two smaller cables, rises the resistance enormously and is also a sign for an inconvenient design. At the minimum, the AWS design overlaps with the 75% layout, the presumably most beneficial solution. Apparently, the cable sizes reach an optimum at this point, confirming the quality of the 75% redundancy solution. Consequently, the outcome of the fig. 6.1 is confirmed by the average layout design.

6.2 Conclusion

By implementing the three different cases, a remarkable difference in the financial losses turned out. Referring to the aim of the thesis and the corresponding eq. (4.2) in chapter 4, the statement that lowering redundancy results in less costs, is verified. In all studied cases the investigation results in $k<1$.

Inserting the default values from table 4.1, k results in

$$k = \frac{C_{\xi=75\%}}{C_{\xi=100\%}} = 0.87. \tag{6.1}$$

In summary, reducing the redundancy in a collection grid results in a greater benefit. For this thesis, a redundancy around 70-75% of reliability is the best solution.

6.3 Future Work

In this study only a few cases are picked out to mark the differences. For a full investigation, a reliable optimum for each individual wind speed and electricity price has to be found. For this purpose, a optimization in several dimensions could help to depict e.g. cross sections over price and wind speed at the same time. To find a general financial optimum, additional components have also to be considered, such as breakers, switchers and other power electronics. Also a sensitivity study is missing in this thesis to demonstrate possible changes if two cable break simultaneously or if a damage is too complicated and demand more repair time than expected. Currently, the energy sector focuses a lot on the development of the electrical grids. Several conferences and studies discuss the sophisticated integration of renewable energies and the appropriate grid capacities [28].

Bibliography

[1] P.-E. Morthorst, Wind energy the facts volume 2 - costs and prices, Tech. rep., EWEA, European Wind Energy Association (2004).

[2] Z. Chen, F. Blaabjerg, Wind farm - a power source in future power systems, Renewable and Sustainable Energy Reviews 13 (6-7) (2009) 1288–1300.

[3] A. Sannino, H. Breder, E. Nielsen, Reliability of collection grids for large offshore wind parks, in: Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference on, 2006, pp. 1 –6.

[4] M. Rock, . Parsons, Laura, Offhore Wind Energy, [online] Available at: <www.eesi.org/files/offshore_wind_101310.pdf>[Accessed 06 December 2012].

[5] Dong Energy, 2012, Walney - Offshore wind farms, Available at: <www.dongenergy.com/walney/Pagex/Index.aspx>, [Accessed 06 December 2012].

[6] Offshore Wind, 2012, [online] Available at <http://www.ewea.org/policy-issues/offshore/>, [Accessed 04 December 2012].

[7] B. Frankén, H. Breder, M. Dahlgren, E. Nielsen, Collection grid topologies for offshore wind parks, in: Electricity Distribution, 2005. CIRED 2005. 18th International Converence and Exhibition on, 2005.

[8] P.-E. Morthorst, S. Awerbuch, The economics of wind energy, Tech. rep., The European Wind Energy Association (March 2009).

[9] E. Eriksson, Wind farm layout - a reliability and investment analysis, Master's thesis, Uppsala Universitet, Teknisk- naturvetenskaplig fakultet UTH-enheten (October 2008).

[10] J. Yang, J. O'Reilly, J. E. Fetcher, Redundancy analysis of offshore wind farm collection and transmission systems, in: Sustainable Power Generation and Supply, 2009, SUPERGEN '09. International Conference on, 2009, pp. 1–7.

[11] Siemens, 2011, Juni, Prototyp der neuen getriebelosen 6-MW-Windturbine von Siemens geht in Testbetrieb [Online] Available at:, <http://www.siemens.com/press/de/pressemitteilungen/?press=/de/pressemitteilungen/2011/renewable_energy/ere201106070.htm>, [Accessed 02 December 2012].

[12] Siemens, Wind turbine with the world's largest rotor goes into operation, 2012, [online] Available at: <www.siemens.com/press/en/feature/2012/energy/2012-07-rotorblade.php>, [Accessed 04 December 2012].

[13] Siemens 2011, Siemens 6.0 MW Offshore Wind Turbine, [online] Available at: <http://www.energy.siemens.com/hq/pool/hq/power-generation/renewables/wind-power/6_MW_Brochure_Jan.2012.pdf>, [Accessed 04 December 2012].

[14] The World of Wind Atlases-Wind Atlases of the World, 2011, RisøNational Laboratory for Sustainable Energy, Technical University of Denmark, [online] Available at: <www.windatlas.dk>, [Accessed 04 December 2012].

[15] ABB, 2010, XLPE Land Cable System User's Guide, [online] Available at <www.05.abb.com>, [Accessed 05. December 2012].

[16] U. Gudmundsdottir, C. Bak, W. Wiechowski, Modeling of long high voltage ac underground cables, PhD with the Institute of Energy Technology, Aalborg University.

[17] Jimmy Ehnberg 2012, Chalmers University of technology, pers. comm., 14 September.

[18] ABB, 2012, XLPE Submarine Cable Systems - Attachment to XLPE Land Cable Systems - User's guide, [online] Available at: <www.abb.com/abblibrary/downloadcenter/?View=Result> [Accessed 04 December 2012].

[19] J. Ehnberg, Lektion kabelförläggning offshore - Elsystem för vindkraft, Högskolan Väst.

[20] Å. Larsson, O. Unosson, Offshore cable installation, Tech. Rep. 30, Vattenfall (January 2009).

[21] E. Hau, Wind turbines - Fundamentals, Technologies, Applications, Economics, Berlin : Springer, cop.2000, 2000.

[22] The free dictionary, 2012, [online] Available at: <www.thefreedictionary.com>, [Accessed 03 December 2012].

[23] J. Seguro, T. Lambert, Modern estimation of the parameters of the weibull distribution for wind energy analysis, Journal of Wind Engineering and Industrial Aerodynamics 85 (1) (2000) 75–84.

[24] R. Gasch, J. Twele, Windkraftanlagen: Grundlagen, Entwurf, Planung und Betrieb, 6th Edition, Vieweg + Teubner, 2010.

[25] H.-J. Wagner, J. Mathur, Physics of wind energy, in: Introduction to Wind Energy Systems, Green Energy and Technology, Springer Berlin Heidelberg, 2009, pp. 17–28.

[26] N. Negra, O. Holmstrøm, B. Bak-Jensen, P. Sorensen, Aspects of relevance in offshore wind farm reliability assessment, Energy Conversion, IEEE Transactions on 22 (1) (2007) 159–166.

[27] Europeans Energy Portal, 2012, [online] Available at <www.energy.eu> [Accessed 04 December 2012].

[28] Wind Energy The Facts Part II - Grid Integration, [online] Available at <www.wind-energy-the-facts.org/documents/download/Chapter2.pdf> [Accessed 07 December 2012].