Master's thesis

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Simplified Loss Model for Offshore Wind Farms

Master's thesis in Energy and Environmental Engineering
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Abstract

In this master's thesis a standardized loss model to analyze electrical losses in array cables for HVAC offshore wind farm grid is presented. Such a loss model can be used for more accurate levelized cost of energy(LCoE) calculations and contribute for validation of new technologies for offshore wind.

A method for calculating power losses in array cables is made in MATLAB based on the standard IEC current rating equations(IEC 60287). The presented model is bench marked with real data from an operating offshore wind farm in the North Sea and results show that the loss model simulates electrical losses in the array cables with an accuracy of 3.6 %. However, further work for the presented loss model is suggested in order to validate the loss model with more confidence.

Sammendrag

Denne masteroppgaven presenterer en standardisert tapsmodell for å analysere de elektriske tapene i fordelingskablene i HVAC offshore vindanlegg. En slik modell kan brukes for mer korrekte marginalkostnad(LCoE) utregninger og bidra til å validere nye teknologier for offshore vind.

En metode for å kalkulere de elektriske tapene i fordelingskablene er blitt laget i MATLAB basert på de standardiserte ligningene for merkestrøm(IEC 60287), utarbeidet av Internationale Elektrotekniske Kommisjons(IEC). Den presenterte modellen er blitt testet mot målte data fra en operativ offshore vind farm i Nordsjøen. Resultater viser at tapsmodellen simulerer de elektriske tapene i fordelingskablene med en nøyaktighet på 3.6%. Videre arbeid for å forbedre tapsmodellen er presentert for å kunne si med sikkerhet at modellen kan simulerer tapene i fordelingskablene i en offshore vind park.

Acknowledgements

I would first like to thank my supervisor Pål Keim Olsen of the Faculty of Information Technology and Electrical Engineering at Norwegian University of Science and Technology(NTNU). Pål has always helped me whenever I ran into a trouble spot or had a question about my writing. He allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed or I asked for it.

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Author

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Nomenclature

G Geometric factor for cables[-]

G' Geometric factor for belted cables[-]

I_1 Primary side current for wind turbine transformer[A]

I_b Cable design current[A]

I_z Sustained current rating of cable current[A]

K Screening Factor[-]

$P_{loadloss}$ Load loss for wind turbine transformer[W]

$R = R_{AC}$ A.C resistance of conductor[$\frac{\Omega}{m}$]

R_{DC} DC resistance[$\frac{\Omega}{m}$]

R_{sc1} Primary side short circuit resistance for turbine transformer[Ω]

R_{th} Specific thermal resistance [$\frac{K.m}{W}$]

S Cross section area of material [m^2]

$S_{transformer}$ Rated apparent power of transformer[W]

T_1 Thermal resistance between conductor and sheath[$\frac{K.m}{m}$]

T_2 Thermal resistance between sheath and armour[$\frac{K.m}{m}$]

T_a Ambient temperature[$^\circ$C]

T_c Conductor(insulation limiting temperature[$^\circ$C]

W_d Dielectric losses per unit length per phase[$\frac{W}{m}$]

ΔT Temperature difference driving heath flow[$^\circ$C]

Δx Distance that heat flow[m]

α_{20} Temperature coefficient of resistance of material[-]

γ_P Proximity effect factor [-]

γ_S Skin effect factor[-]

λ_1 ratio of the total losses in matallic sheath and armour respectively to the total conductor losses(or losses in on sheath or armour to the losses in one conductor) [-]

λ_1'' eddy currents, ratio of the losses in one sheath caused by eddy currents to the losses in on conductor [-]

λ_1' circulating currents, ratio of the losses i one sheath caused by circulating currents in the sheath o the losses in one conductor [-]

ρ_T Thermal resistivity of material [$\frac{K.m}{m}$]

ρ_{20} electrical resistivity of material[[$\Omega.m$]

θ_{ar} Temperature of armour[$^\circ C$]

θ_{cond} Temperature in cable conductor[$^\circ C$]

θ_{sc} Temperature of sheath[$^\circ C$]

d Mean diameter of sheath[mm]

k Material property of thermal conductivity

$k_{transformer}$ transformer no load constant[-]

n_{cond} Number of conductors in a cable[-]

s Axial separation of conductors[mm]

$tan\delta$ Loss Factor for dielectric calculations[Ω/m]

A Area normal to heat flow[m^2]

I Cable current in one conductor[I]

P Electrical power transimitted in cable[W]

Q Heat flow[$\frac{W}{m^2}$]

R Resistance for conductor[Ω]

R_A Resistance for armour[Ω/m]

R_S Resistance for sheath[Ω/m]

V Volt[V]

W Watts[W]

Abbreviation

BMUs	=	bulk metering units.
CF	=	capacity factor.
FEM	=	finite element method.
LCoE	=	Levelized Cost of Energy.
modHVDC	=	Modelar High Voltage Direct Current.
NTNU	=	Norwegian University of Technology and Sience.
OWFs	=	Offshore Wind Farms.
WF!	=	wind farm 1.
WTs	=	wind turbines.
XPLE	=	Cross-linked polyethylene.

1 Introduction

1.1 Background and motivation

Shifting our energy systems away from fossil fuels will require significant increase from renewable energy resources. A fair share of this production is believed to come from Offshore Wind Farms (OWFs), some expect production in 2030 to reach 129[GW][3]. The same forecast points out that the offshore wind market will be truly global by 2030, with Europa and Asia in front. Equinor is opening new offices in Japan to exploit new markets[4] and their new floating offshore wind farm, Hywind, is performing uplifting results[5]. With higher market penetration, developing technologies and falling prices, offshore wind has proved to be competitive to other energy resources, and the first offshore wind farm without subsidies is to be built in the Netherlands [6].

When investing in energy facilities, e.g offshore wind farms, one has to know the minimum price at which electricity must be sold to recoup the lifetime costs of the system, known as the Levelized Cost of Energy (LCoE). LCoE allows comparison of different methods of electricity generation on a consistent basis and is therefore suited to guide discussions and decision making. Electrical losses are important in LCoE calculations as it effects the annual production in an offshore wind farm, see figure 1. One trend in the offshore wind market is longer distances from shore and larger turbines [7]. Larger turbines could mean a reduction of losses since one needs fewer turbines, but longer cables will in most cases increase the losses and thus estimating these cable losses accurately will contribute to more accurate LCoE calculations, see figure 1.

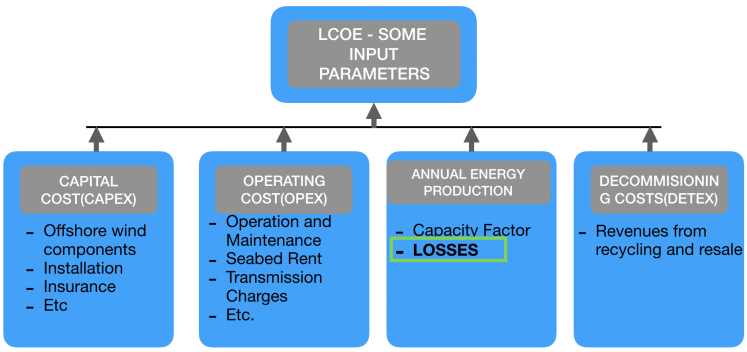

Figure 1: Some LCOE input parameters, losses affects the annual production of the offshore WF

Estimation of losses can also be used to validate new technologies for offshore wind, such as the new Modelar High Voltage Direct Current (modHVDC) generator under development at Norwegian University of Technology and Sience (NTNU)[2], or new type of cables in the offshore wind farm system. Knowing losses in an offshore wind farm with and without, for example, this new type of technology, will factor in for the discussion considering such investments. New technologies are often associated with high investment costs and LCoE can help forecast if the higher investment is worth the extra cost in the long run.

1.2 Objective

The Objective for this master thesis is to make a *simplified model for offshore wind farms that calculates electrical losses over longer time periods.*

1.2.1 Standardized Loss Model

Today there is no standard way of calculating losses in a offshore wind farm. This could potentially mean that 2 contractors end up with different loss predictions for the same system, or that losses for one system are lower because they're simulating with a less accurate loss model. This creates a imbalance when comparing different wind farm topologies and their LCoEs. Hence the loss calculations in this master thesis will be based on the standard IEC 60287 equations.

1.3 Scope, Limitations and Problem definition

1.3.1 Scope

LCoE calculations for a OWF requires a loss model including all components in the system. This a complex task, especially if one wants to model the losses accurately. Thus the focus in this master thesis will be on a smaller part of the system, the array cable system, see figure 2.

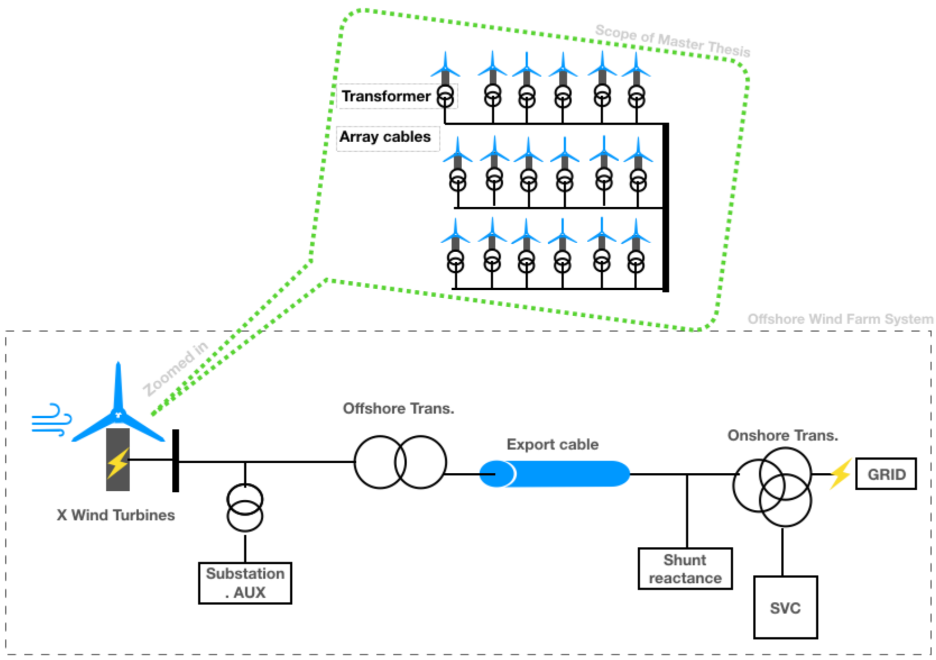

Figure 2: Scope of Master Thesis

1.3.2 Limitations

Available data

The loss model should over a long time period be compared with real data from an operating offshore wind farm. This allows:

- comparison between simulated and real losses over a long time periods
- validating accuracy of the presented loss model

Collecting and analysing data for one year has proven to be time consuming, reasons being half-automated systems on offshore wind farm side for data collection. Especially the output measured data had to be modified in order to use if for analytical purposes. In addition wind farms are often owned by different companies and data authorization is time consuming. Thus data for one month for array cables in a HVAC offshore wind farm has been collected. The data also include turbine transformer and so turbine transformer losses need to be included in the loss model, see figure 2.

1.3.3 Problem definition

Develop a standardized loss model to analyze electrical losses in array cables for HVAC offshore wind farm grid, and validate that loss model with real data from an operating offshore wind farm for a full month.

1.4 Structure of master thesis

- Introduction - short introduction in which the reasoning for solving the problem is described and what the scope of the project thesis is.
- Literature review - reviewing some relevant work with regards to the master thesis.
- Theory - Relevant theory for master thesis.
- Method - Description and limitation of the method used in master thesis
- Results - Results presented.
- Discussion - Results, assumptions and limitations discussed.
- Conclusion and further work - Short conclusion and suggestions for further work.

2 Background Studies

Load capability [8] and low loss cable systems [9] have been studied for a while, but looking at power losses for offshore wind farms is not yet deeply explored. However, some studies have addressed the topic and a selection of this work is presented in this chapter.

2.1 Loses in Offshore Wind Farm Systems

Losses in different offshore wind farm typologies has been investigated in [10]. The wind farm typologies are divided after how the array cable network is laid out and the wind farm system consists of 100 turbines connected to an offshore substation. The main focus of this work has been on the losses and cost associated with the converters for the turbines in the system, but some loss calculation for the array cables has been done. Annual losses have been estimated for array cable to about 10-45 [GWh] depending on the wind farm topology. The cables accounts for a smaller part of the total offshore wind farm loss, which is expected considering only array cables have been included in the wind farm model.

Losses in transmission system (HVAC and HVDC) for offshore wind farm have been carried out in [11]. Losses in transmission cable has been calculated for wind farms with different rating and various distances to shore. The transmission cables, account for 87 % of the losses in the system with 100 km cables and 500 MW wind farm. Important to note that losses for transmission cables will be greater than for array cables, primary because of the cable length but also because of charging currents. Transmission losses are calculated to be about 1.98 - 2.39 % of the annual wind farm production.

Reference [12] points out that electrical losses in onshore and offshore wind farms usually are calculated from the estimated yearly capacity factor (CF), which is obtained with long-term wind conditions and the rated power of the wind farm. These estimated losses are used for wind farm design-outlay and used to foresee the net generation of the wind farm. With this method there is no correlation between electrical losses and actually power flow in the system, [12], and they prove that this method is not suitable to forecast losses in a wind farm as actual losses for a particular WF infrastructure can be lower or higher than the losses at rated power[12]. Using losses at rated power to calculate losses for a wind farm can effect the LCoE of the wind farm as experienced power losses differs for the once calculated at rated power [12]. It is important to note that losses in [12] is simulated for different Weibull distributions and not for wind farm operation over longer time periods, thus not capturing the longtime losses in the wind farm. Also the model is based on onshore wind farms but nerveless their results are of interest as onshore and offshore wind farms share a lot of the same characteristics, e.g array cables to connect the wind turbines (WTs) and WT transformers to step up the voltage.

A model of a offshore wind farm(including array cables, substation transformer, reactive power compensation, export cable and onshore transformer) has been developed in

Simulink/Matlab with the aim of calculating the LCoE with system losses [2]. Three different systems were evaluated; HVAC, HVDC and modHVDC. Weibull-distributed wind speeds were used as input, just as in [12]. The models developed is ridged, meaning changing layout and parameters is difficult or impossible once Simulink is running. This is due to block configuration in Simulink. From their HVAC simulation results one can see that the largest contributor to power losses are cables(transmission and inter-array cables). This is opposite of the result in [10] and shows the impact export cable has on the total power losses in an offshore wind farm. Power factor(PF) in [2] is set to 1, making the model a DC model. Lost power production due to unavailability of WTs is included in [2], but in a simple manner. Simulations are run for one full year and their results have been compared to a real offshore wind farm. Results show a simulated production of 1,964 [TWh], which is 15,53 % higher when compared to actually energy produced of 1,7 [TWh] [2].

2.2 Cables Loss Calculations

Reference [13] presents an overview of work done to identify areas of conservatism within the standard current rating approach(IEC 60287), and to quantify the impact they have on the current rating of the cable. They sought to better understand current depended losses in export cable and specifically those associated with armor losses. Reference [13] also investigates the time dependent nature of conductor temperature. The temperature in the cable is important as it affects the resistance and thus the cable losses. Their model uses electrical resistances calculated from the standard IEC equations, with variable temperature for conductor, sheath and armour. Sheath loss are assumed to be entirely due to circulating currents and armour losses are primarily magnetic losses, assuming no circulating current. Both sheath and armour loss is calculated with both IEC equations and modified IEC equations based on corrections from measured armour and sheath loss. Results show that both armour and sheath temperatures are lower with IEC model compared to measured data, [13]. Also the magnitude of armour loss is much higher with IEC equations compared to measured losses, [14]. Voltage dependent loss was not simulated but accounted for in their final models, [13].

Losses for a whole wind farm are calculated in [12]. For the cable losses only the resistance of the copper conductor has been used, neglecting both armour and sheath losses. A mean conductor size has been used for the array cables, usually two or three different sizes are being used because power transmitted increases down the array cable line as more WTs are connected. Some offshore WTs can regulate their reactive power interchanged with the grid, [15], thus contributing to increased cable current. Reference [12] simplifies their model by setting power factor in the cable to one, neglecting reactive power contribution to the current. This assumption is validated through classical power flow analysis simulations and results show minimal increase in cable current due to reactive power from WTs, [12].

Cable loss calculations are performed based on Brakelmann [16] in reference [11]. Their loss calculations take into account the current distribution along cable and temperature dependence for their equations. The cable loss is calculated with respect to the nominal total cable loss, which is not a accurate way of doing it according to [12]. The dielectric loss in the cable is included which is reasonable due to the high voltages(132-

400[kV]).

AC cables were modelled using a π - section equivalent circuit in [10], thus including charging current loss model in their model. Also they assume any reactive power requirements of the cable being delivered by power electronic converters. AC cable resistance was calculated from conductor area and skin effect was included. No sheath and armour loss were implemented and no thermal dependency was included in [10], which could be a potential affected their cable losses.

2.3 Loss Simulations

2.3.1 Finite Element Method - FEM

In reference [13] a finite element method (FEM) modelling approach is chosen. This includes solving the equations for the cable loss numerical for finite elements of the cable and then assemble it into a larger system of equations that models the entire cable. Thus being able to solve more complex equations and making e.g temperature field plots for cross section of the cable possible. This way of modeling requires a lot of data power and is time consuming. FEM is often used for transient response analysis. In this master thesis the longer time period effects of losses are of interest and so an analytical approach is favoured over FEM. Most of the other work in this chapter has chosen an analytical approach for their loss simulations.

2.4 Summary

As seen in this chapter studies have been carried out on losses in offshore wind farms. A common denominator for almost all of the work is that it has not been validated with real data. Different simulations and loss methods have been exploited but almost none of them have been validated with real data from an operating wind farm, reference [2]is an exception, and that work shows how difficult it is to accurately simulate the losses in an offshore wind farm. Reference [13] has compared results with measured data from a test rig, but not with real data from an operating offshore wind farm. Furthermore none of the studies have focused on only the array cable system over a long time period with the loss model detail and abstractions presented in this master thesis.

3 Theory

This chapter presents relevant theory for the master thesis including theory on thermal calculations and theory for analytical equations used to determine cable losses in the array cables. As mentioned the Loss Model also includes WT transformers so relevant theory for calculating transformer losses is shown.

3.1 Cable Overview

Power cables are made to transfer large amounts of energy. It needs to withstand high currents and voltages while also being mechanically strong. They can either be underground laying or overhead hanging. A typical power cable is shown in figure 3. Conductor and insulation screens can be added for high voltage cables. This screen will be an extra layer around the conductor and around the insulation. The extra screen is added to prevent air filled cavities which would lead to electric discharges [1]. A conductor can either be circular or shaped depending on application. It's normal to use stranded conductors, which mean that many individual wires are bound together to form a conductor. Stranding makes the cable more flexible and lowers the overall inductance.

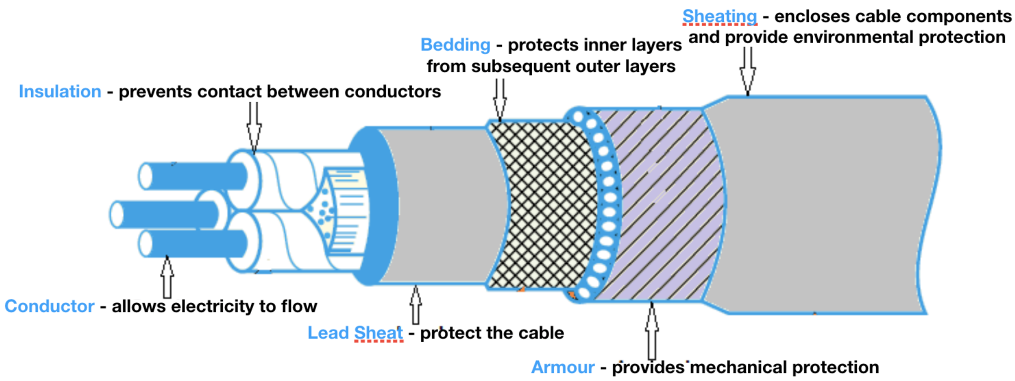

Figure 3: Cable Structure Layers [1]

3.2 Thermal Calculations

3.2.1 Thermal Model of a Cable

Heat is generated in a cable for various reasons - conductor loss(IR^2 loss), dielectric loss, sheath loss, armour loss and direct solar radiation or high temperature ambient sources, see figure 4. Some or all of this heat is dissipated through the cable insulation, bedding, serving and to the surrounding medium. In thermal equilibrium, all heat flows between different layers in the cable are balanced, and the temperature of the conductor is at the maximum permitted for the insulation. At equilibrium the cable is loaded at its maximum rated current.

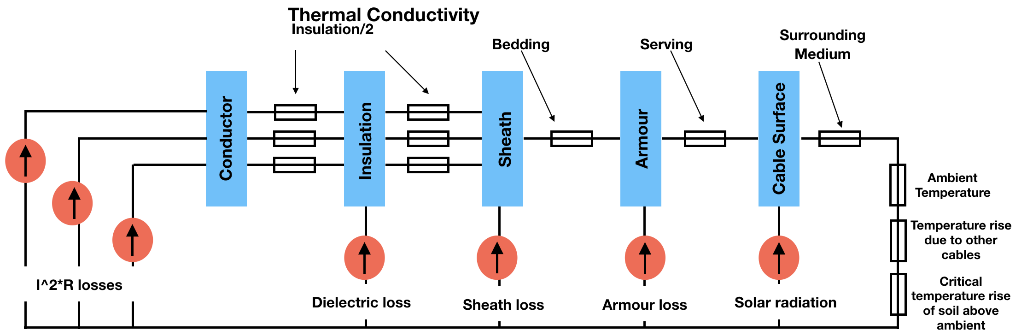

Figure 4: Thermal Model of a Cable[1]

3.2.2 Temperature

Temperature is important for resistance calculations and thus cable losses, see section 3.3. As seen in chapter 4 the temperature for conductor, sheath and armour can be calculated and set to a constant value, or be modeled as a variable. Either way the temperature for each cable layer follows the same equations presented below.

Conductor Temperature

Temperature[°C] in copper conductor in cable is a function of electrical power[W] loading of the cable, greater electrical power loading of cable implies higher temperature in copper conductor. Since the relation between electrical power and current is:

$$P = I^2 \cdot R \tag{3.1}$$

where

P = electrical power transmitted in cable [W]
I = Cable current [A]
R = resistance for conductor[Ω]

the conductor operating temperature can be found from equation 3.2 and graphic representation in figure 5:

$$\theta_{cond} = (\frac{I_b}{I_c})^2 \cdot (T_c - T_a) + T_a \tag{3.2}$$

where

θ_{cond} = temperature in cable conductor [°C]
I_b = cable design current [A]
I_z = sustained current rating of cable [A]
T_a = ambient temperature [°C]
T_c = conductor(insulation) limiting temperature [°C]

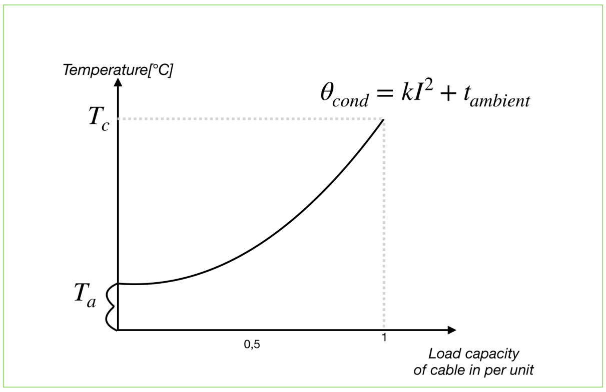

Figure 5: Conductor Temperature

Sheath Temperature

Sheath temperature is calculated based on IEC 60287-1-1:2016+AMD1:2014 CVS. Operating temperature of the sheath is given by:

$$\theta_{sc} = \theta_{cond} - (I^2R + 0.5W_d)T_1 \quad [°C] \tag{3.3}$$

where

θ_{sc} = temperature of sheath [°C]
θ_{cond} = temperature of conductor [°C]
I = current in one conductor(r.m.s value) [A]
R = A.C resistance of conductor [Ω/m]
W_d = dielectric losses per unit length per phase[W/m]
T_1 = thermal resistance between conductor and sheath [K.m/W]

Armour Temperature

Armour temperature is calculated based on IEC 60287-1-1:2016+AMD1:2014 CVS. Operating temperature of the armour is given by:

$$\theta_{ar} = \theta - ((I^2R + 0.5W_d)T_1 + (I^2R(1 + \lambda_1) + W_d)nT_2) \quad [°C] \tag{3.4}$$

where

θ_{ar} = temperature of armour [°C]
λ_1 = ratio of the total losses in matallic sheath and armour respectively to the total conductor losses(or losses in on sheath or armour to the losses in one conductor) [-]
n_{cond} = number of conductors in a cable [-]
T_2 = thermal resistance between sheath and armour [K.m/W]

3.2.3 Thermal Resistance

Thermal resistance is used in thermal circuits to analyze heat transfers and is based on an analogy with Ohms law: $V = I * R_{elec}$. In Ohms law the voltage drive a current of magnitude I. The amount of current that flows in the circuit is inversely proportional to the resistance for a given voltage. For one-dimensional, steady-state heat transfer problems with no internal heat generation, the heat flow is given by:

$$Q = k\,A\,\frac{\Delta T}{\Delta x} \tag{3.5}$$

where

Q = heat flow $[\frac{W}{m^2}]$
A = area normal to the heat flow $[m^2]$
ΔT = temperature difference driving heath flow [°C]
Δx = distance that the heat flow [m]
k = material property of thermal conductivity

If rearranged one can write temperature difference as:

$$\Delta T = Q\,R_{th} \tag{3.6}$$

where

$$R_{th} = \frac{\Delta x}{k\,A} \tag{3.7}$$

where

R_{th} = Thermal resistance.

Thermal resistance is used in standard IEC calculations for sheath and armour losses. Equation 3.6 is similar to Ohms law for electrical circuits and describe how a temperature difference drives a heat flow, see figure 6

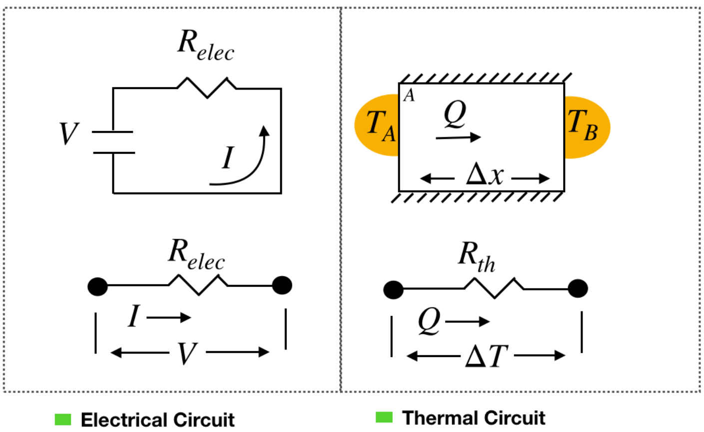

Figure 6: Thermal and electrical equivalent circuits

Thermal resistance calculations is based on standard IEC 60287-2-1:2015 RLV.

3.2.4 Thermal Resistance between conductor and sheath - T_1

Thermal resistance for three-core cables with circular conductors is calculated as:

$$T_1 = K \frac{\rho_T}{2\pi} G \; [\frac{K.m}{W}] \tag{3.8}$$

where

K = screening factor.
ρ_T = thermal resistivity of material [K.m/W]
G = geometric factor

Calculations for ρ_T, K and G can be found in appendix, chapter 8

3.2.5 Thermal Resistance between sheath and armour - T_2

Thermal resistance for three-core cable where each core has an individual sheath is given by:

$$T_2 = \frac{\rho_T}{6\pi} G' \; [\frac{K.m}{W}] \tag{3.9}$$

Calculations for ρ_T and G' can be found in appendix, chapter 8

3.3 Calculating Losses

Losses in array cables(and electrical system in general) represent energy that dissipates from the system, often in terms of heat. Losses associated with grid components and infrastructure can be divided into load and no-load losses. The former depend on the amount of current flowing through the system and the latter are voltage dependent. For this master thesis the voltage and frequency of the array cables is assumed to be constant.

3.3.1 Load Loss

- Joule losses or IR^2-losses. These losses are current driven and increases with loading of cable.

3.3.2 No Load Loss

- Hysteries losses. Occurs in magnetic materials due to fluctuating magnetic flux. Energy is lost as heat due to the need of reversing the magnetization of the material.
- Eddy current losses. Currents due to fluctuating magnetic field induced in conductors are called Eddy currents. These currents flow perpendicular to the magnetic field and causes joule losses in the material. Eddy currents can also effect the proximity effect. Proximity effect changes the effective cross-section of an AC conductor.
- Dielectric losses. Voltage dependent loss present in dielectric materials.
- Charging current losses. A cable can be modeled as a resistance, capacitance and inductance. Both capacitance and inductance require reactive power(either consuming or producing reactive power). This in turn causes additional IR^2-losses.

3.3.3 Transformer Loss

3.3.4 Transformer losses

A transformer draws current even if there is no load connected to it, i.e open circuit as seen in figure 7. These no-load losses are eddy currents and hysteresis losses. Eddy currents are swirling currents in a conductor induced by a changing magnetic field. These currents heat up the conductor and thereby represent joule losses. Hysteresis loss is due to the magnetization and demagnetization of the core in the transformer as current flows in forward and reverse directions. A transformer will also have joule losses in the copper windings on both side of the transformer, this loss is therefore current dependent(load dependent). In figure 7 a simplified transformer equivalent circuit is described. Here R_0 represents the current dependent copper losses and R_{series} represents hysteresis and eddy current losses. All reactants are neglected as one assumes that they represent small losses compared to the restive losses [17]. See appendix, chapter 8, for calculations of transformer losses.

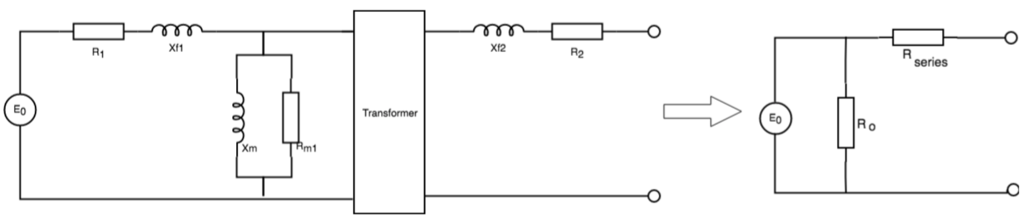

Figure 7: Transformer equivalent circuit [2]

The loss calculation for the transformer is based on the equations given in [2].

Load Loss Calculations for Transformer

$$P_{loadloss} = 3 \cdot I_1^2 \cdot R_{sc1} \tag{3.10}$$

where

R_{sc1} = primary side short circuit resistance[Ω]
I_1 = primary side current [A]

No-Load loss Calculations for Transformer

No-load losses are calculated as a percentage of the apparent power of the transformer.

$$P_{no-loadtransformer} = S_{transformer} \cdot k_{transformer} \tag{3.11}$$

where

$S_{transformer}$ = rated apparent power of transformer
$k_{transformer}$ = transformer no load constant, see appendix for calculation.

3.3.5 Cable Losses

Losses can occur in different parts of the conductor. There are four groups of electrical losses associated with power transfer in power cables[14].

1. Losses occurring in the conductor itself. I^2R joule losses(load loss)
2. Induced losses in the metallic screen of each cable
3. Induces losses in the armour of the cable
4. Voltage dependent losses in the insulation of the cable. Dielectric losses due to varying magnetic field (no-load loss). These will not be significant for array cable in wind farm but be significant for export cable.

In terms of the importance to the overall cable losses, the prioritized order of calculating losses is normally: Conductor Loss > Sheath Loss > Armour Loss > Dielectric Loss. There are some cables with low armour loss where this might not be completely true[14]. The armour losses are also the loss which are subject to the greatest uncertainty, as seen in[13].

Another important factor to note for long HVAC cables is that the conductor current, that drives most of the losses mentioned above, will not be constant along the length of the export cable but influenced by how the reactive power compensation is arranged. This means the cable will operate at slightly different temperatures, as the amount of current dictates the temperature of the cable. Usually more current implies a temperature rise in the cable, which gives higher losses as resistance increases.

DC Resistance - Resistance without Proximity and Skin Effect

For any given material the DC resistance can be calculated as:

$$R_{DC} = \frac{\rho_{20}}{S} \quad [\Omega] \tag{3.12}$$

where

R_{DC} = DC resistance of material $[\Omega.m^{-}1]$
ρ_{20} = electrical resistivity of material at 20 °C [Ω.m]
S = cross sectional area of material$[m^2]$ or $[1e^{-}6mm^2]$

As mention above the temperature in a cable is not constant, see figure 5. Thus the DC resistance of a conductor need to iterative be calculated[18] as:

$$R_t = R_{20}[1 + \alpha_{20}(t - 20)] \quad [\Omega/m] \tag{3.13}$$

where

R_t = resistance of conductor at t [°C]
R_{20} = resistance of conductor at [20 °C]
t = conductor temperature [°C]
α_{20} = temperature coefficient of resistance of material at 20°C[-]

AC resistance - Resistance with Proximity and Skin Effect

The AC resistance per unit length of a conductors is given by the following equation:

$$R_{AC} = R_{DC}[1 + \gamma_S + \gamma_P] \quad [\Omega] \tag{3.14}$$

where

R_{AC} = the AC resistance of the conductor [Ω]
R_{DC} = the DC resistance of the conductor [Ω]
γ_S = skin effect factor [-]
γ_P = proximity effect factor [-]

Hence the AC resistance of a cable is always higher than the DC resistance and the primary reasons for this is *skin effect* and *proximity effect*. While the above equations for DC and AC resistance are straight forward, the skin effect and proximity effect are a little more complex and calculations can be found in Appendix. Note that both skin effect and proximity effect include the resistance in their calculations and therefore their both dependent on temperature as resistance is temperature dependent.

Copper Losses

See appendix, chapter 8, for copper loss(joule loss) calculations.

Sheath Losses

Power loss in sheath consists of losses caused by circulating currents and eddy currents.

$$\lambda_1 = \lambda_1^{'} + \lambda_1^{''} \quad [-] \tag{3.15}$$

where

λ_1 = sheat loss factor [-]
$\lambda_1^{'}$ = circulating currents, ratio of the losses i one sheath caused by circulating currents in the sheath o the losses in one conductor [-]
$\lambda_1^{''}$ = eddy currents, ratio of the losses in one sheath caused by eddy currents to the losses in on conductor [-]

Sheath loss is expressed as a loss factor of the total loss in the conductor(s)

$$W_s = W_c\lambda_1 \quad [W] \tag{3.16}$$

where

W_s = sheath loss [W]
W_c = conductor losses [W]

For different type of cables there are different type of sheath loss factor(λ_1) calculations. For three-core cable of which each core has a spearate lead sheath $\lambda_1^{''}$ is zero and the loss factor for the sheath is given by:

$$\lambda_1^{'} = \frac{R_s}{R}\frac{1.5}{1+(\frac{R_s}{X})^2} \quad [-] \tag{3.17}$$

where

$X = 2\omega 10^{-7} \ln\frac{2s}{d}$ [Ω/m]
s = axial separation of conductors [mm]
d = mean diameter of sheath [mm]
R_s = A.C resistance of cable sheath [Ω/m]

Resistance of sheath is given by;

$$R_s = R_{SO}[1 + \alpha_{20}(t - 20)] \quad [\Omega/m] \tag{3.18}$$

where

R_{SO} = resistance of cable sheath at 20 °C [Ω/m]

Armour Losses

For three-core cables - steel wire armour the armour loss factor is calculated as:

$$\lambda_2 = 1.23\frac{R_A}{R}(\frac{2c}{d_A})^2\frac{1}{(\frac{2.77R_A 10^6}{\omega})^2+1} \quad [-] \tag{3.19}$$

where

R_A = resistance of armour [Ω/m]]
d_A = mean diameter of armour [mm]
c = distance between the axis of a conductor and the cable centre [mm]

The armour loss is then given by:

$$W_a = W_c\lambda_2 \quad [W] \tag{3.20}$$

where

W_a = armour loss [W]
W_c = conductor losses [W]

Dielectric Loss

Insulation, e.g Cross-linked polyethylene (XPLE) is a dielectric material and when subjected to a varying electric field there will be energy losses. Reason is that the varying field causes small realignments of weakly bonded molecules, which leads to the production of heat. For lower voltages the loss is usually insignificant, see chapter 8.

Dielectric loss is dependent on the loss tangent, or tan delta(tanδ). In simple the tan delta is is the angle between the varying vector field and the loss components of the material. Higher values of tanδ implies higher dielectric loss. Tanδ used for simulations in this matster thesis can be found in appendix, chapter 8. Note that dielectric loss only occurs for a.c cables due to the alternating field.

Dielectric loss per unit length in each phase is given by:

$$W_d = \omega\ C\ U_o^2\ tan\delta \quad [F/m] \tag{3.21}$$

where

$\omega = 2\pi f$
C = capacitance per unit length [F/m]
U_0 = voltage to earth [V]
tanδ = loss factor, see appendix.

Capacitance for circular conductors is given by:

$$C = \frac{\epsilon}{18ln\frac{D_i}{d_c}}10^-9 \quad [F/m] \tag{3.22}$$

where

ϵ = relative permittivity of the insulation, see appendix.
D_i = external diameter of the insulation(excluding screen) [mm]
d_c = diameter of conductor, including screen, if any [mm]

4 Model/Methodology

As described earlier the main objective is to make a loss model that can predict losses in array cables for an offshore wind farm over a longer time period. In this chapter the methodology of the model is presented. The model is built on analytical equations from IEC, described in chapter 3, and is not made with the intention of capturing the accurate loss at any instantaneous time but rather estimating the losses over a longer time period.

4.1 Wind Farms

4.1.1 General Offshore Wind Farms

Most offshore wind farm consist of elements shown in figure 8. Offshore wind farms differs from onshore wind farms because the power is generated far away from the electrical grid. This requires long export cables from the offshore substation to shore, see figure 8. As explained in chapter 1 the model presented later in this chapter will consist of turbine transformers and array cables, see red box in figure 8.

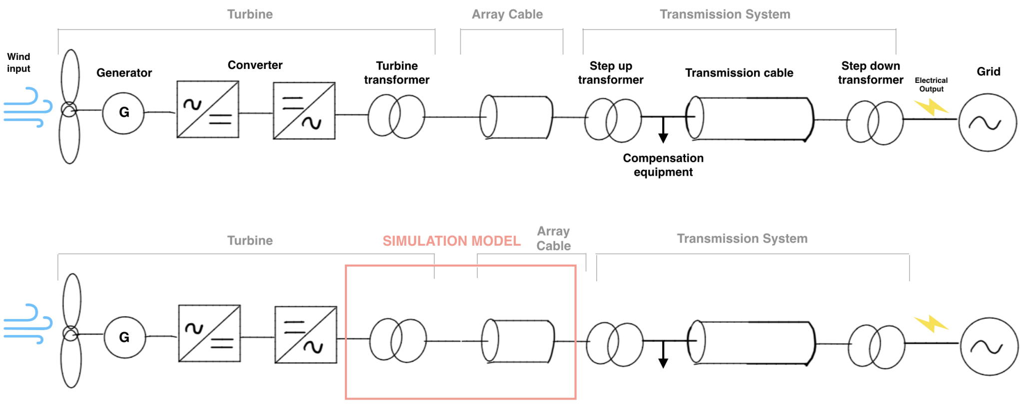

Figure 8: Overview of components in a offshore wind farm model. Red box = simulation model for master thesis

4.1.2 Wind Farm Layout and Data Availability

The model presented in this chapter will be bench marked with a real wind farm situated in the North Sea where array cables are about 20-40 m depth. Due to confidentiality the name of the offshore wind farm and its owner will be held anonymous and referred to as wind farm 1 (WF!) and Company X.

Wind Farm 1 consists of 4 bulk metering units (BMUs), which each contain 3 strings of 5-6 turbines, see figure 9 . Each BMU can be controlled separately and there is 2 export cables from the offshore substation to shore, thus the system has high degree of redundancy. The green points in figure 9 shows where real data is fetched. It is important to point out that the input measurements are located before the wind turbine transformer. The larger green point in figure9 is the output measurement. This input and output data is used to bench mark the model presented in this chapter by comparing simulated data with real data. In this way one can validate the accuracy of the model presented in this chapter.

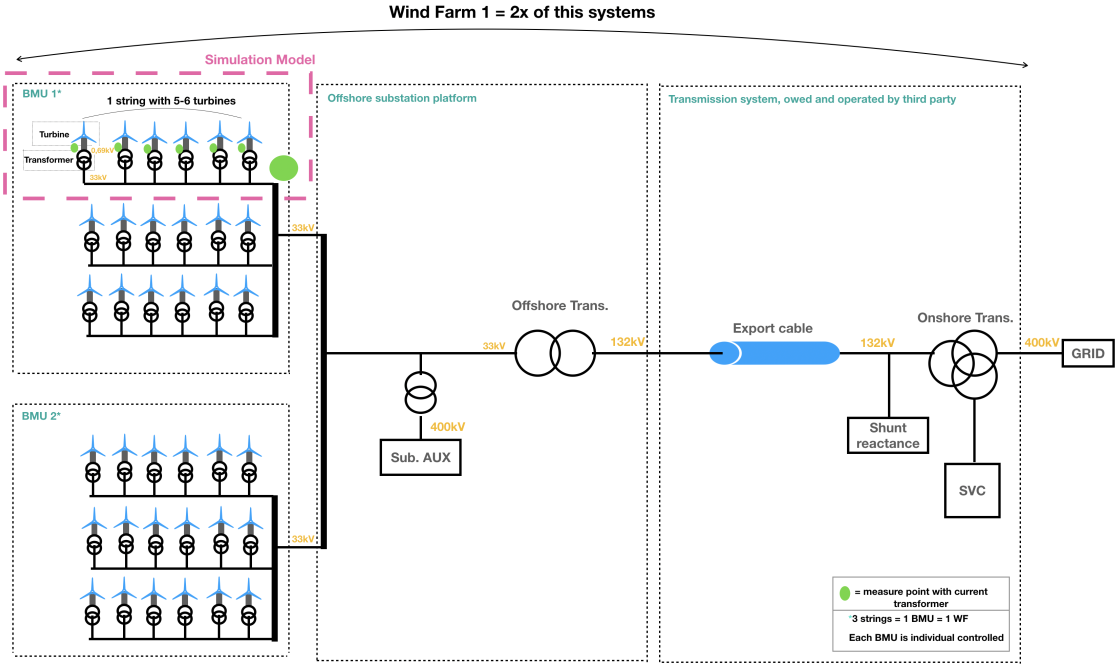

Figure 9: Simplified overview of Wind Farm 1

Data from company X is limited to the green points in figure 9, thus the simulation model is limited to only include turbine transformer and array cables. One string with 6 turbines will be model and compared to String B from BMU 1 in figure 10. This ensures that the model is as close as possible to provided data from Company X.

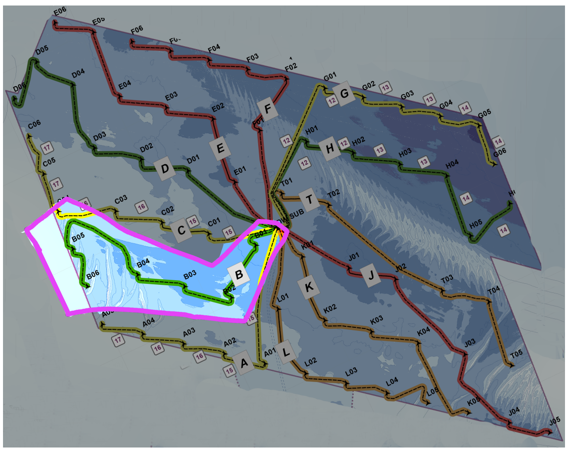

Figure 10: Wind Farm 1 array cable overview, 4 BMUs each containing 3 strings with 5-6 turbines. All strings are connected at the offshore substation, see figure 9 for overview of whole wind farm

4.2 Loss Model Framework

Cable losses are by nature a complex system to analyse. There are many factors that effect the losses and one type of loss or change in parameter can affect multiple other losses in the cable. The presented loss model below is divided into levels of abstractions/complexity. There are 2 main abstractions, temperature and cable losses. Each abstraction is divided into different levels of complexity, see figure 11. A combination of temperature model and cable loss model form the Loss Model. The idea is to build a model, from the simplest of models to the more complex. In addition the Loss Model is divided into constant and variable temperature and one have to choose between resistance with or without proximity and skin effect factor, more on this below.

4.2.1 IEC Standards

Standard International Electrotechnical Commission(IEC) equations has been used as base for most of the thermal and loss calculations. The main standard used in this master thesis is IEC 60287 *Calculation of the continuous current rating of cables (100% load factor)* which is the International Standard that defines equations to be used in determining the current carry capacity of cable. What specific standard that have been used will be specified.

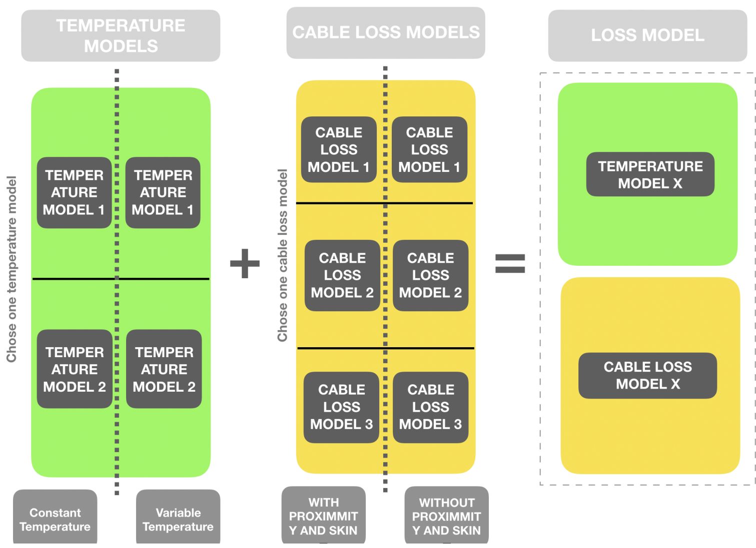

Figure 11: Overview on how Loss Model is built

4.2.2 Temperature Models and Temperature Behaviour

First abstraction one need to choose degree of complexity of is temperature. Temperature is an important factor because it impacts the losses, see chapter 3. R_{ac} , sheath/screen and armour losses are all temperature dependent somehow. Thus it's important to model them accurately with respect to temperature and understand how temperature affect these losses.

4.2.3 Temperature behaviour

The loss model, see figure 11, is divided into constant and variable temperature. The variable temperature is more complex to implement because it affects many of the the functions described in chapter 3.

Copper conductor, where the current flows, is the inner layer of the cable. In the loss model one assume that this is the driving factor for temperature in both sheath and armour, see chapter 3. This is not entirely true as there will be temperature rises in sheath and armour, even with no loading of the cable. Charging current is causing this temperature rise at no load, but one assume that these charging currents are relatively small compared to the load current because of the short cable distances (ca 1[km]) and low voltages (33[kV]) in the array system (see [2] for charging current equation). Thus the additional temperature rise from charging currents is neglected.

Constant

Temperature for copper conductor in the cable is set as a constant, the constant is chosen to be the maximum operating temperature of the cable used in array cables in WF1. In this way one captures the maximum potential loss in the array cables.The constant temperature assumes that the wind farm runs on a maximum constant power output.

Variable

A more realistic temperature behaviour for a WF is variable temperature because temperature in copper conductor is given by the amount of power produced by the WF. Since power produced from an offshore wind farms varies, copper and temperature for the rest of the cable also changes.

4.2.4 Temperature Models

Two temperature models are made based on chapter 3. Temperature model 1 is most basic, and the temperature model 2 more complex, see figure 11 for graphic representation. Both temperature model 1 and 2 are stationary models.

Model 1: All parts of Cable at Same Temperature

Least complex of temperature models is where one assumes that there is no thermal resistance or thermal capacitance. Thus temperature for conductor, sheath and armour momentarily changes with power transmitted through the cable, see figure 12. The quadratic graph for dynamic temperature is explained in chapter 3.

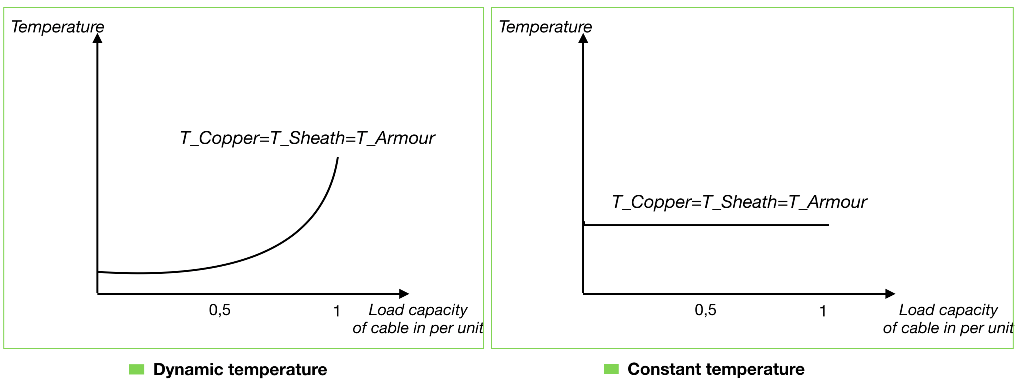

Figure 12: Temperature Model 1

Model 2: Different Temperatures in Cable Layers

Model includes thermal resistance. Thus temperature in sheath/screen and armour are lower than for conductor. See chapter 3 on how one calculate the different temperatures. Model does not include thermal capacitance.

Temperature model 2 is similar to temperature model used in IEC 60287 to find current rating of cables. Their objective is to find the the maximum current a cable can withstand in terms of temperature. Most cables has a maximum operating temperature of 90 degrees Celsius.

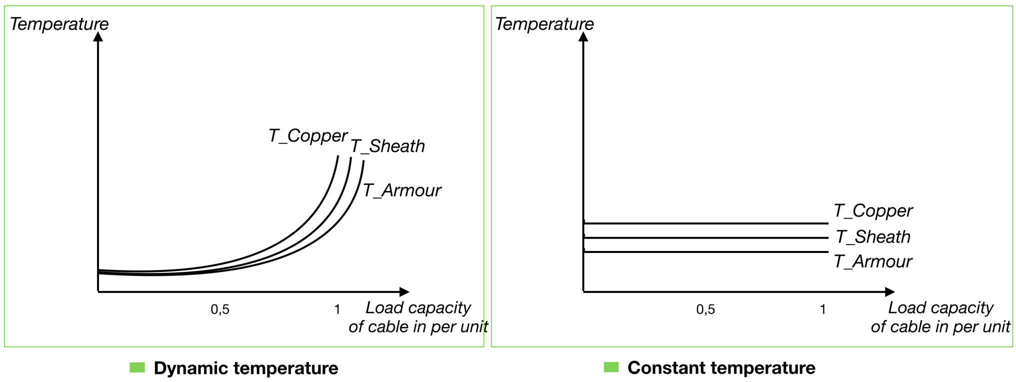

Figure 13: Temperature Model 2

4.2.5 Ambient Temperature - North Sea

As seen in figure 5 the conductor temperature will not be lower than ambient temperature. Ambient temperature in IEC 60287 only includes ambient temperature at sea level surfaces on land for different locations around the world. As seen in chapter 4 the array cables are located out in the ocean in an area with sea depths of 20-40 meters. Figure 14 shows that for depths up to about a couple of 100 meters the temperature does not change a lot[19]. Hence one can assume the same ambient temperature for array cables as sea temperature on the surface. Sea temperature at array locations in the North Sea is calculated to be in average about about 12 degrees °C, see figure 15 [20].

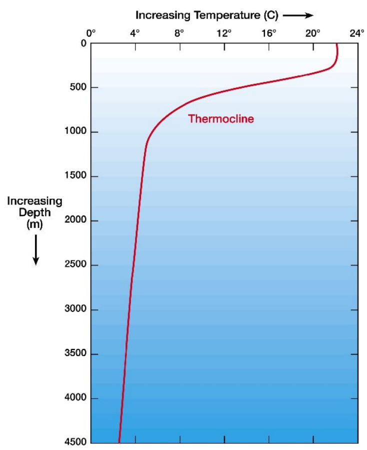

Figure 14: Simple temperature-depth ocean water profile

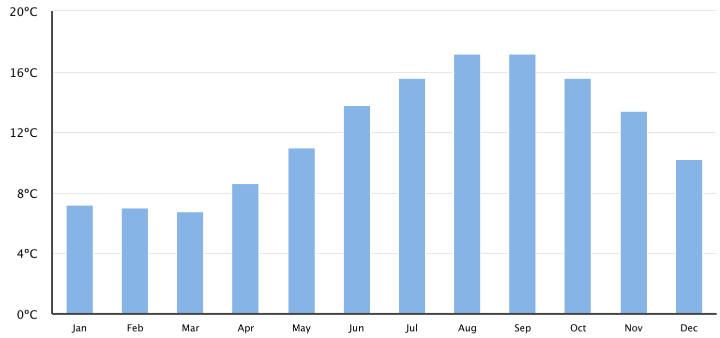

Figure 15: Average sea temperature(2018) used for temperature calculations for array cable

4.2.6 Cable Loss models

Figure 11 shows three different cable loss models where the layers are divided after how much one assumes each loss will contribute to the total loss in the cable. One assumes that cable loss model 1 will contribute more to the over all cable losses compared to cable loss model 3. By dividing these cable losses into cable loss models one can observe the effect of each loss to the total cable loss. The cable loss models are cumulative so cable loss model 3 also include cable loss model 2 and 1, see figure 16. Based up on council with Dr. James Pilgrim [14] one assumes that the copper losses(I^2R) are contributing the most to the overall cable losses, followed by sheath and armour losses. Dielectric loss is neglected due to relative low voltage(33[kV]) for array cables as recommended by Dr. Pilgrim and IEC 60287. Temperature rise for resistance due to charging currents in array cables are neglected as explained in 4.2.3. Overview of the cable loss models is shown in figure 16.

Figure 16: Cable Loss Model Overview

Cable Loss model One - Copper Loss

Copper loss is given by equation in appendix. Current and temperature in the copper is determined by electrical power transmitted in the cable. The resistance can either be calculated as AC or DC resistance, see chapter 3. For temperature model 1 and 2 the cable loss model 1 will give the same result as IR^2 losses does not include any thermal resistance, see appendix.

Cable 1 Loss model Two - Copper + Sheath Loss

Sheath loss is given by equation in chatper 3. Sheath temperature is proportional to copper temperature.

Cable Loss model Three - Copper + Sheath + Armour Loss

Armour loss is proportional to copper conductor loss and dependent on sheath and copper conductor temperatures. One assumes that armour temperature is lower than sheath and copper temperature for temperature model 2. For temperature model 1, copper, sheath and armour temperature is the same, see chapter 3.

4.2.7 Dielectric Loss

As mentioned in chapter 3 dielectric loss occurs in the insulation of the cable. The cable loss model neglect this loss as the array cable voltage is relative low (33kV). This is the same assumption made in IEC 60287. However this loss can not be neglected for export cable where voltages are higher.

4.2.8 String/cable

The loss model is first simulated with just one cable before simulated for a whole string. In that way one can see if the same trends occurs for both one cable isolated and for a full string.

4.2.9 Resistance With and Without Proximity and Skin Effects

As seen in chapter 3 there are two ways of calculating resistance for a material. Both AC and DC resistances are implemented for each simulation and presented in 2 separate matrices presented in chapter 5. This is done to see how much proximity and skin effect influence losses in array cables for offshore wind farms. If the effects are low one can simplify the Loss Model and only use resistance without skin and proximity effect, see appendix.

4.3 Components

As described the loss model includes two components from the wind farm, turbine transformer and array cable, see figure 8. They will both have losses associated with them and their model is described below.

4.3.1 Transformer

No-load losses are assumed to be constant and calculated as a percentage of the rated power of the transformer.

$$P_{noload_transformater} = 0.0006 * S_{transformer} \quad (4.1)$$

Short circuit voltage e_r is set to 0.9. Temperature in copper winding's is set to be constant. Load loss is calculated using electrical power output, power factor(PF) and voltage(E_1) on primary side from the wind turbine generator, see appendic for calcualtions. The PF is chosen to to be variable, calculated from the active and reactive power from the wind turbine generator. In this way the power output from the transformer should be closer to the reality than if one used constant power factor. Flowchart for the transformer is showed in figure 17.

Parameters for the transformer were given by Company X and can be found in appendix.

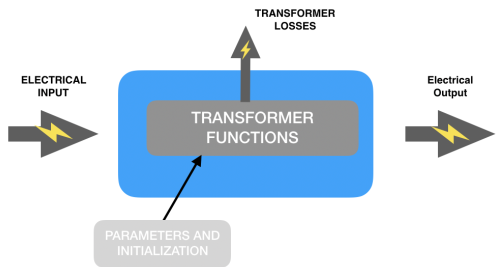

Figure 17: Flowchart for transformer in Loss Model

4.3.2 Array cable

The array cable is based on data sheet provided by company X. Due to confidentially the data sheet and outlay of the cable used can not be shared, but a simplified version of the cable is shown in figure 19. **Yellow** color show what areas of cable that is included in the Loss Model, see figure 18. The cable is a 33[kV] three core multi cable with trefoil conductor formation, see appendix for more cable parameters.

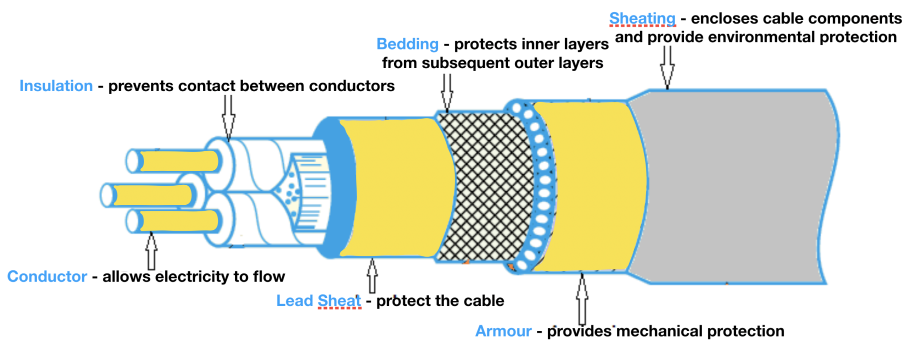

Figure 18: Cable overview

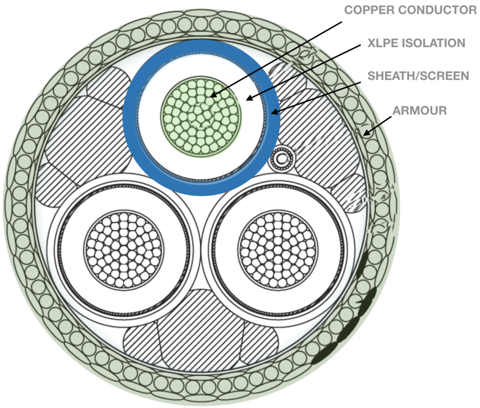

Figure 19: Overview of cable used for simulations

Cable loss model, described earlier, gives what loss to include in the loss model, see figure 20 for simplified flow chart of how cable losses are calculated in the Loss Model. The temperature models are also included but not shown in this flow chart.

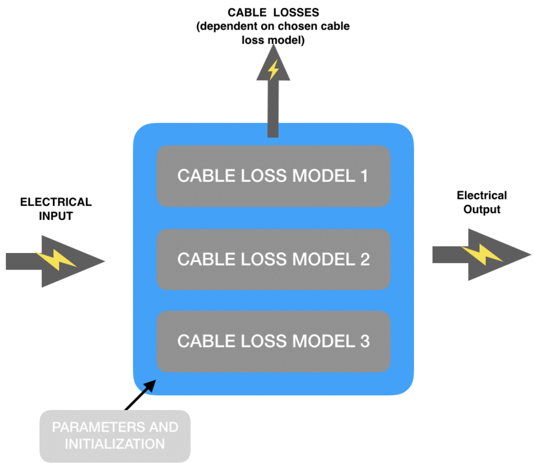

Figure 20: How losses are calculated. For equations see chapter 3

4.4 Simulation Framework

There are many intertwined parameters, functions and variables between cable design, losses and temperatures, and Mathworks MATLAB(referanse)is therefore used to run simulations for the Loss Model. In addition text extraction from large files and changing parameters for functions is easy with MATLAB. There are other programs that can calculate losses in array cable system, but these software's are not tailored for only loss calculations, which makes a custom MATLAB Script more suited.

The MATLAB code needs to be structured so that it can be replicated for all the simulations models. A short description on how the results are presented is shown in Appendix, chapter 8.

4.4.1 Explanation of MATLAB Code

Each Loss Model combines one temperature model with one cable loss model. The Loss Model runs a combination of these models for 30 days and gives an output based on input power from turbine generators. After one simulation is done another one is performed with a different combination of temperature and cable loss model.

Loss Calculation

The basic principal for transformer and array cable is mentioned but in general each component takes a power input, subtract the power loss and gives out a power output equal to power input minus power loss, see figure 21.

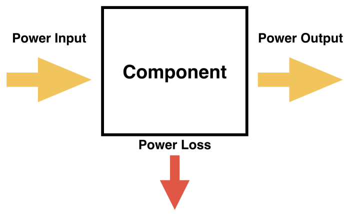

Figure 21: Loss calculations flow chart

Input

The input to the Loss Model is reactive[$kVar$] and active power[kW] delivered by the wind turbine generator. This data is sampled every 10 minutes and the same for every Loss Model. The data available were only within a time period of 30 days in March 2018, and so the simulations also runs for 30 days since one of the main objectives is to bench mark the Loss Model with real data.

Output

The output from the loss model is 30 days of electrical energy[MWh] produced by the wind farm. This output is compared to real data output from big green point in figure 9.

Flowchart

Figure 22 is a general flowchart of the Loss Model. This is the foundation for each simulation. What differs between them are the functions, parameters, initialization and variables.

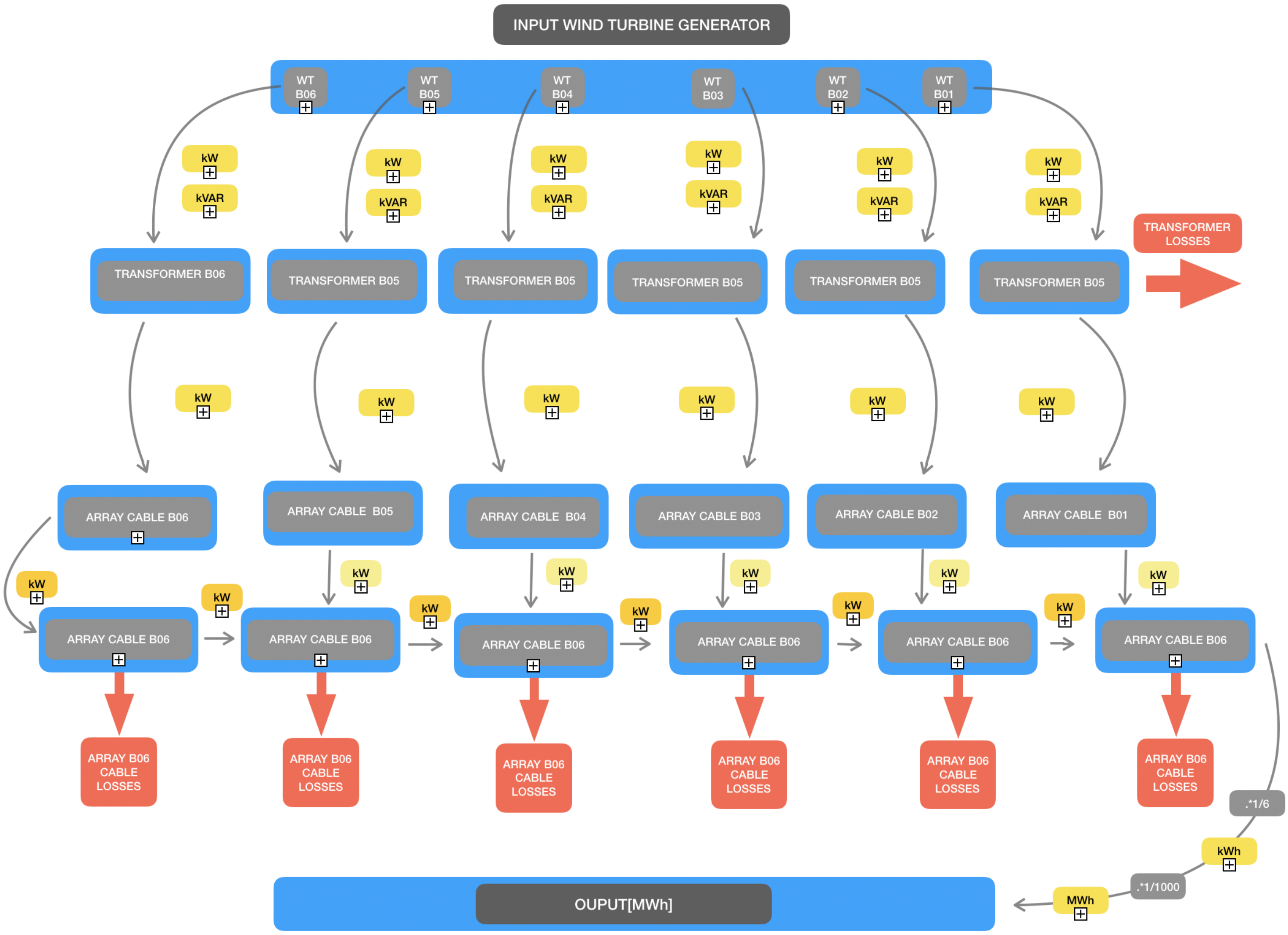

Figure 22: Flow Chart for Matlab Code

4.5 Model assumptions/limitations

4.5.1 Data

Available data

As mentioned the data available from Company X is for only 30 days.

Components

Ideal one should have had data isolated for each component, both transformer and array cable. Data from Wind Farm X includes both losses from turbine transformer and array cable, thus the model also has to include both these losses in order to compare it to real data.

Input to Loss Model

Input to Loss Model is equal to real input. Model should ideally also be tested with e.g a Weibull wind distribution or data from other wind farms. The input used in the loss model will not capture lost production due to downtime of the WT or reduciton of production due to operation control of wind farm(throttling of wind turbines).

4.5.2 Transformer

Dynamic power factor(PF) for the transformers

Real PF for WF1 is available through active[W] and reactive[Var] power measurements at each wind generator. This PF is used in transformer loss function i order to model the losses more accurate. Transformer losses are also held constant for every Loss Model simulation.

No load loss

No load loss for wind turbine transformer is set to a constant value, see appendix.

4.5.3 Cables

Equal spacing array cable

Equal spacing between wind turbines on one string

Power factor for cables set to one

PF equal one means that reactive power from turbines are neglected, thus the reactive current is assumed to not contribute to the current in the conductors, same assumption as in [12].

Voltage and Frequency

System frequency and voltage is constant.

Dielectric Losses

Based on council with Dr Pilgrim the dielectric losses are neglected in the cables due to low voltage in array cables.

5 Results

This chapter presents results from Loss model simulations described in chapter 4. There are two Loss Model results, divided in resistance *with* and *without* proximity and skin effect, see chapter 3. The main results, where the accuracy of the model is showed, includes all losses in the system described in chapter 4. Result matrices with only cable loss fraction is also presented. As mention in chapter 4 there are no results for temperature model 2 with cable loss model 1 as the results will be the same as temperature model 1 with cable loss model 1. Other findings of interest can be derived from these Loss Model matrices but they will be presented in chapter 6.

Colors within results matrices represent how accurate $\frac{Loss_{Simulated}}{Loss_{Measured}}$ is.

RED: $\frac{Loss_{Simulated}}{Loss_{Measured}} >= 8\%$

YELLOW: $8\% > \frac{Loss_{Simulated}}{Loss_{Measured}} > 5\%$

GREEN: $\frac{Loss_{Simulated}}{Loss_{Measured}} <= 5\%$

5.1 Resistance - Without Proximity & Skin Effect

5.1.1 Simulated Loss/Measured Loss

All results in figure 23 have been simulated with resistance without proximity and skin effect, see chapter 3. Entry 4:3 in figure 23 is the most accurate with $\frac{Loss_{Simulated}}{Loss_{Measured}} = -3.95\%$. Negative sign means that simulated loss is higher than actually loss.

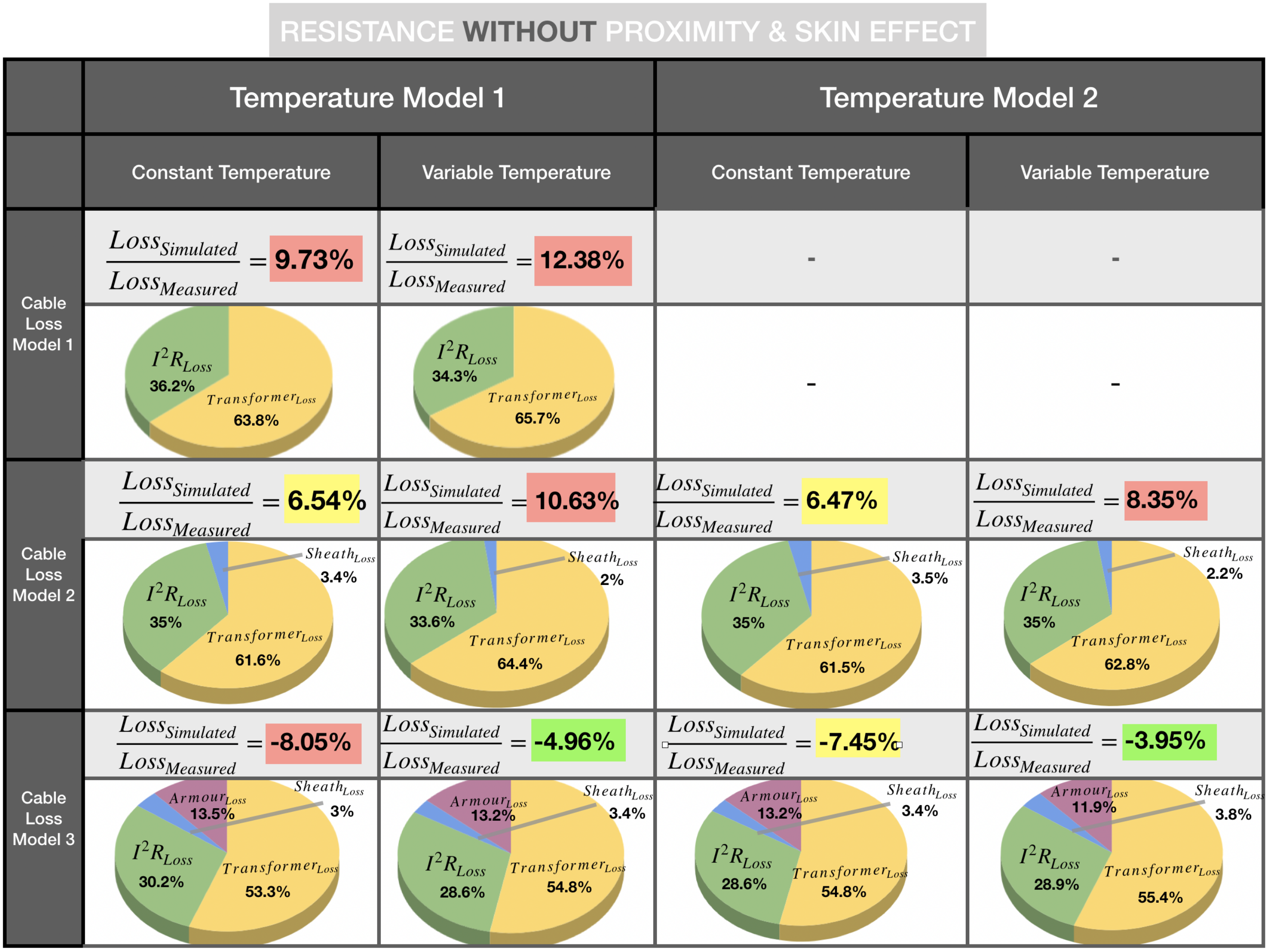

Figure 23: Results without proximity and skin effect

5.1.2 Cable Loss Fractions

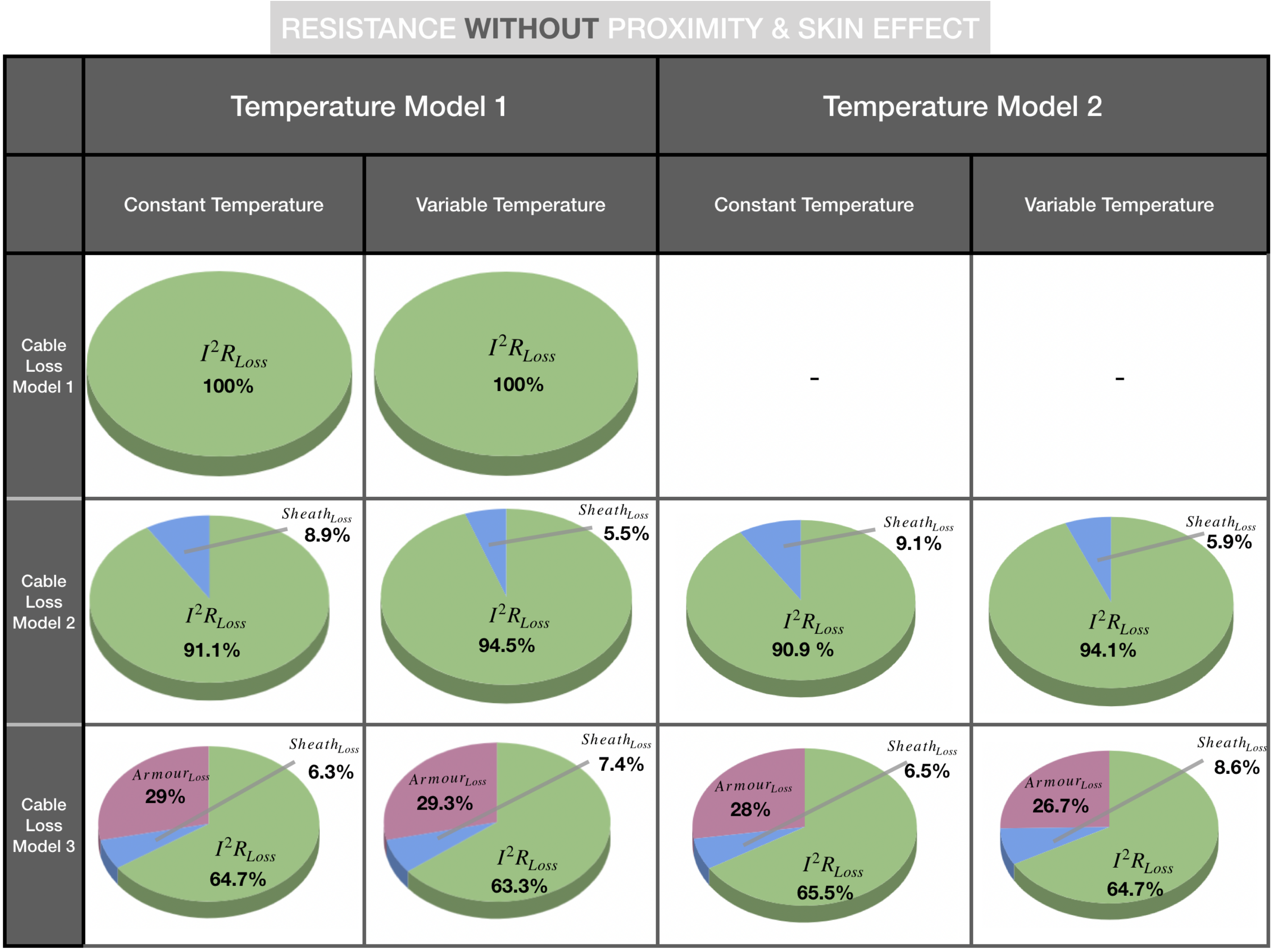

Figure 24: Cable loss fractions without proximity and skin effect

5.2 Resistance - With Proximity & Skin Effect

5.2.1 Simulated Loss/Measured Loss

All results in figure 25 have been simulated with resistance with proximity and skin effect, see chapter 3. Entry 4:3 in figure 25 is the most accurate with $\frac{Loss_{Simulated}}{Loss_{Measured}} = -3.61\%$. Negative sign means that simulated loss is higher than actually loss.

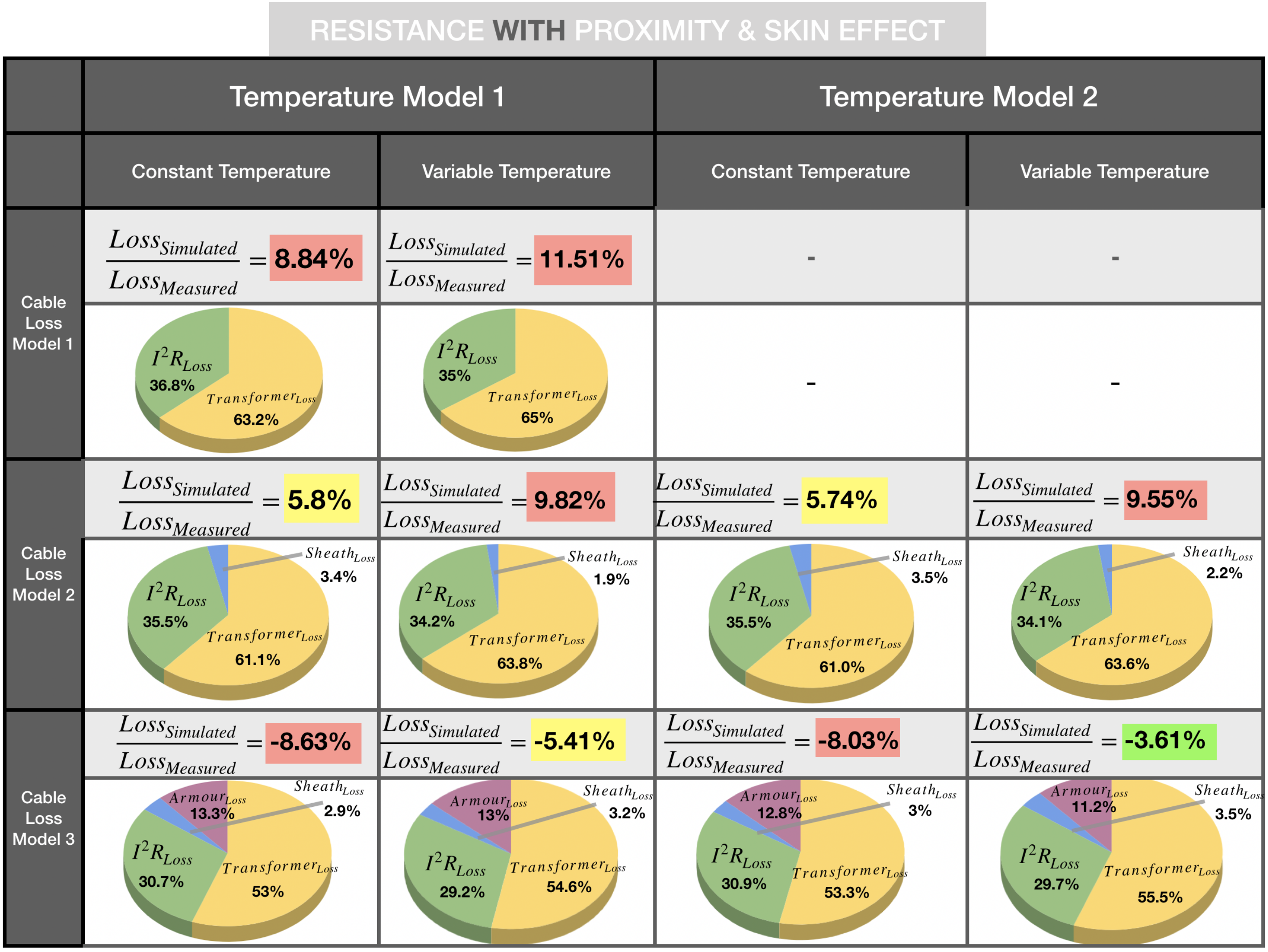

Figure 25: Results with proximity and skin effect

5.2.2 Cable Loss Fractions

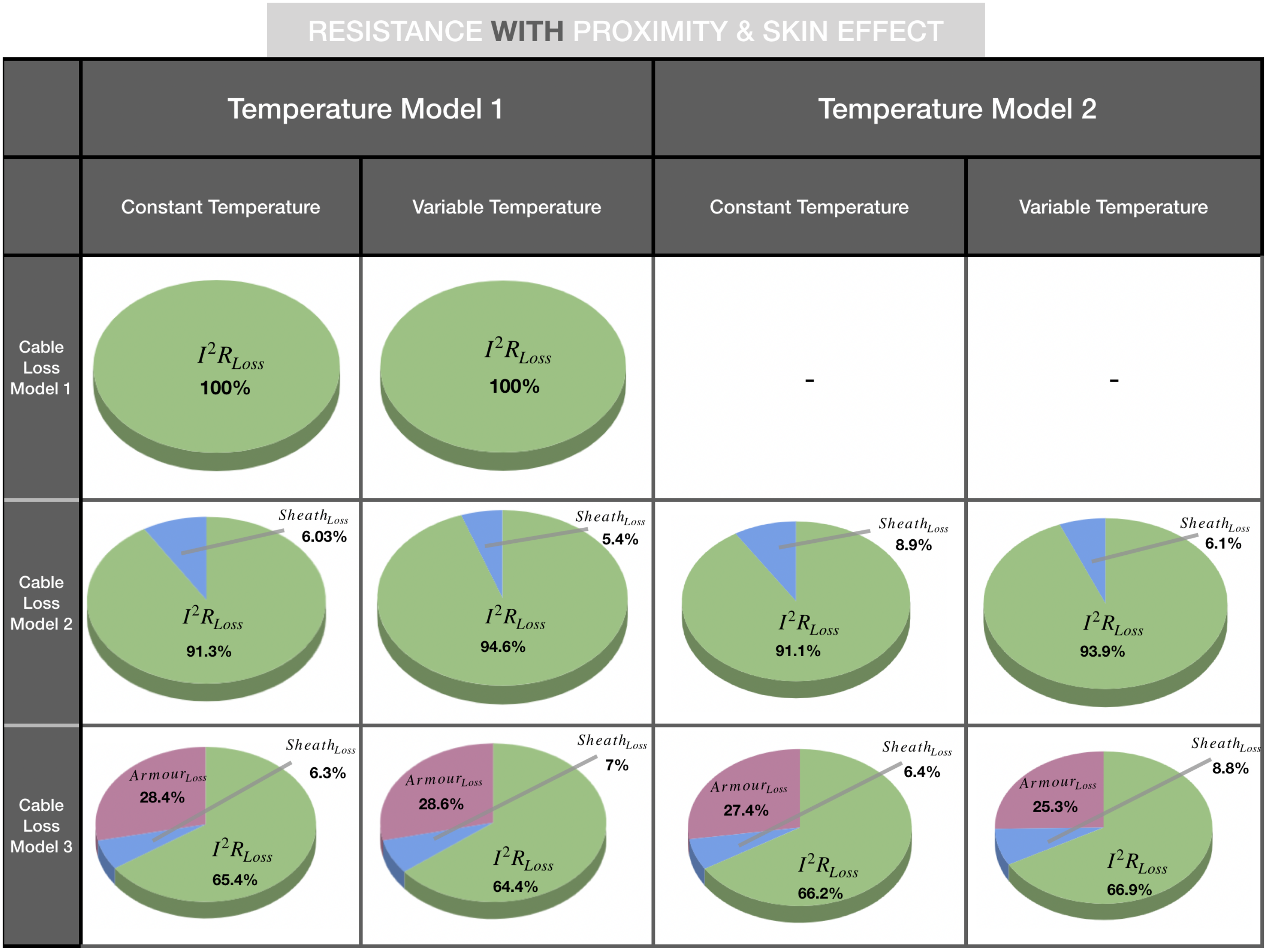

Figure 26: Cable loss fractions with proximity and skin effect

6 Discussion

6.1 Uncertainties with Loss model

Some Loss Models are calculating the losses within a margin of 5% compared to measured data, see chapter 5. However there are some uncertainties that could effect these results.

6.1.1 Effect of Including Transformer Losses in Loss Model

As mention earlier data from a real offshore WF including only array cables were not possible to obtain. Thus turbine transformer losses were included in the Loss Model. As seen from the results in chapter 5 the transformer loss accounts for about 55% of the total losses in the Loss Model with best accuracy, see figure 27. A change in transformer loss could therefore affect the Loss Model substantial, especially if there would be a larger change in transformer losses, thus introduces a uncertainty in the Loss Model results.

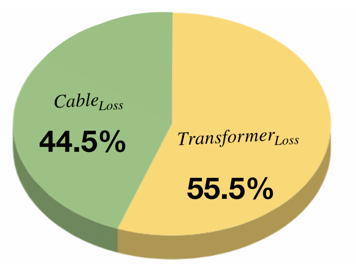

Figure 27: Loss fraction between array cables and WT transformers

Transformer losses are calculated with dynamic PF for accurate calculations of load losses but there are uncertainties when setting the no load loss to a constant value. It is not known how accurate this simplification is, see apendix and [2]. Also the transformer loss model, see chapter 3, should be validated to see if assumptions and simplifications yield. Despite these uncertainties some simple calculations were done to check that transformer losses are in the realistic range. Transformer losses at 1 per unit power generation(full capacity load) for string B(see figure 10) are approximately 255 [MWh] accordingly to data sheath provided by Company X. Measured data shows that the turbine generator for a specific turbine actually run in average on 0.5 per unit generation over the time period, see figure **??**. If one assumes that all turbines for string B has the same average generation, then transformer loss for string B would be 127[Mwh] see figure 28. Results from Loss Model simulations give approximately 107[Mwh] transformer losses for the same string(String B), which is about 15% lower than the average transformer loss based on data sheet, see table 2. This is not valid to confirm the accuracy of the transformer loss model but shows that the transformer losses are in the right range and don't produce unrealistic values, this needs to be further investigated. It should be mentioned that having data considering only array cables would have eliminated the uncertainty of having transformer losses included in the model.

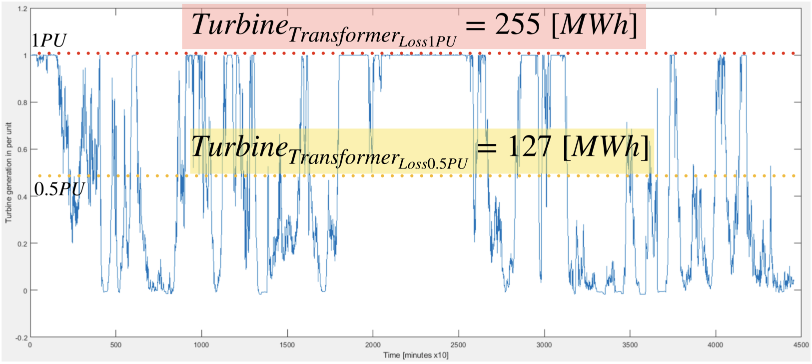

Figure 28: Transformer losses at 1p.u and 0.5p.u generation

$TransformerLoss_{Average}$	127 [MWh]
$TransformerLoss_{Simulated}$	107 [MWh]
$(1 - \frac{TransformerLoss_{Simulated}}{TransformerLoss_{Average}}) * 100$	15%

Table 2: Average transformer loss based on rated power loss vs transformer loss simulated

6.1.2 Temperature

Temperature in conductor, sheath and armour affect the losses as seen in figure **??**. From figure 29 one can observe that the temperature for sheath and armour is considerably lower than conductor temperature, about 16% lower for sheath and about 25% lower for armour. As stated in [13] there is reason to believe that the standard IEC 60287 equations are subject to some conservatism regarding the rating of wind farm cables, hence using the IEC 60287 equations introduces a uncertainty to how accurate the temperatures for sheath and armour are. Especially armour and sheath temperature can be too low when using IEC equations as seen in [13]. Also no thermal capacitance was included in the Loss Model, which would have affected the thermal network and heat flow between different layers of the cable.

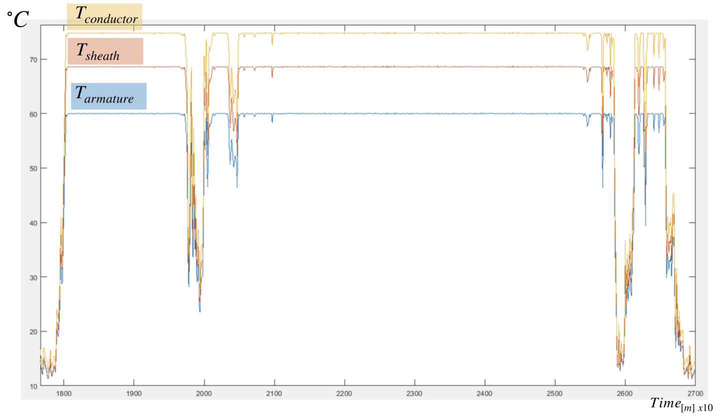

Figure 29: Temperature for different layers of cable

Some time series for array cable B03 are showing unrealistic cable temperature values, see figure 30. The reason for these unrealistic values are not clear, but one suspects it could be caused by the input data to the Loss Model or a bug in the MATLAB code, this needs to be further investigated.

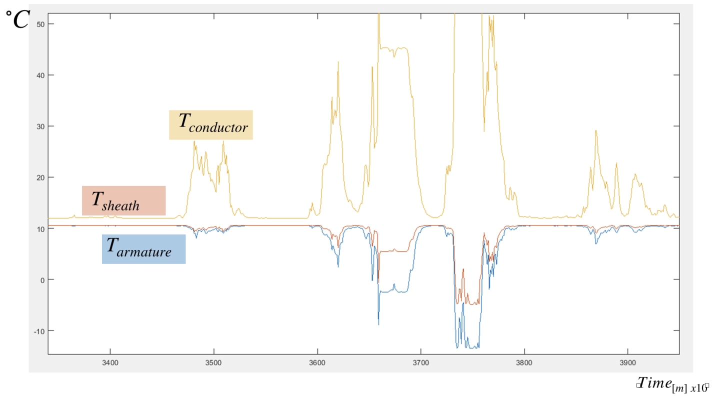

Figure 30: Unrealistic cable temperatures for a time series for WT B03

6.1.3 Reactive Power from Wind Turbines

Power factor for the cables is set to one in the Loss Models simulations, assuming there is no reactive contribution to the current that flows in the cable, same assumption made in [12]. However, data from Company X shows that Wind Farm 1 turbines are delivering reactive power to the export cable, see figure 31, lowering the reactive power requirements for the export cable from the electrical grid. Some simple tests were run for the Loss model with best accuracy where this reactive current supplied to the export cable was added to the load current Results show an increase of approximately 9%, see table 3. This increase is due to higher temperatures in the cable layers. Hence it seems like the simplification of setting PF = 1 in the loss model could underestimate the losses. It should be mentioned that the reactive current added to load current was calculated based on just one WT with average values for reactive current, see figure 31. It is not known the effect a dynamic model where the reactive current is calculated for each time series for each WT would affected the Loss Model, this should be further investigated.

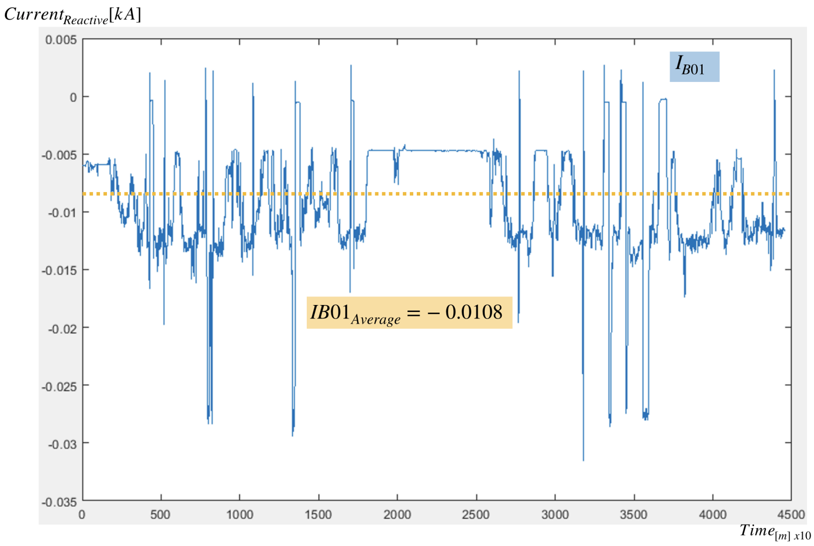

Figure 31: Reactive current from WT B01

6.1.4 Cable Length

Array cable length is set to a constant value of 1km in the Loss Model. Actually drawings of the wind farm show that the array cable length is not constant, but varying with over 100%, see figure 32. This would potentially increase the losses as longer cable lengths would increase the electrical losses in the array cables. Thus using a dynamic cable length model could have been implemented. This could especially effect losses substantially if one are looking at array cables for a whole wind farm, including all array cables. For further work effects of using a dynamic cable length or a average cable length should be investigated.

	Without **Reactive Current Contribution from WT**	***With*** **Reactive Current Contribution from WT**
Turbine Trafo Loss	107.95 [MWh]	107.95 [MWh]
IR^2Loss	57.8 [MWh]	58.4 [MWh]
Sheath Loss	6.76 [MWh]	6.72 [MWh]
Armour Loss	21.8 [MWh]	21.97 [MWh]
Array Cable $Loss_{total}$	86.42 [MWh]	87.08 [MWh]
P $In_{Simulated}$	13320 [MWh]	13320 MWh]
P $Out_{Simulated}$	13126 [MWh]	13125 [MWh]
P $Loss_{Simulated}$	194.4 [MWh]	195.03 [MWh]
P $In_{Measured}$	13320 [MWh]	13320 [MWh]
P $Out_{Measured}$	13132.41 [MWh]	13132.41 [MWh]
P $Loss_{Simulated}$	187.59 [MWh]	187.59 [MWh]
$\frac{P\ Loss_{Simulated}}{P\ Loss_{Measured}}$	-3.61	-3.96
$\frac{3.96}{3.61} - 1 * 100$	ca 9%	

Table 3: Results with and without reactive current contribution to current in conductor

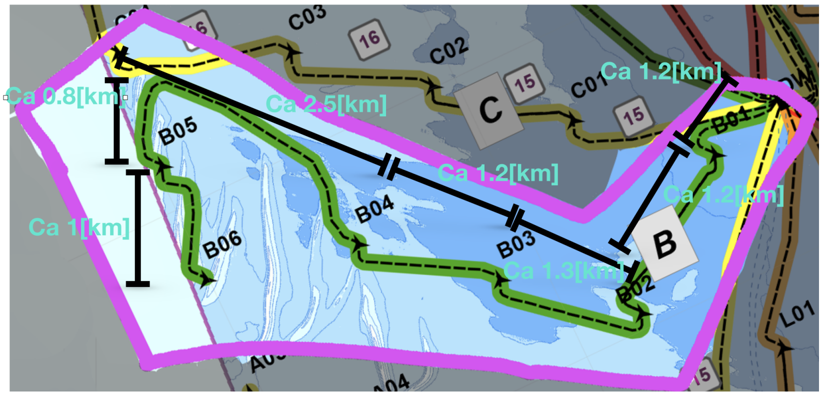

Figure 32: Approximately cable lengths WF1

6.1.5 Output Data from Company X

There are some uncertainties related to the output data from Company X. As mentioned earlier data has been collected semi-automatically from different data systems. The output data is initially meant as a report on monthly production for the Crown of State in England. The data are collected from current transformers within the wind farm system but due to measurement noise and inaccuracy some of the data is updated several times. Ideally the data should have been collected with the purpose of data analysis and not needed to be modified. This is something Company X needs to look into.

6.2 Accuracy of Loss Model

There are as seen some uncertainties with Loss Model results, but just analyzing the results show that the Loss Model is able to quite accurately calculate the losses in an offshore WF.

Loss Model Results without Proximity and Skin effect

As seen in figure 23 the most accurate result is the combination of cable loss model 3 and temperature model 2 with $\frac{P\ Loss_{Simulated}}{P\ Loss_{Measured}} = -3.95\%$.

Loss Model Results with Proximity and Skin effect

The same combination of temperature and cable loss model gives the most accurate results for resistance with Proximity and Skin effect with $\frac{P\ Loss_{Simulated}}{P\ Loss_{Measured}} = -3.6\%$, see figure 25. As expected the Loss Model run with proximity and skin effect for resistance performs better, in terms of accurate loss calculations, than Loss Model simulated without proximity and skin effect, see chapter 3. Overall the difference between simulating resistance with and without proximity and skin effect are considerable, see figure 33. Hence one can not exclude proximity and skin effect in resistance for cable loss calculations for HVAC array cable system for offshore wind farms as it effects the losses considerable.

Difference for Resistance with and Without Proximity and Skin Effect

	Temperature Model 1		Temperature Model 2	
	Constant Temperature	Variable Temperature	Constant Temperature	Variable Temperature
Cable Loss Model 1	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 9.14\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 7.02\%$	-	-
Cable Loss Model 2	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 11.31\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 7.62\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 11.28\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = -14.37\%$
Cable Loss Model 3	$\frac{With_{P\&SE}}{Without_{P\&SE}} = -7.2\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = -9.07\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = -7.78\%$	$\frac{With_{P\&SE}}{Without_{P\&SE}} = 8.61\%$

$$\frac{With_{P\&SE}}{Without_{P\&SE}} = \left(1 - \left(\frac{\frac{Loss_{Simulated}}{Loss_{Measured}}\ \textbf{with}_{Proximity\&SkinEffect}}{\frac{Loss_{Simulated}}{Loss_{Measured}}\ \textbf{without}_{Proximity\&SkinEffect}}\right)\right) \cdot 100$$

Figure 33: Difference using resistance with and without proximity and skin effect

6.2.1 Cable Losses

In terms of the importance to the overall cable losses, the order is normally [14]:

1. Losses occurring in the conductor itself. I^2R losses.
2. Induced losses in sheath
3. Induces losses in the armour of the cable
4. Voltage dependent losses in the insulation of the cable (Dielectric losses due to varying magnetic field)

As seen in figure 26 the armour losses are surprisingly high and have a higher impact when it comes to losses compared to sheath losses.

As mention the most accurate Loss Model is the one with combination of temperature model 2 and cable loss model 3 with resistance including proximity and skin effect. Figure 34 shows % difference in cable losses when running the loss model with constant or variable temperature. For all simulations(all entries in Loss Model matrix) the cable losses are higher with constant temperature, see figure 34. This has to do with the basic assumption from IEC 60287 that cables run at full capacity, implying cables operating at maximum operating temperature. Hence temperature for Loss Models with constant temperature is set to 90°C. This is not a good assumption as power output of wind farms is inherently linked to the varying wind field at the offshore wind farm site, meaning that it is rare to achieve long periods of full rated power output. Effects of this can been seen in figure 35. Interesting to note that sheath losses have less % change for constant and variable temperature simulations. Also there is not a big difference between temperature model 1 and 2. When including armour loss(Cable loss model 3) one can see that the difference in constant and variable temperature is higher, especially for temperature model 2. This could mean that armour loss for array cables are more affected by temperature change, especially when temperature of each layer of the array cable is modelled with varying temperature.

RESISTANCE WITH PROXIMITY & SKIN EFFECT

	Temperature Model 1	Temperature Model 2
	% difference between constant and variable temperature for cable losses	% difference between constant and variable temperature for cable losses
Cable Loss Model 1	8.19 %	-
Cable Loss Model 2	4.83 %	4.25 %
Cable Loss Model 3	6.74 %	9.59 %

Figure 34: Difference between constnat and variable temperature for conductor

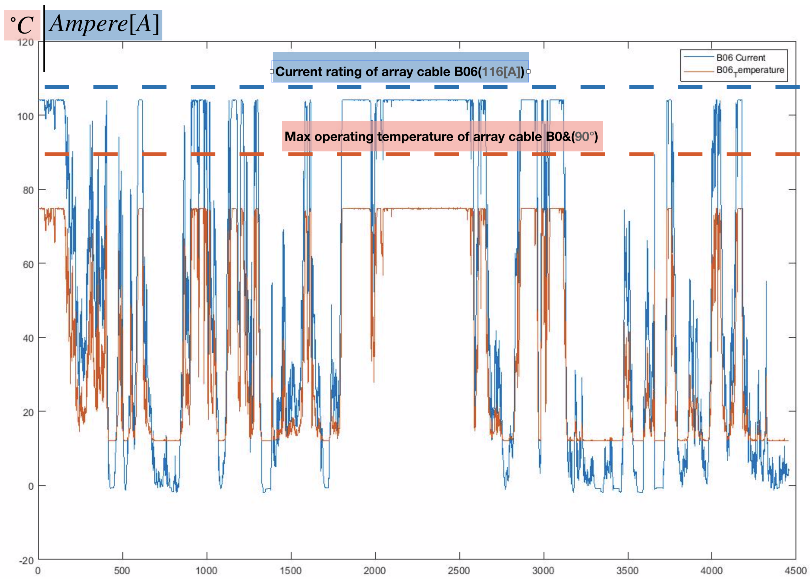

Figure 35: Rated and real temperature and current in cable conductor

6.3 Loss Model and Global Losses in Offshore Wind Farms

Losses for array cable in Loss Model are only about 1% of the total energy delivered from Sting B. This could potentially mean that annual production from wind turbines are not that much effected by array cable losses, hence not affecting the LCoE for the offshore wind farm much, see figure 1. This needs to be investigated further but it could potentially mean that when calculating LCoE for a whole offshore wind farm the losses in the array cables can be estimated with just IR^2 losses. This simplifies the analytic model significantly. However, figure 26 shows how important it is to include armour and sheath losses and this will be important for export cable as export cable accounts for a much lager share of the offshore wind farm total electrical losses [11].

7 Conclusion and Further Work

7.1 Conclusion

A method for calculating losses in array cables for offshore wind farms has been presented in this master thesis. Results shows that suggested model is able to simulate the losses with an accuracy of 3.6%. However there are are too many uncertainties to validate the model presented with confidence. The biggest uncertainties have to to with measured data where wind turbine transformer losses and cable losses had to be included in the model.

7.2 Further Work

The method for this master thesis should be remade where validation is run just for array cables, not including wind turbine transformer. In this way one can with confidence state if the loss model method presented in this master thesis is accurate. This involves Company X to make better systems for data collection from their offshore wind farms. This is possible as there are enough measurement units in the offshore wind farm to isolate each component for analytical purposes. The method presented in this master thesis should also be validated with other offshore wind farms and also for longer time series, preferably for a full year.

Modifications of Loss Model for Future work

Thermal Capacitance

A third temperature model should be included with thermal capacitance. Hypothesis: temperature in sheath/screen and armour will be higher than in temperature model 2 due to the time constant a thermal capacitance introduces, see figure 36.

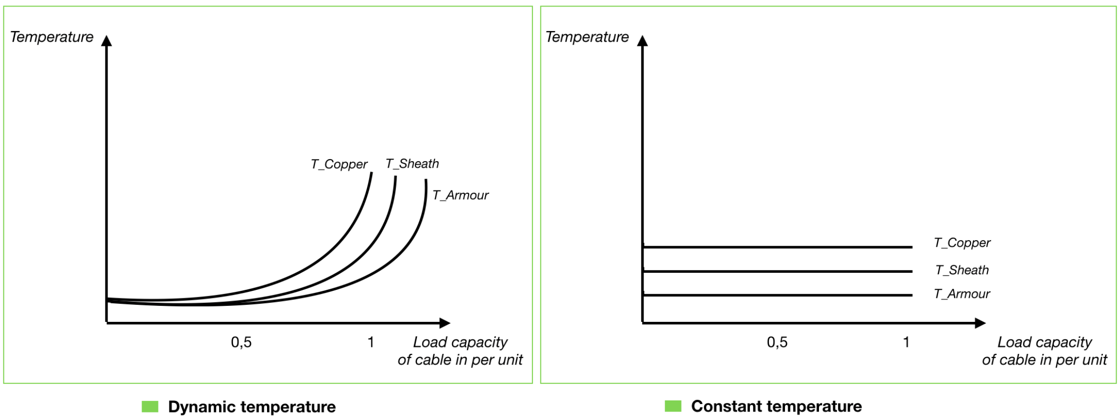

Figure 36: Temperature model with thermal capacitances

7.2.1 Reactive Power from Wind Turbines

Contribution from reactive power delivered from the offshore wind turbines to the export cable should be included in the Loss Model as the reactive current has a considerable effect on the current through the cable.

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8 Appendix

8.1 Loss Calculations

8.1.1 Transformer Loss Calculations

For transformer loss calculations the relative reactive short circuit voltage must be set:

$$e_r = 0.9 \tag{8.1}$$

where

- e_r=Short circuit resistance in percent of rated voltage

The value is based on [2].

Rated power of transformer are given from data sheath from Company X. Then:

$$R_{SC1} = \frac{e_r}{100} \cdot \frac{E_1^2}{S_{transformer}} \tag{8.2}$$

where

- R_{SC1} = Primary short circuit resistance [Ω]
- E_1 = Transformer voltage primary side [V]

Current on primary side is given as:

$$I_1 = \frac{S_{transformer}}{\sqrt(3) \cdot E_1 \cdot \cos(\phi)} \tag{8.3}$$

where

- I_{11} = Transformer current primary side [A]
- E_1 = Phase shift between voltage and current

Total load loss is then:

$$P_{loadloss} = 3 \cdot I_1^2 \cdot R_{sc1} \tag{8.4}$$

No-load losses for transformer are constant and set to 0.0006 [2]:

$$P_{nl_transformer} = 0.0006 \cdot S_{transformer} \tag{8.5}$$

8.1.2 Cables losses

IR^2 Losses

Joule losses in conductor in array cables are calculated as:

$$I_{cable} = \frac{Incoming_{power}}{\sqrt{3}} * V_{array} * PF * n_{cables} \quad [kA] \tag{8.6}$$

$$P_{Copper} = I_{cable}^2 * 3 * R * n_{cables} \quad [MW] \tag{8.7}$$

where

$Incoming_{power}$ = Electric power from respective Wind Turbine Generator, for example turbine B06 [kW]
PF = Power factor, cosϕ
P_{Copper} = 3Φ joule losses for conductor in array cable [MW]

8.1.3 Dielectric Loss

From standard IEC 60287-1-1+AMD1:2014 CVS:

Type of cable	ϵ	$tan\delta$
XLPE up to and including 36kV	2.5	0.004

Table 4: Parameters for dielectri loss calculations

3 phase dielectric loss is given by:

$$Dielectric_{Loss} = 3 * Dielectric_{Loss_{phase}} * n_c ables \tag{8.8}$$

where

$Dielectric_{Loss_{phase}}$ = Dielectric loss for each phase Is given in chapter 3

8.1.4 Calculating Reactive Current from Wind Turbines

$$I_c = \frac{Q}{\sqrt{3} * V_{array} * sin\theta * n_{cables}} \tag{8.9}$$

where

Q = reactive power delivered by wind turbine [kVar]

8.2 Thermal Resistance Calculations

8.2.1 Parameters for Thermal Resistance(T_1) between Conductor and Sheath

	$185mm^2$	$500mm^2$
External diameter of insulation(d_i)	33[mm]	45.1[mm]
Thermal Resistivity for XLPE(ρ_t)	3.5[K.m/W]	3.5[K.m/W]
Thickness of insulation between conductor and sheath, t_1	10[mm]	9.24[mm]
Diameter of conductor(circular), d_c	15.34[mm]	25.24[mm]
Thickness of insulation between conductors, t	25[mm]	24.6[mm]
$\frac{t}{t_1}$	ca 0.5	0.37
$\frac{t_1}{d_c}$	0.65	0.36
Thickness of metallic screen on core δ_1	0.5[mm]	0.985[mm]

Table 5: Parameters for calculations of thermal resistance T_1

Parameters in table 5 are used to calculate G in figure 37. G= 1.45 for cable with $185mm^2$ conductor and G= 1.05 for cable with $500mm^2$ conductor.

Parameters in table 5 are used to calculate K in figure 38. K= 0.5 for cable with $185mm^2$ conductor and K= 0.4 for cable with $500mm^2$ conductor.

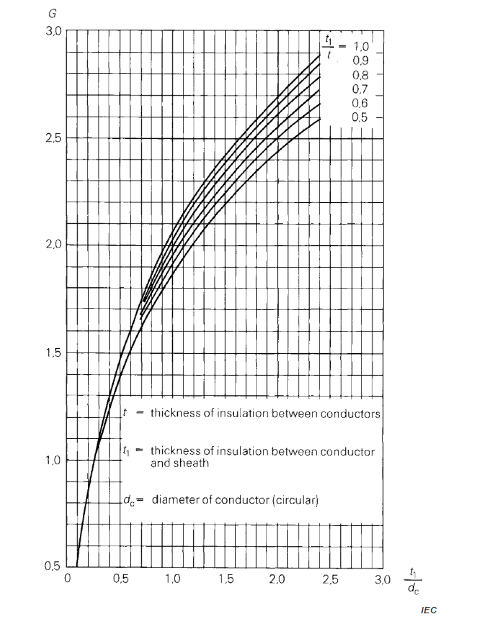

Figure 3 – Geometric factor *G* for three-core belted cables with circular conductors (see 4.1.2.2.4)

Figure 37: Geometric Factor G

8.2.2 Parameters for Thermal Resistance(T_2) between Sheath and Armour

Parameters in table 6 are used to calculate G' in figure 39. G'= 0.11 for cable with $185mm^2$ conductor and G'= 0.12 for cable with $500mm^2$ conductor.

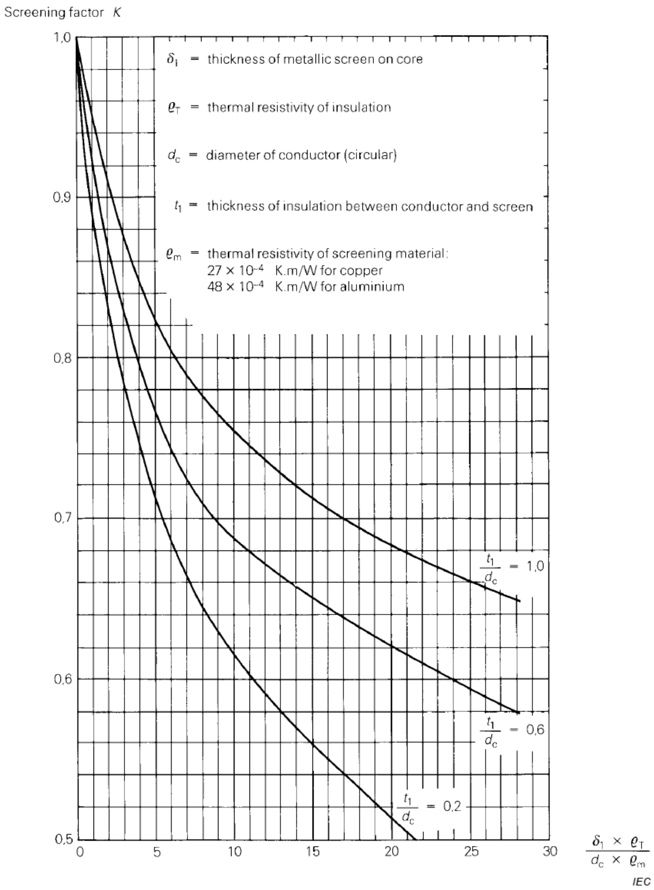

Figure 4 – Thermal resistance of three-core screened cables with circular conductors compared to that of a corresponding unscreened cable (see 4.1.2.3.1)

Figure 38: Screening Factor K

	$185mm^2$	$500mm^2$
Thickness of material between sheath and armour	0.5[mm]	0.6[mm]
Outer diameter of sheath	28[mm]	36[mm]

Table 6: Parameters for calculations of thermal resistance T_{II}

Cable Current Rating

Current rating for cables, used in 3.2 is shown in table 7

IEC 60287-2-1:2015 RLV © IEC 2015 – 37 –

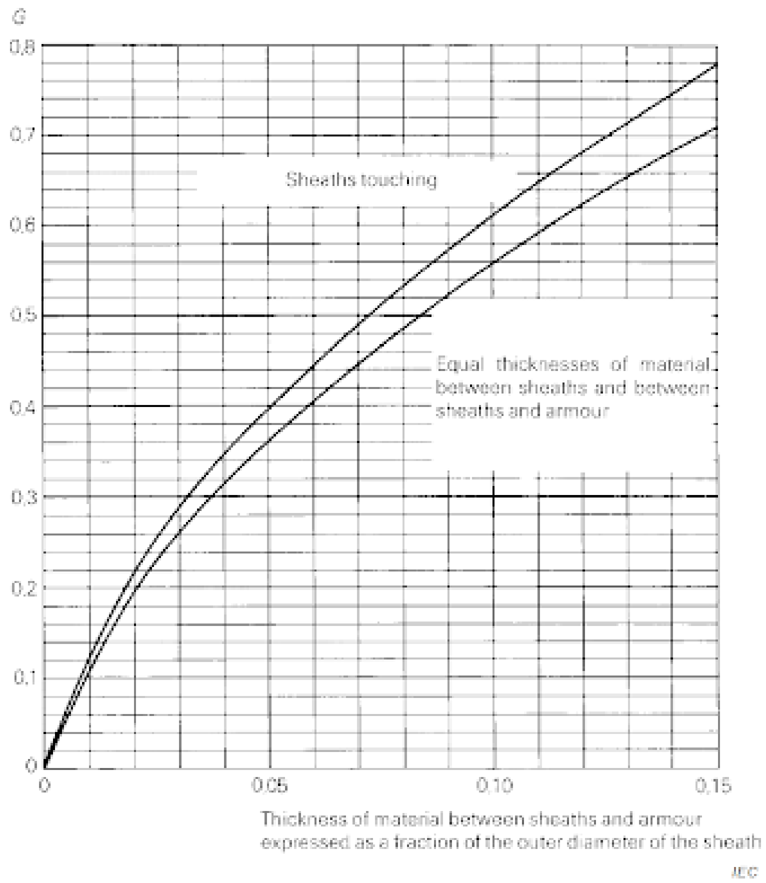

Figure 6 – Geometric factor $\overline{G}$ for obtaining the thermal resistances of the filling material between the sheaths and armour of SL and SA type cables (see 4.1.3.2)

Figure 39: Geometric factor marked G'

	Current Raring [A]
Array Cable B06	116
Array Cable B05	232
Array Cable B04	350
Array Cable B03	467
Array Cable B02	538
Array Cable B01	700

Table 7: Current rating for array cables in string B, see figure 9

8.3 Array Cable Parameters Measurements

Cable data in master thesis is based on data sheath from Company X for array cables with 185mm^2 and 500mm^2 conductors.

8.3.1 Resistance for Copper

For the standard IEC60287-1-1:2006, the resistivity at 20 degrees Celsius for copper, based on 1mm^2 conductor is 1.7241*10^-8[Ω*m]. The resistance is then:

For Array Cable with 185mm^2 copper conductor

$$R_{Conductor} = \frac{1.7241 * 10 - 8 * 10^6 * 10^3}{185} / = 0.0931[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.10}$$

For Array Cable with 500mm^2 copper conductor

$$R_{Conductor} \frac{1.7241 * 10 - 8 * 10^6 * 10^3}{500} = 0.034482[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.11}$$

8.3.2 Resistance for Steel

Based on standard IEC 60287 1-1:2006+ resistivity for steal is calculated to $13.8 * 10^-8$ [ohm*m] at 20 degrees Celsius,

For Array Cable with 185mm^2 copper conductor

$$R_{sheath} = \frac{13.8 * 10 - 8 * 10^6 * 10^3}{183} / = 0.746[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.12}$$

$$R_{armour} = \frac{13.8 * 10 - 8 * 10^6 * 10^3}{3141} / = 0.044[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.13}$$

For Array Cable with 500mm^2 copper conductor

$$R_{sheath} = \frac{13.8 * 10 - 8 * 10^6 * 10^3}{472} / = 0.2924[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.14}$$

$$R_{armour} = \frac{13.8 * 10 - 8 * 10^6 * 10^3}{4764} / = 0.029[\frac{\Omega}{km}] \text{ @ } 20°C \tag{8.15}$$

	185mm^2	500mm^2
Diameter of conductor	15.34[mm]	15.34[mm]
Distance between conductor axis	40[mm]	49.26[mm]
Area of sheath	183 [mm^2]	472[mm^2]
Area of armour	3141 [mm^2]	4764[mm^2]
Area of armour	3141 [mm^2]	4764[mm^2]
Mean diameter of armour	22.17 [mm]	66.50[mm]

Table 8: Cable Data

8.3.3 Proximity factor and Skin effect

Skin effect is given by:

$$\gamma_s = \frac{X_s}{192 + 0.8 \cdot (X_s)^4} \tag{8.16}$$

with

$$(X_s)^2 = \frac{8\pi \cdot f}{R} \cdot 10^-7 \cdot Ks \tag{8.17}$$

where

- f = supply frequency, Hz
- $Current_{rating}$ = Current at rated power [A]
- Ks = skin effect coefficient

For a three core cable proximity factor is given by:

$$\gamma_p = \frac{X_p}{192 + 0.8 \cdot (X_p)^4} \cdot \frac{d_c}{s}^2 \cdot (0.312 \cdot \frac{d_c}{s}^2 + \frac{1.18}{\frac{X_p}{192+0.8 \cdot (X_p)^4} + 0.27}) \tag{8.18}$$

with

$$(X_p)^2 = \frac{8\pi \cdot f}{R} \cdot 10^-7 \cdot Kp \tag{8.19}$$

where

- d_c = diameter of the conductor (mm)
- s = distance between conductor axis (mm)
- Kp = proximity effect coefficient

$Kp = Ks = 1$ from values given for round stranded copper conductors in standard IEC-60287.

8.4 Presentation of results

Main objectives in this master thesis is to bench mark the presented Loss Model with real data. The real data comes from WF1 provided by Company X. By comparing real output data from WF1 and simulated output values from the different Loss Models one can identify what Loss Models that are more accurate. The results are presented in a matrix to easy get a understanding and overview of the results, see figure 40.

8.4.1 Loss Factor

$\frac{Loss_{Simulated}}{Loss_{Measured}}$ is being used to relatively compare the different Loss Model simulations with real data. In other words making it possible to validate accuracy of the Loss Model.

Transformer loss, is calculated by adding each transformer loss in figure 22, mathematically given by:

$$Transformer_{Loss_{total}} = \sum_{i=1}^{6} TransformerLoss_{Bi} \tag{8.20}$$

where

$TransformerLoss_{Bi}$ = Transformer loss for turbine i[MWh]
i = number of wind transformers per string [−]
6 turbine transformers, see 10.

Array cable loss is calculated by adding each transformer loss in figure 22, mathematically given by:

$$\text{Transformer}_{\text{Loss}_{\text{total}}} = \sum_{i=1}^{6} \text{ArrayyLoss}_{\text{B}i} \tag{8.21}$$

where

$\text{ArrayLoss}_{\text{B}i}$ = Array cable loss for turbine i [MWh]
i = number of wind array cables per string [−]
6 array cables in String B, see 10.

8.4.2 Loss Model Matrix

As mention the results will be presented in a matrix. The matrix is made to present $\frac{\text{Loss}_{\text{Simulated}}}{\text{Loss}_{\text{Measured}}}$ for each combination of temperature and cable loss model. It also shows what temperature model that have been used, either constant or variable. In addition is also shows the percentage of each loss relative to the total loss, see figure 40.

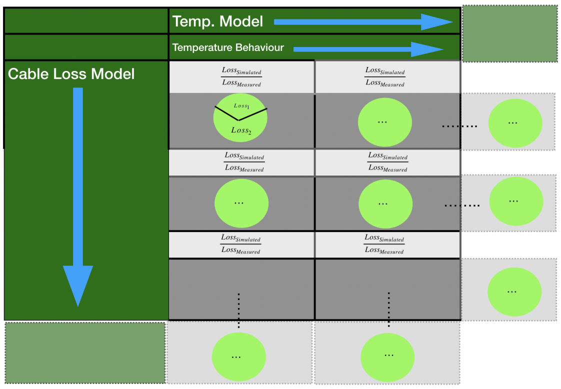

Figure 40: Result Matrix

8.5 MATLAB - Code

Code for one Loss Model including temperature model 2 and cable loss model 3 with variable temperature and resistance with proximity and skin effect.

```
%{
Master Thesis: Standarized loss model for Offshore Wind Farms
By EivLea
Version: ver.00.02232

   and Screen loss based on IEC 60287 for 1 cable
Comments: Losses based on Temperature model 2 with variable temperature for
conductor for 1 string.
Losses included: IR^2 losses + Sheat Loss + Armour Loss
%}

%----------------------LOSSES USING DC RESISTANCE FOR COPPER ----------------------

%Input
load('ReactivePower_DOW_B.mat'); %loading real reactive power data from string B [kVar]
load('ActivePower_DOW_B.mat');   %loading real active power data from string B   [kW]
%Active Power
DOWB06ActivePowerTimeaverage = table2array(DOWB06ActivePowerTimeaverage); %converting data type table to type double for DOWB string
DOWB05ActivePowerTimeaverage = table2array(DOWB05ActivePowerTimeaverage);
DOWB04ActivePowerTimeaverage = table2array(DOWB04ActivePowerTimeaverage);
DOWB03ActivePowerTimeaverage = table2array(DOWB03ActivePowerTimeaverage);
DOWB02ActivePowerTimeaverage = table2array(DOWB02ActivePowerTimeaverage);
DOWB01ActivePowerTimeaverage = table2array(DOWB01ActivePowerTimeaverage);
%Reactive Power
DOWB06ReactivePowerTimeaverage = table2array(DOWB06ReactivePowerTimeaverage); %converting data type table to type double for DOWB string
DOWB05ReactivePowerTimeaverage = table2array(DOWB05ReactivePowerTimeaverage);
DOWB04ReactivePowerTimeaverage = table2array(DOWB04ReactivePowerTimeaverage);
DOWB03ReactivePowerTimeaverage = table2array(DOWB03ReactivePowerTimeaverage);
DOWB02ReactivePowerTimeaverage = table2array(DOWB02ReactivePowerTimeaverage);
DOWB01ReactivePowerTimeaverage = table2array(DOWB01ReactivePowerTimeaverage);
```

```
%Output in [MWh], see own document

%Global variables for input from user for array cable
global V_array
global f
global Length
global Area
global C
global E_mean
global t
global t_s % Sheath Temperature [degress celcius]
global t_a % Armour Temperature [degress celcius]
global a   % Temperature coefficient for copper at 20 degrees celcius(IEC60287)
global a_s % Temperature coefficient for sheath at 20 degrees celcius
global a_a % Temperature coefficient for armour at 20 degrees celcius
global n_cables
global cosphi
global dc % diameter of the conductor [mm]
global s  % distance between conductor axis [mm]
global c  % Distance between the axis of a conductor and the cable centre[mm]

%Global variabels for array cables
global R_DC   %DC resistence
global R_20
global R_AC   %AC restistance
global R_90
global R_s_20 %Sheath resistance
global R_a    %Armour Resistance

%Global variables for sheath
global m_d   % Mean diameter of sheath or creen [mm]
global m_d_a % Mean diameter of armour [mm]

%Global parameteres for capacitance
global C_calc    % capacitance per unit length[F/m]
global tan_delta % loss factor of insulation [-]
global e         % reletive permittivity of insulation [-]
global Di        % external diameter of insulation(excluding screen [mm]

%Global parameters for Thermal resistance 1
global K     % Form factor
global rho_T % Thermal resistivity of insulation(T1) [K.m/W]
global G     % Geometric form factor, see appendix for calculation

%Global parameters for Thermal resistance 2
global G_marked
```

```
%Global variables for transformer
global S_transformer
global E_1
global E_2
global e_r

%TRANSFORMERS
global Rsc_1 %Short circuit resistance, primary side

%Data from company X
S_transformer = 6800e3;                      %[VA]
E_1 = 690;                                   %[V]
E_2 = 33e3;                                  %[V]
e_r = 0.9;                                   % Short circuit
    resistance in percent of rated voltage [-]
Rsc_1 = Rsc_1_calc(e_r,E_1,S_transformer); %Primary short
    circuit resistance [ohm];

P_noloadloss = 0.0006*S_transformer*1e-3; %No load losses [
    kW]

%Transformer B06, outer most Wind Turbine on String B
for i = 1:length(DOWB06ActivePowerTimeaverage) %for whole
    string of data
P_before_trans_B06(i) = DOWB06ActivePowerTimeaverage(i); %
    initializing active power[kW] deliverd from generator
    before transformator
Q_before_trans_B06(i) = DOWB06ReactivePowerTimeaverage(i); %
    initializing reactive power[kVAR] deliverd from generator
     before transformator
cosphi_real_data_B06(i) = P_before_trans_B06(i)/sqrt(
    P_before_trans_B06(i)^2+Q_before_trans_B06(i)^2);

P_generator_trans_loss_B06_RDC(i) =
    Generator_Transformer_Load_Loss_calc(P_before_trans_B06(i
    ),E_1, cosphi_real_data_B06(i),Rsc_1) + P_noloadloss; %
    load losses transformer [kW]
Output_trans_B06(i) = P_before_trans_B06(i) -
    P_generator_trans_loss_B06_RDC(i); %output from generator
     [kW]
end

%Transformer B05 on String B
for i = 1:length(DOWB05ActivePowerTimeaverage) %for whole
    string of data
P_before_trans_B05(i) = DOWB05ActivePowerTimeaverage(i); %
    initializing active power[kW] deliverd from generator
    before transformator
Q_before_trans_B05(i) = DOWB05ReactivePowerTimeaverage(i); %
    initializing reactive power[kVAR] deliverd from generator
     before transformator
cosphi_real_data_B05(i) = P_before_trans_B05(i)/sqrt(
```

```
    P_before_trans_B05(i)^2+Q_before_trans_B05(i)^2);

P_generator_trans_loss_B05_RDC(i) =
    Generator_Transformer_Load_Loss_calc(P_before_trans_B05(i
    ),E_1, cosphi_real_data_B05(i),Rsc_1) + P_noloadloss; %
    load losses transformer [kW]
Output_trans_B05(i) = P_before_trans_B05(i) -
    P_generator_trans_loss_B05_RDC(i); %output from generator
     [kW]
end

%Transformer B04 on String B
for i = 1:length(DOWB04ActivePowerTimeaverage) %for whole
    string of data
P_before_trans_B04(i) = DOWB04ActivePowerTimeaverage(i); %
    initializing active power[kW] deliverd from generator
    before transformator
Q_before_trans_B04(i) = DOWB04ReactivePowerTimeaverage(i); %
    initializing reactive power[kVAR] deliverd from generator
     before transformator
cosphi_real_data_B04(i) = P_before_trans_B04(i)/sqrt(
    P_before_trans_B04(i)^2+Q_before_trans_B04(i)^2);

P_generator_trans_loss_B04_RDC(i) =
    Generator_Transformer_Load_Loss_calc(P_before_trans_B04(i
    ),E_1, cosphi_real_data_B04(i),Rsc_1) + P_noloadloss; %
    load losses transformer [kW]
Output_trans_B04(i) = P_before_trans_B04(i) -
    P_generator_trans_loss_B04_RDC(i); %output from generator
     [kW]
end

%Transformer B03 on String B
for i = 1:length(DOWB03ActivePowerTimeaverage)           %
    for whole string of data
P_before_trans_B03(i) = DOWB03ActivePowerTimeaverage(i); %
    initializing active power[kW] deliverd from generator
    before transformator
if P_before_trans_B03(i)== 0 %WT not in use, but zero value
    can't be used in calculation later on
   P_before_trans_B03(i) = 0.0000000001;
end
Q_before_trans_B03(i) = DOWB03ReactivePowerTimeaverage(i); %
    initializing reactive power[kVAR] deliverd from generator
     before transformator
cosphi_real_data_B03(i) = P_before_trans_B03(i)/sqrt(
    P_before_trans_B03(i)^2+Q_before_trans_B03(i)^2);

P_generator_trans_loss_B03_RDC(i) =
    Generator_Transformer_Load_Loss_calc(P_before_trans_B03(i
    ),E_1, cosphi_real_data_B03(i),Rsc_1) + P_noloadloss; %
    load losses transformer [kW]
Output_trans_B03(i) = P_before_trans_B03(i) -
```

```
    P_generator_trans_loss_B03_RDC(i); %output from generator [kW]
end

%Transformer B02 on String B
for i = 1:length(DOWB02ActivePowerTimeaverage) %for whole string of data
P_before_trans_B02(i) = DOWB02ActivePowerTimeaverage(i); %initializing active power[kW] deliverd from generator before transformator
Q_before_trans_B02(i) = DOWB02ReactivePowerTimeaverage(i); %initializing reactive power[kVAR] deliverd from generator before transformator
cosphi_real_data_B02(i) = P_before_trans_B02(i)/sqrt(P_before_trans_B02(i)^2+Q_before_trans_B02(i)^2);

P_generator_trans_loss_B02_RDC(i) = Generator_Transformer_Load_Loss_calc(P_before_trans_B02(i),E_1, cosphi_real_data_B02(i),Rsc_1) + P_noloadloss; %load losses transformer [kW]
Output_trans_B02(i) = P_before_trans_B02(i) - P_generator_trans_loss_B02_RDC(i); %output from generator [kW]
end

%Transformer B01 on String B
for i = 1:length(DOWB01ActivePowerTimeaverage) %for whole string of data
P_before_trans_B01(i) = DOWB01ActivePowerTimeaverage(i); %initializing active power[kW] deliverd from generator before transformator
Q_before_trans_B01(i) = DOWB01ReactivePowerTimeaverage(i); %initializing reactive power[kVAR] deliverd from generator before transformator
cosphi_real_data_B01(i) = P_before_trans_B01(i)/sqrt(P_before_trans_B01(i)^2+Q_before_trans_B01(i)^2);

P_generator_trans_loss_B01_RDC(i) = Generator_Transformer_Load_Loss_calc(P_before_trans_B01(i),E_1, cosphi_real_data_B01(i),Rsc_1) + P_noloadloss; %load losses transformer [kW]
Output_trans_B01(i) = P_before_trans_B01(i) - P_generator_trans_loss_B01_RDC(i); %output from generator [kW]
end

%----------------------LOSSES USING DC RESISTANCE FOR COPPER---------------------

fprintf('R_DC model, Temp2. Loss Model 3');
fprintf('\n');
%ARRAY CABLES
```

```
V_array = 33e3; % 33kv [Wind Farm] [V]
f = 50;         % supply frequency [hz]
Length = 1;     % Length of array cable, data from Dudgeon [
   km]
Area = 185;     % Conductor cross-section [mm^2, data
   Company X
R_20 = 0.0931;  % resitivity @20 degress celcius calculated
   from IEC60028 [ohm/km]
%R_90 = 0.1188; % calculated from resitivity from IEC60028
   @90 degress celcius [ohm/km]
C  = 9.799e-11; % Per phase cable capacitance [F/m]
E_mean = 3000;  % Mean electric field voltage for insulation
    [Vrms/mm]
t = 90;         % maximum operating temperature of cable [
   degress Celcius]
t_s = 90;       % maximum operating temperature of sheath [
   degress Celcius] Same as t since this is baed on Temp.
   Model 1
a = 3.93e-3;    % Temperature coefficient for copper at 20
   degress based on IEC 60287
a_s = 4.5e-3;   % Temperature coefficient for steel at 20
   degress based on IEC 60287
n_cables = 1;   % Number of cables in paralell [-]
   Output_Array_cable_B06
cosphi = 1;     % power factor [-]

%Armour parameters
%t_a = 90;       % maximum operating temperature of sheath [
   degress Celcius] Same as t since this is baed on Temp.
   Model 1
a_a = 4.5e-3; % Temperature coefficient for steel at 20
   degress based on IEC 60287

%Temperature Model 2 calculations
tan_delta = 0.004; % for 36kv cable with XLPE insulation
e = 2.5;           % %for 36kv cable with XLPE insulation

%Parameters for T1
rho_T = 3.5;  % Thermal resistivity of insulation(T1) [K.m/W
   ]

array_index =1; %to index while loop
while array_index <= length(DOWB06ReactivePowerTimeaverage)
   %running through all elements

Area = 185; % Conductor cross-section [mm^2, data Company X
R_20 = 0.0931; % resistance @20 degress celcius calculated
   from IEC60028 [ohm/km]
current_rating_B06 = 116e-3; % [kA]
t_B06(array_index) = Temperature_Array_Cable_B06(
   Output_trans_B06(array_index),cosphi, n_cables, V_array,
   current_rating_B06); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B06(array_index),
```

```
    Length); % calculating DC cable resistance from IEC60287
    [ohm]
R_s_20 = 0.746; % resistance @20 degress celcius for steel
    calculated from IEC60028 for 185mm^2 copper conductor [
    ohm/km]
m_d = 18;     % Mean diameter of screen [mm]
s = 40;       % distance between conductor axis [mm]

%Parameters for Armour
R_a = 0.044; % resitivity @20 degress celcius for steel
    calculated from IEC60028 for 185mm^2 [ohm/km]
c = 24;       % Distance between the axis of a conductor and
    the cable centre for 185mm^2 conductor[mm]
m_d_a = 55;   % Mean diameter of armour [mm]

%Temperature Model 2 calculations
Di = 33;              % external diameter of insulation
    exluding screen for 185mm^2 [mm]
dc = 15.34;           % diameter of the 185mm^2 conductor [mm]
C_calc = Capacitance_Calc(e, Di, dc); %Per phase cable
    capacitance [F/m]'
d_loss = Dielectric_Loss_Calc(f, C_calc,V_array, tan_delta,
    Length,n_cables); %  dielectric loss [kW]

%Parameters for T1
K = 0.5;      % Screening factor for 185mm^2 cable
G = 1.4;      % Geometric form factor for 185mm^2 cable
T1 = T1_Calc(K, rho_T,G); % Thermal resistance per core
    between conductor and sheath [K.m/W]

%Parameters for T2
G_marked = 0.011; %for 185mm^2 cable
T2 = T2_Calc(rho_T,G_marked);

%ARRAY CABLE B06
P_copper_B06(array_index)= Copper_Losses_DC(Output_trans_B06
    (array_index),cosphi, n_cables, V_array,R_DC); % I^2R
    losses[kW]
t_s_B06(array_index) = Temperature_Sheath_Screen_Calc(t_B06(
    array_index), P_copper_B06(array_index), d_loss, T1); %
    Temp. Sheath [ C ]
S_loss_B06(array_index) = Sheath_Loss_Calc(P_copper_B06(
    array_index),t_s_B06(array_index),R_DC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B06(array_index) = (Output_trans_B06(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
           % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B06(array_index),R_DC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B06(array_index)= Temperature_Armour_Calc(t_s_B06(
    array_index),I_cable_Ampere_B06(array_index),R_DC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B06(array_index) =  Armour_Loss_Calc(P_copper_B06(
```

```
    array_index),t_a_B06(array_index),R_DC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B06(array_index)= Output_trans_B06(
    array_index) - P_copper_B06(array_index) - S_loss_B06(
    array_index)- A_Loss_B06(array_index); %[kW]
Loss_array_B06_RDC(array_index)= P_copper_B06(array_index) +
     S_loss_B06(array_index)+ A_Loss_B06(array_index); %loss
    in array cable B06-B05 [kW]

I_cable_B06(array_index) = Output_trans_B06(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B06(array_index) = Loss_array_B06_RDC(
    array_index)/ Output_Array_cable_B06(array_index); %[-]

%ARRAY CABLE B05
Power_input_B05(array_index) = Output_Array_cable_B06(
    array_index) + Output_trans_B05(array_index); %input
    power to Array cable B05

current_rating_B05 = 232e-3; % [kA]
t_B05(array_index) = Temperature_Array_Cable_B06(
    Power_input_B05(array_index),cosphi, n_cables, V_array,
    current_rating_B05); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B05(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm]

P_copper_B05(array_index)= Copper_Losses_DC(Power_input_B05(
    array_index),cosphi, n_cables, V_array,R_DC); %I^2R
    losses[kW]
t_s_B05(array_index) = Temperature_Sheath_Screen_Calc(t_B05(
    array_index), P_copper_B05(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B05(array_index) = Sheath_Loss_Calc(P_copper_B05(
    array_index),t_s_B05(array_index),R_DC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B05(array_index) = (Output_trans_B05(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
           % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B05(array_index),R_DC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B05(array_index)= Temperature_Armour_Calc(t_s_B05(
    array_index),I_cable_Ampere_B05(array_index),R_DC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B05(array_index) =  Armour_Loss_Calc(P_copper_B05(
    array_index),t_a_B05(array_index),R_DC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B05(array_index)= Power_input_B05(
    array_index) - P_copper_B05(array_index)- S_loss_B05(
    array_index)- A_Loss_B05(array_index); %[kW]
Loss_array_B05_RDC(array_index)= P_copper_B05(array_index)+
```

```
    S_loss_B05(array_index)+ A_Loss_B05(array_index); %loss in array cable B05-B04 [kW]

I_cable_B05(array_index) = Power_input_B05(array_index)/(sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B05(array_index) = Loss_array_B05_RDC(array_index)/ Output_Array_cable_B05(array_index); %[-]

%ARRAY CABLE B04
Power_input_B04(array_index) = Output_Array_cable_B05(array_index) + Output_trans_B04(array_index); %input power to Array cable B04

current_rating_B04 = 350e-3; % [kA]
t_B04(array_index) = Temperature_Array_Cable_B06(Power_input_B04(array_index),cosphi, n_cables, V_array, current_rating_B04); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B04(array_index), Length);  % calculating DC cable resistance from IEC60287 [ohm

P_copper_B04(array_index)= Copper_Losses_DC(Power_input_B04(array_index),cosphi, n_cables, V_array,R_DC); %I^2R losses[kW]
t_s_B04(array_index) = Temperature_Sheath_Screen_Calc(t_B04(array_index), P_copper_B04(array_index), d_loss, T1); % temperature sheath [degress Celcius]
S_loss_B04(array_index) = Sheath_Loss_Calc(P_copper_B04(array_index),t_s_B04(array_index),R_DC, m_d,s,f,Length, a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B04(array_index) = (Output_trans_B04(array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;         % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B04(array_index),R_DC, m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B04(array_index)= Temperature_Armour_Calc(t_s_B04(array_index),I_cable_Ampere_B04(array_index),R_DC,Lambda1,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B04(array_index) =  Armour_Loss_Calc(P_copper_B04(array_index),t_a_B04(array_index),R_DC, m_d_a,c,f,Length, a_a,R_a); %Armour loss [kW]


Output_Array_cable_B04(array_index)= Power_input_B04(array_index) - P_copper_B04(array_index)- S_loss_B04(array_index)-A_Loss_B04(array_index); %[kW]
Loss_array_B04_RDC(array_index)= P_copper_B04(array_index)+ S_loss_B04(array_index)+ A_Loss_B04(array_index); %loss in array cable B04-B03 [kW]

I_cable_B04(array_index) = Power_input_B04(array_index)/(sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B04(array_index) = Loss_array_B04_RDC(
```

```
    array_index)/ Output_Array_cable_B04(array_index); %[-]

%ARRAY CABLE B03
Power_input_B03(array_index) = Output_Array_cable_B04(
    array_index) + Output_trans_B03(array_index); %input
    power to Array cable B03

current_rating_B03 = 476e-3; % [kA]
t_B03(array_index) = Temperature_Array_Cable_B06(
    Power_input_B03(array_index),cosphi, n_cables, V_array,
    current_rating_B03); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B03(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm

P_copper_B03(array_index)= Copper_Losses_DC(Power_input_B03(
    array_index),cosphi, n_cables, V_array,R_DC); %I^2R
    losses[kW]
t_s_B03(array_index) = Temperature_Sheath_Screen_Calc(t_B03(
    array_index), P_copper_B03(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B03(array_index) = Sheath_Loss_Calc(P_copper_B03(
    array_index),t_s_B03(array_index),R_DC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B03(array_index) = (Output_trans_B03(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
          % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B03(array_index),R_DC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B03(array_index)= Temperature_Armour_Calc(t_s_B03(
    array_index),I_cable_Ampere_B03(array_index),R_DC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B03(array_index) =  Armour_Loss_Calc(P_copper_B03(
    array_index),t_a_B03(array_index),R_DC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B03(array_index)= Power_input_B03(
    array_index) - P_copper_B03(array_index)- S_loss_B03(
    array_index)-A_Loss_B03(array_index); %[kW]
Loss_array_B03_RDC(array_index)= P_copper_B03(array_index)+
    S_loss_B03(array_index)+ A_Loss_B03(array_index); %loss
    in array cable B03-B02 [kW]

I_cable_B03(array_index) = Power_input_B03(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B03(array_index) = Loss_array_B03_RDC(
    array_index)/ Output_Array_cable_B03(array_index); %[-]

%-------------------New dimension of Array Cable 500 [mm]

Area = 500;                                   % Conductor
    cross-section [mm^2], data Company X
R_20 = 0.0345;                                % resitivity
```

```
    @20 degress celcius calculated from IEC60028 for 500mm^2
    [ohm/km]
R_DC = DC_resistance_calc(R_20, a, t, Length); % calculating
     DC cable resistance from IEC60287 [ohm]
R_s_20 = 0.2924;                                   % resistance
     @20 degress celcius for steel calculated from IEC60028
    for 472mm^2 sheat [ohm/km]

s = 49.26;                                         % distance
    between 500mm^2 conductor axis [mm]
m_d = 22.17;                                       % Mean
    diameter of screen for 500mm^2 [mm]

%Parameters for Armour
c = 30.1;       % Distance between the axis of a conductor
    and the cable centre for 500mm^2 conductor[mm]
R_a = 0.029;    % resitivity @20 degress celcius for steel
    calculated from IEC60028 for 500mm^2 [ohm/km]
m_d_a = 66.5;  % Mean diameter of armour [mm]

%Temperature Model 2 calculations
Di = 45.1;             % external diameter of insulation
    exluding screen for 500mm^2 [mm]
dc = 25.24;            % diameter of the 500 mm^2 conductor [
    mm]
C_calc = Capacitance_Calc(e, Di, dc); %Per phase cable
    capacitance [F/m]'
d_loss = Dielectric_Loss_Calc(f, C_calc,V_array, tan_delta,
    Length,n_cables); %  dielectric loss [kW]

%Parameters for T1
K = 0.4;      % Screening factor for 500mm^2 cable
G = 1.05;      % Geometric form factor for 500mm^2 cable
T1 = T1_Calc(K, rho_T,G); % Thermal resistance per core
    between conductor and sheath [K.m/W]

%Parameters for T2
G_marked = 0.012; %for 500mm^2 cable
T2 = T2_Calc(rho_T,G_marked);

%ARRAY CABLE B02
Power_input_B02(array_index) = Output_Array_cable_B03(
    array_index) + Output_trans_B02(array_index);        %
    input power to Array cable B02

current_rating_B02 = 583e-3; % [kA]
t_B02(array_index) = Temperature_Array_Cable_B06(
    Power_input_B02(array_index),cosphi, n_cables, V_array,
    current_rating_B02); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B02(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm
```

```
P_copper_B02(array_index)= Copper_Losses_DC(Power_input_B02(
    array_index),cosphi, n_cables, V_array,R_DC); %I^2R
    losses[kW]
t_s_B02(array_index) = Temperature_Sheath_Screen_Calc(t_B02(
    array_index), P_copper_B02(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B02(array_index) = Sheath_Loss_Calc(P_copper_B02(
    array_index),t_s_B02(array_index),R_DC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B02(array_index) = (Output_trans_B02(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
           % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B02(array_index),R_DC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B02(array_index)= Temperature_Armour_Calc(t_s_B02(
    array_index),I_cable_Ampere_B02(array_index),R_DC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B02(array_index) =  Armour_Loss_Calc(P_copper_B02(
    array_index),t_a_B02(array_index),R_DC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B02(array_index)= Power_input_B02(
    array_index) - P_copper_B02(array_index)- S_loss_B02(
    array_index)-A_Loss_B02(array_index);            %[kW]
Loss_array_B02_RDC(array_index)= P_copper_B02(array_index)+
    S_loss_B02(array_index)+ A_Loss_B02(array_index);
                                                %loss in
    array cable B02-B01 [kW]

I_cable_B02(array_index) = Power_input_B02(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables);        %[kA]
Prosent_Loss_B02(array_index) = Loss_array_B02_RDC(
    array_index)/ Output_Array_cable_B02(array_index); %[-]

%ARRAY CABLE B01
Power_input_B01(array_index) = Output_Array_cable_B02(
    array_index) + Output_trans_B01(array_index); %input
    power to Array cable B01

current_rating_B01 = 700e-3; % [kA]
t_B01(array_index) = Temperature_Array_Cable_B06(
    Power_input_B01(array_index),cosphi, n_cables, V_array,
    current_rating_B01); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B01(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm]

P_copper_B01(array_index)= Copper_Losses_DC(Power_input_B01(
    array_index),cosphi, n_cables, V_array,R_DC); %I^2R
    losses[kW]
t_s_B01(array_index) = Temperature_Sheath_Screen_Calc(t_B01(
    array_index), P_copper_B01(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
```

```
S_loss_B01(array_index) = Sheath_Loss_Calc(P_copper_B01(array_index),t_s_B01(array_index),R_DC, m_d,s,f,Length,a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B01(array_index) = (Output_trans_B01(array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;        % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B01(array_index),R_DC,m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B01(array_index)= Temperature_Armour_Calc(t_s_B01(array_index),I_cable_Ampere_B01(array_index),R_DC,Lambda1,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B01(array_index) =  Armour_Loss_Calc(P_copper_B01(array_index),t_a_B06(array_index),R_DC, m_d_a,c,f,Length,a_a,R_a); %Armour loss [kW]

Output_Array_cable_B01(array_index)= Power_input_B01(array_index) - P_copper_B01(array_index)- S_loss_B01(array_index)-A_Loss_B01(array_index); %[kW]
Loss_array_B01_RDC(array_index)= P_copper_B01(array_index)+S_loss_B01(array_index)+A_Loss_B01(array_index); %loss in array cable B01-Substation Platform [kW]

I_cable_B01(array_index) = Power_input_B01(array_index)/(sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B01(array_index) = Loss_array_B01_RDC(array_index)/ Output_Array_cable_B01(array_index); %[-]

array_index = array_index + 1; %determiate while loop
end

Mean_prosent_loss_B06 = mean(Prosent_Loss_B06); % Mean Array Cable B06 Loss[kW]/Output B06[kW] [-]
Mean_prosent_loss_B05 = mean(Prosent_Loss_B05); % Mean Array Cable B05 Loss[kW]/Output B05[kW] [-]
Mean_prosent_loss_B04 = mean(Prosent_Loss_B04); % Mean Array Cable B04 Loss[kW]/Output B04[kW] [-]
Mean_prosent_loss_B03 = mean(Prosent_Loss_B03); % Mean Array Cable B03 Loss[kW]/Output B03[kW] [-]
Mean_prosent_loss_B02 = mean(Prosent_Loss_B02); % Mean Array Cable B02 Loss[kW]/Output B02[kW] [-]
Mean_prosent_loss_B01 = mean(Prosent_Loss_B01); % Mean Array Cable B01 Loss[kW]/Output B01[kW] [-]

%LOSS TURBINE TRANSFORMER STRING B
Loss_Transformator_StringB_R_DC_Total_kW = sum(P_generator_trans_loss_B06_RDC)+sum(P_generator_trans_loss_B05_RDC)+sum(P_generator_trans_loss_B04_RDC)+sum(P_generator_trans_loss_B03_RDC)+sum(P_generator_trans_loss_B02_RDC)+sum(P_generator_trans_loss_B01_RDC); %[kW]
Loss_Transformator_StringB_R_DC_Total_kWh = Loss_Transformator_StringB_R_DC_Total_kW.*(1/6);      %[
```

```
kWh]
Loss_Transformator_StringB_R_DC_Total_MWh = Loss_Transformator_StringB_R_DC_Total_kWh.*(1/1000); %[MWh]
Turbine_Transformors_StringB_RDC_Loss_MWh = Loss_Transformator_StringB_R_DC_Total_MWh %[MWh]

%LOSS ARRAY CABLES STRING B
Loss_Array_Cables_kW = sum(Loss_array_B06_RDC)+sum(Loss_array_B05_RDC)+sum(Loss_array_B04_RDC)+sum(Loss_array_B03_RDC)+sum(Loss_array_B02_RDC)+sum(Loss_array_B01_RDC); % [kW]
Loss_Array_Cables_kWh = Loss_Array_Cables_kW.*(1/6); %[kWh]
Loss_Array_Cables_MWh = Loss_Array_Cables_kWh.*(1/1000); %[MWh]
Array_Cables_StringB_RDC_Loss_MWh = Loss_Array_Cables_MWh %[MWh]

%COPPER LOSS ARRAY CABLES STRING B
Copper_Loss_StringB_kW = sum(P_copper_B06)+sum(P_copper_B05)+sum(P_copper_B04)+sum(P_copper_B03)+sum(P_copper_B02)+sum(P_copper_B01); % [kW]
Copper_Loss_StringB_kWh = Copper_Loss_StringB_kW.*(1/6); %[kWh]
Copper_Loss_StringB_MWh = Copper_Loss_StringB_kWh.*(1/1000); %[MWh]
Copper_Loss_StringB_RDC_Loss_MWh = Copper_Loss_StringB_MWh %[MWh]

%SHEATH LOSS ARRAY CABLES STRING B
Sheath_Loss_StringB_kW = sum(S_loss_B06)+sum(S_loss_B05)+sum(S_loss_B04)+sum(S_loss_B03)+sum(S_loss_B02)+sum(S_loss_B01); % [kW]
Sheath_Loss_StringB_kWh = Sheath_Loss_StringB_kW.*(1/6); %[kWh]
Sheath_Loss_StringB_MWh = Sheath_Loss_StringB_kWh.*(1/1000); %[MWh]
Sheath_Loss_StringB_RDC_Loss_MWh = Sheath_Loss_StringB_MWh %[MWh]

%ARMOUR LOSS ARRAY CABLES STRING B
Armour_Loss_StringB_kW = sum(A_Loss_B06)+sum(A_Loss_B05)+sum(A_Loss_B04)+sum(A_Loss_B03)+sum(A_Loss_B02)+sum(A_Loss_B01); % [kW]
Armour_Loss_StringB_kWh = Armour_Loss_StringB_kW.*(1/6); %[kWh]
Armour_Loss_StringB_MWh = Armour_Loss_StringB_kWh.*(1/1000); %[MWh]
Armour_Loss_StringB_RDC_Loss_MWh = Armour_Loss_StringB_MWh %[MWh]
```

```
%INPUT POWER STRING B
Input_StringB_kW = sum(P_before_trans_B06)+sum(
    P_before_trans_B05)+sum(P_before_trans_B04)+sum(
    P_before_trans_B03)+sum(P_before_trans_B02)+sum(
    P_before_trans_B01); %[kW]
Input_StringB_kWh = Input_StringB_kW.*(1/6);
                   % [kWh]
Input_StringB_MWh = Input_StringB_kWh.*(1/1000);
               % [MWh]
El_Input_Simulated_StringB_March_MWh_RDC = Input_StringB_MWh
    ; % Total power input simulated March String B [MWh]

%OUTPUT POWER STRING B
Output_StringB_kWh = Output_Array_cable_B01.*(1/6);
                   % [kWh];
Output_StringB_MWh = Output_StringB_kWh.*(1/1000);
                    % [MWh]
El_output_Simulated_StringB_March_MWh_RDC = sum(
    Output_StringB_MWh) % Total power output Simulated March
    String B [MWh]

Loss_Factor_Simulated_RDC =
    El_output_Simulated_StringB_March_MWh_RDC/
    El_Input_Simulated_StringB_March_MWh_RDC %[-]

%{
plot(Prosent_Loss_B06,'g') %plotting array Cable B06 Loss[kW
    ]/Output B06[kW]
xlabel('Time [Minutes] x 10');
ylabel('Array Cable B06 Loss[kW]/Output B06[kW]');
%}

%----------------------LOSSES USING AC RESISTANCE FOR COPPER
    ---------------------

%SAME OUTPUT FOR TRANSFORMERS, see code above for
    transformer equations
fprintf('R_AC model,Temp2, Loss Model 3');
fprintf('\n');

%ARRAY CABLES

V_array = 33e3; % array voltage (33Kv) [Wind Farm] [V]
f = 50;         % supply frequency [hz]
Length = 1;     % Length of array cable, data from Dudgeon [
    km]
Area = 185;     % Conductor cross-section [mm^2, data
    Company X
R_20 = 0.0931;  % resitivity @20 degress celcius calculated
    from IEC60028 for 185mm^2 copper conductor [ohm/km]
%R_90 = 0.1188; % calculated from resitivity from IEC60028
    @90 degress celcius [ohm/km]
C  = 9.799e-11; % Per phase cable capacitance [F/m]
```

```
E_mean = 3000;  % Mean electric field voltage for insulation [Vrms/mm]
t = 90;         % maximum operating temperature of cable [degress Celcius]
a = 3.93e-3;    % Temperature coefficient for copper at 20 degress based on IEC 60287
n_cables = 1;   % Number of cables in paralell [-]
cosphi = 1;     % power factor [-]


array_index =1; %to index while loop

while array_index <= length(DOWB06ReactivePowerTimeaverage) %running through all elements

%For R_AC calculations 185mm^2
R_20 = 0.0931;                                               % resitivity @20 degress celcius calculated from IEC60028 for 185mm^2 copper conductor [ohm/km]
current_rating_B06 = 116e-3; % [kA]
t_B06(array_index) = Temperature_Array_Cable_B06(Output_trans_B06(array_index),cosphi, n_cables, V_array, current_rating_B06); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B06(array_index), Length); % calculating DC cable resistance from IEC60287
dc = 15.34;                                                  % diameter of 185mm^2 conductor [mm]
s = 40;                                                      % distance between 185mm^2 conductor axis [mm]
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                           % [ohm]

%Parameters for Sheath/Screen
R_s_20 = 0.746; % resistance @20 degress celcius for steel calculated from IEC60028 for 185mm^2 sheath [ohm/km]
m_d = 18;     % Mean diameter of screen [mm]
s = 40;       % distance between conductor axis [mm]

%Parameters for Armour
R_a = 0.044; % resitivity @20 degress celcius for steel calculated from IEC60028 for 185mm^2 [ohm/km]
c = 24;       % Distance between the axis of a conductor and the cable centre for 185mm^2 conductor[mm]
m_d_a = 55;  % Mean diameter of armour [mm]

%Temperature Model 2 calculations
Di = 33;            % external diameter of insulation exluding screen for 185mm^2 [mm]
dc = 15.34;         % diameter of the 185mm^2 conductor [mm]
C_calc = Capacitance_Calc(e, Di, dc); %Per phase cable capacitance [F/m]'
d_loss = Dielectric_Loss_Calc(f, C_calc,V_array, tan_delta,
```

```
    Length,n_cables); %  dielectric loss [kW]

%Parameters for T1
K = 0.5;      % Screening factor for 185mm^2 cable
G = 1.4;      % Geometric form factor for 185mm^2 cable
T1 = T1_Calc(K, rho_T,G); % Thermal resistance per core
    between conductor and sheath [K.m/W]

%Parameters for T2
G_marked = 0.011; %for 185mm^2 cable
T2 = T2_Calc(rho_T,G_marked);


%ARRAY CABLE B06
P_copper_B06(array_index)= Copper_Losses_DC(Output_trans_B06
    (array_index),cosphi, n_cables, V_array,R_AC); %I^2R
    losses[kW]
t_s_B06(array_index) = Temperature_Sheath_Screen_Calc(t_B06(
    array_index), P_copper_B06(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B06(array_index) = Sheath_Loss_Calc(P_copper_B06(
    array_index),t_s_B06(array_index),R_AC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B06(array_index) = (Output_trans_B06(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
            % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B06(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B06(array_index)= Temperature_Armour_Calc(t_s_B06(
    array_index),I_cable_Ampere_B06(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B06(array_index) =  Armour_Loss_Calc(P_copper_B06(
    array_index),t_a_B06(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B06(array_index)= Output_trans_B06(
    array_index) - P_copper_B06(array_index)- S_loss_B06(
    array_index)-A_Loss_B06(array_index); %[kW]
Loss_array_B06_RAC(array_index)= P_copper_B06(array_index)+
    S_loss_B06(array_index)+A_Loss_B06(array_index); %loss in
     array cable B06-B05 [kW]

I_cable_B06(array_index) = Output_trans_B06(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B06(array_index) = Loss_array_B06_RAC(
    array_index)/ Output_Array_cable_B06(array_index); %[-]

%ARRAY CABLE B05
Power_input_B05(array_index) = Output_Array_cable_B06(
    array_index) + Output_trans_B05(array_index); %input
    power to Array cable B05

current_rating_B05 = 232e-3; % [kA]
```

```
t_B05(array_index) = Temperature_Array_Cable_B06(
    Power_input_B05(array_index),cosphi, n_cables, V_array,
    current_rating_B05); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B05(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC
    resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                  % [ohm]

P_copper_B05(array_index)= Copper_Losses_DC(Power_input_B05(
    array_index),cosphi, n_cables, V_array,R_AC); %I^2R
    losses[kW]
t_s_B05(array_index) = Temperature_Sheath_Screen_Calc(t_B05(
    array_index), P_copper_B04(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B05(array_index) = Sheath_Loss_Calc(P_copper_B05(
    array_index),t_s_B05(array_index),R_AC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B05(array_index) = (Output_trans_B05(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
           % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B05(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B05(array_index)= Temperature_Armour_Calc(t_s_B05(
    array_index),I_cable_Ampere_B05(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B05(array_index) =  Armour_Loss_Calc(P_copper_B05(
    array_index),t_a_B05(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B05(array_index)= Power_input_B05(
    array_index) - P_copper_B05(array_index)- S_loss_B05(
    array_index)-A_Loss_B05(array_index); %[kW]
Loss_array_B05_RAC(array_index)= P_copper_B05(array_index)+
    S_loss_B05(array_index)+A_Loss_B05(array_index); %loss in
     array cable B05-B04 [kW]

I_cable_B05(array_index) = Power_input_B05(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B05(array_index) = Loss_array_B05_RAC(
    array_index)/ Output_Array_cable_B05(array_index); %[-]

%ARRAY CABLE B04
Power_input_B04(array_index) = Output_Array_cable_B05(
    array_index) + Output_trans_B04(array_index); %input
    power to Array cable B04

current_rating_B04 = 350e-3; % [kA]
t_B04(array_index) = Temperature_Array_Cable_B06(
    Power_input_B04(array_index),cosphi, n_cables, V_array,
    current_rating_B04); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B04(array_index),
```

```
    Length);  % calculating DC cable resistance from IEC60287
     [ohm]
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC
    resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                % [ohm]


P_copper_B04(array_index)= Copper_Losses_DC(Power_input_B04(
    array_index),cosphi, n_cables, V_array,R_AC); %I^2R
    losses[kW]
t_s_B04(array_index) = Temperature_Sheath_Screen_Calc(t_B04(
    array_index), P_copper_B04(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B04(array_index) = Sheath_Loss_Calc(P_copper_B04(
    array_index),t_s_B04(array_index),R_AC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B04(array_index) = (Output_trans_B04(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
           % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B04(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B04(array_index)= Temperature_Armour_Calc(t_s_B04(
    array_index),I_cable_Ampere_B04(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B04(array_index) =  Armour_Loss_Calc(P_copper_B04(
    array_index),t_a_B04(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B04(array_index)= Power_input_B04(
    array_index) - P_copper_B04(array_index)- S_loss_B04(
    array_index)-A_Loss_B04(array_index); %[kW]
Loss_array_B04_RAC(array_index)= P_copper_B04(array_index)+
    S_loss_B04(array_index)+A_Loss_B04(array_index); %loss in
     array cable B04-B03 [kW]

I_cable_B04(array_index) = Power_input_B04(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B04(array_index) = Loss_array_B04_RAC(
    array_index)/ Output_Array_cable_B04(array_index); %[-]

%ARRAY CABLE B03
Power_input_B03(array_index) = Output_Array_cable_B04(
    array_index) + Output_trans_B03(array_index); %input
    power to Array cable B03

current_rating_B03 = 476e-3; % [kA]
t_B03(array_index) = Temperature_Array_Cable_B06(
    Power_input_B03(array_index),cosphi, n_cables, V_array,
    current_rating_B03); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B03(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC
```

```
    resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                      % [ohm]

P_copper_B03(array_index)= Copper_Losses_DC(Power_input_B03(
    array_index),cosphi, n_cables, V_array,R_AC); %I^2R
    losses[kW]
t_s_B03(array_index) = Temperature_Sheath_Screen_Calc(t_B03(
    array_index), P_copper_B03(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B03(array_index) = Sheath_Loss_Calc(P_copper_B03(
    array_index),t_s_B03(array_index),R_AC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B03(array_index) = (Output_trans_B03(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
            % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B03(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B03(array_index)= Temperature_Armour_Calc(t_s_B03(
    array_index),I_cable_Ampere_B03(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B03(array_index) =  Armour_Loss_Calc(P_copper_B03(
    array_index),t_a_B03(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B03(array_index)= Power_input_B03(
    array_index) - P_copper_B03(array_index)- S_loss_B03(
    array_index)-A_Loss_B03(array_index); %[kW]
Loss_array_B03_RAC(array_index)= P_copper_B03(array_index)+
    S_loss_B03(array_index)+A_Loss_B03(array_index); %loss in
     array cable B03-B02 [kW]

I_cable_B03(array_index) = Power_input_B03(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B03(array_index) = Loss_array_B03_RAC(
    array_index)/ Output_Array_cable_B03(array_index); %[-]

%-------------------New dimension of Array Cable 500 [mm]

Area = 500;                                             %
    Conductor cross-section [mm^2], data Company X
R_20 = 0.0345;                                          %
    resitivity for 500mm^2 conductor @20 degress celcius
    calculated from IEC60028 [ohm/km]
current_rating_B02 = 583e-3; % [kA]
t_B02(array_index) = Temperature_Array_Cable_B06(
    Power_input_B02(array_index),cosphi, n_cables, V_array,
    current_rating_B02); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B02(array_index),
    Length);    % calculating DC cable resistance for 500mm^2
     conductor from IEC60287 [ohm]
dc = 25.23;                                                %
    diameter of 500mm^2 conductor[mm]
s = 49.26;                                                 %
```

```
    distance between 500mm^2 conductor axis [mm]
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                % 500mm^2 conductor resistance [ohm]

R_s_20 = 0.2924;                                   % resistance @20 degress celcius for steel calculated from IEC60028 for 472mm^2 sheat [ohm/km]

s = 49.26;                                         % distance between 500mm^2 conductor axis [mm]
m_d = 22.17;                                       % Mean diameter of screen for 500mm^2 [mm]

%Parameters for Armour
c = 30.1;       % Distance between the axis of a conductor and the cable centre for 500mm^2 conductor[mm]
R_a = 0.029; % resitivity @20 degress celcius for steel calculated from IEC60028 for 500mm^2 [ohm/km]
m_d_a = 66.5;  % Mean diameter of armour [mm]

%Temperature Model 2 calculations
Di = 45.1;            % external diameter of insulation exluding screen for 500mm^2 [mm]
dc = 25.24;           % diameter of the 500 mm^2 conductor [mm]
C_calc = Capacitance_Calc(e, Di, dc); %Per phase cable capacitance [F/m]'
d_loss = Dielectric_Loss_Calc(f, C_calc,V_array, tan_delta, Length,n_cables); %  dielectric loss [kW]

%Parameters for T1
K = 0.4;      % Screening factor for 500mm^2 cable
G = 1.05;      % Geometric form factor for 500mm^2 cable
T1 = T1_Calc(K, rho_T,G); % Thermal resistance per core between conductor and sheath [K.m/W]

%Parameters for T2
G_marked = 0.012; %for 500mm^2 cable
T2 = T2_Calc(rho_T,G_marked);


%ARRAY CABLE B02
Power_input_B02(array_index) = Output_Array_cable_B03(array_index) + Output_trans_B02(array_index);       % input power to Array cable B02
P_copper_B02(array_index)= Copper_Losses_DC(Power_input_B02(array_index),cosphi, n_cables, V_array,R_AC); %I^2R losses[kW]
t_s_B02(array_index) = Temperature_Sheath_Screen_Calc(t_B02(array_index), P_copper_B02(array_index), d_loss, T1); % temperature sheath [degress Celcius]
```

```
S_loss_B02(array_index) = Sheath_Loss_Calc(P_copper_B02(
    array_index),t_s_B02(array_index),R_AC, m_d,s,f,Length,
    a_s,R_s_20); % Sheath loss [kW]
I_cable_Ampere_B02(array_index) = (Output_trans_B02(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
            % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B02(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B02(array_index)= Temperature_Armour_Calc(t_s_B02(
    array_index),I_cable_Ampere_B02(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B02(array_index) =  Armour_Loss_Calc(P_copper_B02(
    array_index),t_a_B02(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B02(array_index)= Power_input_B02(
    array_index) - P_copper_B02(array_index)- S_loss_B02(
    array_index)-A_Loss_B02(array_index);            %[kW]
Loss_array_B02_RAC(array_index)= P_copper_B02(array_index)+
    S_loss_B02(array_index)+A_Loss_B02(array_index);
                                                       %loss
    in array cable B02-B01 [kW]

I_cable_B02(array_index) = Power_input_B02(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables);        %[kA]
Prosent_Loss_B02(array_index) = Loss_array_B02_RAC(
    array_index)/ Output_Array_cable_B02(array_index); %[-]

%ARRAY CABLE B01
Power_input_B01(array_index) = Output_Array_cable_B02(
    array_index) + Output_trans_B01(array_index); %input
    power to Array cable B01

current_rating_B01 = 700e-3; % [kA]
t_B01(array_index) = Temperature_Array_Cable_B06(
    Power_input_B01(array_index),cosphi, n_cables, V_array,
    current_rating_B01); % [ C ]
R_DC = DC_resistance_calc(R_20, a, t_B01(array_index),
    Length);  % calculating DC cable resistance from IEC60287
     [ohm]
R_AC_per_meter = AC_Resistance_Calc(R_DC,dc,s,f); % AC
    resistance based on IEC 60287 1-1 2006 [ohm/m]
R_AC = R_AC_per_meter*1000*Length;                 % 500mm^2
    conductor resistance [ohm]

P_copper_B01(array_index)= Copper_Losses_DC(Power_input_B01(
    array_index),cosphi, n_cables, V_array,R_AC); %I^2R
    losses[kW]
t_s_B01(array_index) = Temperature_Sheath_Screen_Calc(t_B01(
    array_index), P_copper_B01(array_index), d_loss, T1); %
    temperature sheath [degress Celcius]
S_loss_B01(array_index) = Sheath_Loss_Calc(P_copper_B01(
    array_index),t_s,R_AC, m_d,s,f,Length,a_s,R_s_20); %
```

```
    Sheath loss [kW]
I_cable_Ampere_B01(array_index) = (Output_trans_B01(
    array_index)/(sqrt(3)*V_array*cosphi*n_cables))*1000/3;
            % RMS for one cable[A]
Lambda1 = lambda_marked_1_calc(t_s_B01(array_index),R_AC,
    m_d,s,f,Length,a_s,R_s_20); %Loss factor for sheath [-]
t_a_B01(array_index)= Temperature_Armour_Calc(t_s_B01(
    array_index),I_cable_Ampere_B01(array_index),R_AC,Lambda1
    ,d_loss,3,T2); %temperature armour[degress celcius]
A_Loss_B01(array_index) =  Armour_Loss_Calc(P_copper_B01(
    array_index),t_a_B01(array_index),R_AC, m_d_a,c,f,Length,
    a_a,R_a); %Armour loss [kW]

Output_Array_cable_B01(array_index)= Power_input_B01(
    array_index) - P_copper_B01(array_index)- S_loss_B01(
    array_index)-A_Loss_B01(array_index); %[kW]
Loss_array_B01_RAC(array_index)= P_copper_B01(array_index)+
    S_loss_B01(array_index)+A_Loss_B01(array_index); %loss in
     array cable B01-Substation Platform [kW]

I_cable_B01(array_index) = Power_input_B01(array_index)/(
    sqrt(3)*V_array*cosphi*n_cables); %[kA]
Prosent_Loss_B01(array_index) = Loss_array_B01_RAC(
    array_index)/ Output_Array_cable_B01(array_index); %[-]

array_index = array_index + 1; %determiate while loop
end
%LOSS TURBINE TRANSFORMER STRING B AC RESISTANCE
Turbine_Transformors_StringB_RAC_Loss_MWh =
    Loss_Transformator_StringB_R_DC_Total_MWh   %[MWh]

%LOSS ARRAY CABLES STRING B AC RESISTANCE
Loss_Array_Cables_kW = sum(Loss_array_B06_RAC)+sum(
    Loss_array_B05_RAC)+sum(Loss_array_B04_RAC)+sum(
    Loss_array_B03_RAC)+sum(Loss_array_B02_RAC)+sum(
    Loss_array_B01_RAC); % [kW]
Loss_Array_Cables_kWh = Loss_Array_Cables_kW.*(1/6);       %[
    kWh]
Loss_Array_Cables_MWh = Loss_Array_Cables_kWh.*(1/1000);   %[
    MWh]
Array_Cables_StringB_RAC_Loss_MWh = Loss_Array_Cables_MWh %[
    MWh]

%COPPER LOSS ARRAY CABLES STRING B
Copper_Loss_StringB_kW = sum(P_copper_B06)+sum(P_copper_B05)
    +sum(P_copper_B04)+sum(P_copper_B03)+sum(P_copper_B02)+
    sum(P_copper_B01); % [kW]
Copper_Loss_StringB_kWh = Copper_Loss_StringB_kW.*(1/6);
        %[kWh]
Copper_Loss_StringB_MWh = Copper_Loss_StringB_kWh.*(1/1000);
      %[MWh]
Copper_Loss_StringB_RAC_Loss_MWh = Copper_Loss_StringB_MWh
       %[MWh]
```

```
%SHEATH LOSS ARRAY CABLES STRING B
Sheath_Loss_StringB_kW = sum(S_loss_B06)+sum(S_loss_B05)+sum
    (S_loss_B04)+sum(S_loss_B03)+sum(S_loss_B02)+sum(
    S_loss_B01); % [kW]
Sheath_Loss_StringB_kWh = Sheath_Loss_StringB_kW.*(1/6);
        %[kWh]
Sheath_Loss_StringB_MWh = Sheath_Loss_StringB_kWh.*(1/1000);
     %[MWh]
Sheath_Loss_StringB_RAC_Loss_MWh = Sheath_Loss_StringB_MWh
      %[MWh]

%ARMOUR LOSS ARRAY CABLES STRING B
Armour_Loss_StringB_kW = sum(A_Loss_B06)+sum(A_Loss_B05)+sum
    (A_Loss_B04)+sum(A_Loss_B03)+sum(A_Loss_B02)+sum(
    A_Loss_B01); % [kW]
Armour_Loss_StringB_kWh = Armour_Loss_StringB_kW.*(1/6);
        %[kWh]
Armour_Loss_StringB_MWh = Armour_Loss_StringB_kWh.*(1/1000);
     %[MWh]
Armour_Loss_StringB_RAC_Loss_MWh = Armour_Loss_StringB_MWh
      %[MWh]

%INPUT POWER STRING B
Input_StringB_kW = sum(P_before_trans_B06)+sum(
    P_before_trans_B05)+sum(P_before_trans_B04)+sum(
    P_before_trans_B03)+sum(P_before_trans_B02)+sum(
    P_before_trans_B01); %[kW]
Input_StringB_kWh = Input_StringB_kW.*(1/6);
                   % [kWh]
Input_StringB_MWh = Input_StringB_kWh.*(1/1000);
               % [MWh]
El_Input_Simulated_StringB_March_MWh_RAC = Input_StringB_MWh
     % Total power input simulated March String B [MWh]

%OUTPUT POWER STRING B
Output_StringB_kWh = Output_Array_cable_B01.*(1/6);
                   % [kWh];
Output_StringB_MWh = Output_StringB_kWh.*(1/1000);
                    % [MWh]
El_output_Simulated_StringB_March_MWh_RAC = sum(
    Output_StringB_MWh) % Total power output Simulated March
    String B [MWh]

Loss_Factor_Simulated_RAC =
    El_output_Simulated_StringB_March_MWh_RAC/
    El_Input_Simulated_StringB_March_MWh_RAC %[-]
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