Transient analysis of circuit breakers in an offshore wind power system based on the Cassie-Mayr model

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Master thesis

STUDENT REPORT
AALBORG UNIVERSITY

Preface

This report is produced by OES10-4-S20 in cooperation with Aalborg University Esbjerg and Semco Maritime. This report is written as a master thesis in spring 2020. The study focuses on the development of a mathematical model to simulate the behavior of an offshore breaker's electric arc which will be used for a transient analysis of the circuit breaker. The mathematical model will be based on the Cassie-Mayr model.

I would like to thank my supervisor at Aalborg University Amin Hajizadeh for supervising me under the difficult circumstances corona made for this project period. I would also like to thank my supervisor at Semco Maritime Michael Kinch, Principal Electrical Engineer, for guidance and supervising my project. At last, I would like to thank Mohamad Reza Kikhavandi for his knowledge and support for PowerFactory.

Please notice that the figures and simulations without references are made by OES10-4-S20. The figures are made by using the program and software IPE, Simulink, and PowerFactory.

"All good men and women must take responsibility to create legacies that will take the next generation to a level we could only imagine." —Jim Rohn

Aalborg University, May 29, 2020

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Abstract på dansk

Offshore vindenergi er blevet en populær vedvarende energikilde af flere grunde; Installationsområderne offshore er større end onshore, de påvirker ikke den visuelle præsentation eller støjniveauet i naturen og vindprofilerne offshore er større. Det er derfor muligt, at bygge større vindmøller offshore end onshore og opnå en højere energiproduktion.
I design processen for offshore vindmølleparker er der mange aspektiver af ingeniørarbejde, som er gældende. Generelt kan design processen deles op i to dele: Den ene del foregår på vindmøllen og dens komponent dele, den anden del foregår fra energiproduktionen fra vindmøllen til en onshore station, som transporterer energien rundt i Danmark. Den sidste del har ført til et forhøjet fokus på transmissionen af energiproduktionen fra vindmøllen til transmissionslinjen.
Energinet har lavet mange reguleringer omkring forbindelsen fra en offshore vindmøllepark til det offentlige grid. Hovedfokusområderne fra Energinet indeholder blandt andet hvordan vindmøllerne opererer i tilfælde af en grid fejl og om de kan opretholde deres energiproduktion uden forstyrrelser. Andre områder gælder også i forhold til at reducere forstyrrelser i elektriciteten.
Den mest ødelæggende form for forstyrrelse i elektriciteten kommer fra transienter i elektriske komponenter. Transienter opstår hver gang pludselige ændringer sker i systemet, hvilket ofte er et resultat af at bryde strømstyrken eller spændingen. Brydningsprocessen af strømstyrke er meget kompleks på grund af det fysiske fænomen, som opstår når bryderen bryder. Dette resultere i en form for en elektrisk bue og det er derfor nødvendigt at have en god model af en offshore bryder, når man laver analyser af en offshore vindmøllepark for, at forstå hvad der sker.
I dette speciale er hovedfokusområdet derfor at lave en matematisk model, som kan bruges til at beskrive den elektriske bue i en offshore bryder. Målet med projektet er at få lavet den matematiske model og implementere den i softwareprogrammet PowerFactory, som kan bruges i industrien til at lave transiente analyser af hele offshore vindmølleparker. Den matematiske model vil tage fokus i de udviklede Cassie-Mayr modeller og den modificerede udgave af Cassie-Mayr modellen: Schwarz-Avdonin modellen.

Nomenclature

Symbol	Description	Unit
U	Voltage	$[V]$
P	Power	$[W]$
S	Reactive power	$[SA]$
R	Resistance	$[\Omega]$
Z	Impedance	$[\Omega]$
X	Reactance	$[\Omega]$
PF	Power factor	$[\%]$
ω	Frequency	$[Hz]$
U_{Base}	Voltage base value	$[V]$
S_{Base}	Reactance base value	$[SA]$
L_{Base}	Impedance base value	$[H]$
L_{Sat}	Saturated impedance	$[H]$
R_{Sat}	Saturated resistance	$[R]$

Electric arc modelling constants

g	Arc conductance	$[S]$
g_c	Cassie arc conductance	$[S]$
g_m	Mayr arc conductance	$[S]$
g_{arc}	Cassie-Mayr total arc conductance	$[S]$
τ_c	Cassie time constant	$[s]$
τ_m	Mayr time constant	$[s]$
τ_g	Time constant depending on g	$[s]$
i_a	Arc current	$[A]$
u_s	Steady-state arc voltage	$[V]$
P_0	Steady-state cooling power	$[W]$
P_g	Arc cooling power depending on g	$[W]$
r_{arc}	Arc resistance	$[\Omega]$
β	Free parameter	$[S^{-1}]$
α	Free parameter	$[S^{-1}]$

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Abstract:

This project focuses on the development of a mathematical model to describe how the electric arc of a circuit breaker behaves. The mathematical models will be based on Cassie-Mayr and the modified version of it; Schwarz-Avdonin. First the mathematical models have been derived and thereafter implemented into the software Simulink to conduct an analysis of how the models act. Hereafter an implementation of the models has been made into the software PowerFactory with the wish to make a transient analysis of an offshore wind power plant. In conclusion it was possible to develop mathematical models to describe the behavior of the electric arc, however, more work needs to be conducted before it is possible to make a transient analysis in PowerFactory.

Contents

Chapter 1

Introduction

In a society where the demand for renewable energy is high wind energy has seen its growth both onshore and offshore. Especially offshore has become increasingly popular due to the bigger installation areas and wind profile offshore leading to the development of larger offshore wind power installations. This has lead to an increasing focus on the operation of power from the wind power plant to the transmission system.
Energinet has made regulations concerning the governing connection of a wind power plant to the public electricity grid as well as demands for its operation. The main concerns from Energinet are regarding the fault-ride through where it is a requirement for the wind turbines to stay connected to the grid without disrupting or reducing the output. Another concern is to control reactive and active power under operation and at last to reduce power fluctuations and disturbances. It has been observed that power fluctuation is a bigger problem for larger wind farms which is often the case offshore [1] [2].
The most damaging type of power disturbance comes from transients in the electrical components. The transient appears each time an abrupt circuit change occurs in the wind power plant which is usually the result of breaking the voltage or current. The breaking process of current is especially complex due to the physical phenomena taking place resulting in an electric arc of the circuit breaker. It is, therefore, necessary to use an appropriate model of the circuit breaker to perform any analysis and to obtain an understanding of the wind power plant.

The first known formal theory of arc interruption was introduced in 1928 by Joseph Slepian. It states that a successful interruption is achieved when the dielectric strength of the gap increases at a faster rate than the rate at which the reapplied system voltage grows [3].
The first model made to describe the electric arc was designed by A. M. Cassie in 1939 which represents the phenomena of the electric arc for large values of current

[4]. This model can only be used to describe the arc characteristic for high current and cannot be used to describe it when current is almost zero.
In 1943 O. Mayr made a new model which represents the phenomena of the electric arc for small values of current and it was thereby possible to describe the arc characteristic when the current is crossing zero [5].
However, a new arc model which is known as the Cassie-Mayr model or the Habedak model was later introduced by combining the Cassie and Mayr model into one which made it possible to obtain more information on the breaking capability [6]. By combining them it was possible to have one model which could describe the breaking with high current and with current close to zero. In 2000 a new modified version of the Mayr model was introduced as the Schavemaker model which uses a constant time parameter but describes arc characteristic during current zero-cross [7].
A study made in 2015 by ABB [8] was conducted to compare different arc models. The comparison analysis consists of the ideal switch-, Cassie-, Mayr-, Cassie-Mayr-, and Schwarz-Avdonin circuit breaker model, and simulations were made for capacitive and inductive scenarios. The results show that Cassie, Mayr, Cassie-Mayr, and Schwarz-Avdonin were fairly similar. The Schwarz-Avdonin arc model is a modified version of the Cassie-Mayr model which uses the same structures but has parameters depending on other factors. The ideal switch arc model different the most due to the parameter represents the chopping current which is hard to find an accurate value of. The study concludes, however, that the Cassie, Mayr, and Cassie-Mayr arc model seems to be the most appropriate model to use since this model is recommended by IEC 60071-4:2004 standard.
These results lead to the following problem statement of this master thesis

1.0.1 Motivation and objectives of study

During this thesis, an analysis of the transient behavior of an offshore circuit breaker will be analyzed and modeled. The circuit breaker model will be based on Cassie- and Mayr- models describing the electric arc behavior of the circuit breaker as well as the modified version of the Cassie-Mayr model, Schwarz-Avdonin.
This electric arc model will first be developed, conducted, and analyzed in Simulink to obtain the general behavior of each model. Thereafter, the models will be implemented in PowerFactory to conduct a transient analysis of an offshore wind power plant.

Chapter 2

Representation of the offshore wind power plant in PowerFactory

In this chapter, a representation of the wind power plant designed and build in PowerFactory will be represented. This offshore wind power plant will consists of circuit breakers where the mathematical model of the electric arc will be implemented. In this chapter information, sizes, and design aspects of the electrical components will be described as well as a loadflow and a short circuit calculation will be conducted based on the offshore wind power plant.
For a more detailed overview of how the offshore wind power plant has been designed refers to the previous written project of the author [9].

2.1 Design of offshore wind power plant

For this project, the following offshore wind power plant has been designed based on the following specification which can be found in table 2.1.

Table 2.1: Design requirements for the offshore wind farm [9].
* Max 4000 A on busbar for MV side.

P	cosø	S	U (HV)	U (MV)	I (HV)	I (MV)	WTG	WTG's	String
[MW]		[MVA]	[kV]	[kV]	[A]	[A]*	[MW]	[No.]	[No.]
420	0.95	442	155	66	1647	3867	10	42	6

The specification for each string with the wind turbines can be found in table 2.2.

Table 2.2: Design requirements for the offshore wind farm per string [9].

WTG's	S	I
[No.]	[MVA]	[A]
7	74	645

The general overview of the wind power plant's base overview can be seen in figure 2.1 based on the specification stated above. The OSS TRF MV bus bar is the common point for all six strings consisting of a total amount of 42 wind turbines, this setup can be seen in figure 2.2. The chosen wind turbines for this project are based on the PowerFactory type 4a wind turbine with a full-scale power converter. From the OSS MV TRF bus bar, the substation is in parallel with reactor 1 and series with circuit breaker 1. Thereafter two HV cables are connected, one with the length of 70 km representing the cable from the substation to shore and one of 20 km from shore to the onshore station. In parallel with the cable from shore to the onshore station is reactor 2. Both reactors are implemented to compensate for the reactive power through the cable. Between the shore station bus bar and the grid, circuit breaker 2 is connected.

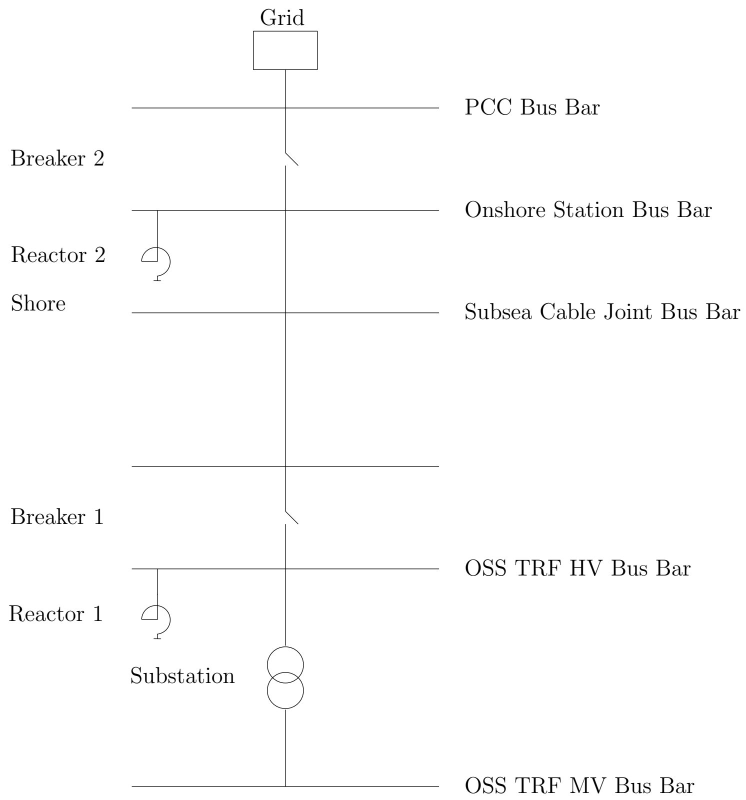


Figure 2.1: Overview of the base grid of the wind power plant.

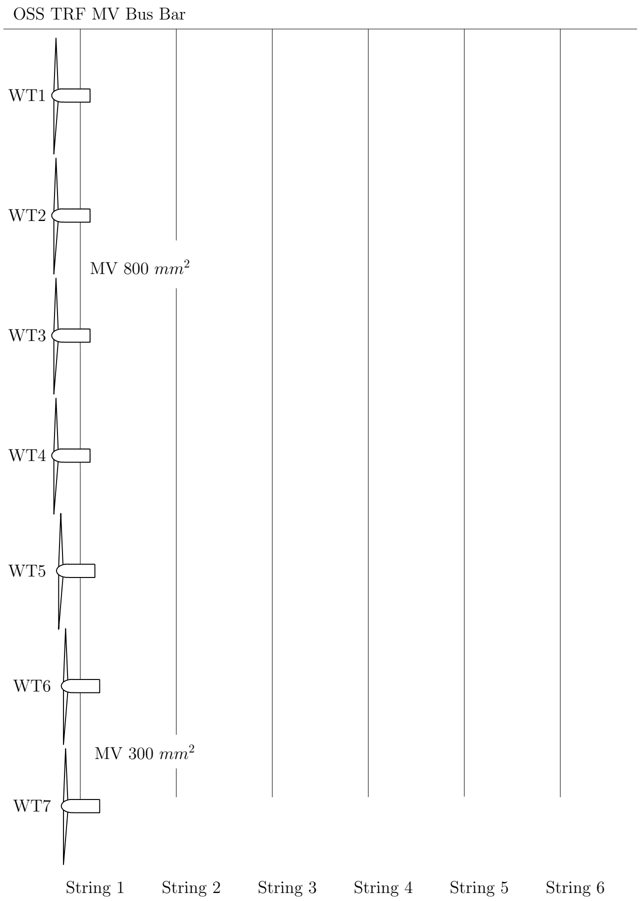


Figure 2.2: Overview of the wind turbines on their strings connected to a common bus bar OSS TRF MV Bus Bar.

Based on this model setup some of the electrical components need to be specified and designed in PowerFactory such as the shunt reactors and the transformer.

2.1.1 Design of electrical component to base model in PowerFactory

Design of shunt reactors

Reactors are used to compensate for the reactive power in the cable and are placed in both ends of the cables. A simple way of designing the size of the reactors is by calculating the loadflow in PowerFactory. When conducting this loadflow the wind farm and substation are not connected to the model so the only impact comes from the cables. Based on the amount of reactive power delivered from the cables to the grid the two shunt reactors will be designed based on that size. From the load flow the amount of reactive power delivered from the cables to the grid is 137 MVAR resulting in each reactor having the size of 68.5 MVAR.

However, in case of a change in power factor, it is wished to ensure that the reactors still can compensate for the amount of reactive power delivered to the grid from the impact of the cables.
A simulation has been conducted to check this scenario of change of power factor and how well the reactors can compensate for it. The change has been based on chaining the power factor from inductive to capacitive over a time period. The reactor sizes will be based on the sizes determined from the loadflow previously and the following simulation was obtained in figure 2.3.

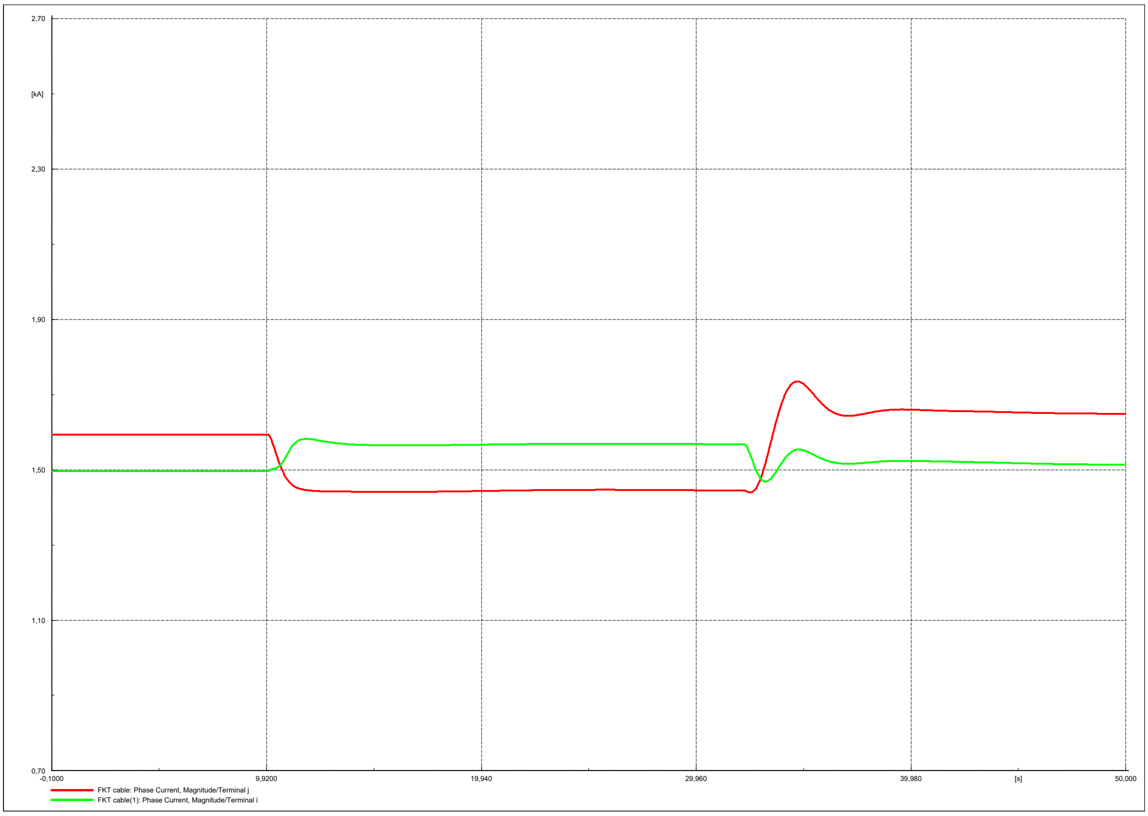


Figure 2.3: Phase current measured at terminal j bottom cable (red) and phase current measured at terminal i top cable (green) and their response to change of power factor.

From figure 2.3 it can be seen how the current through the cables differs at each end when the changes happen. This difference in current is wished to be neglected, otherwise, the current running through the cables will exceed the current rating of the cables of 1647 A stated in table 2.1. Therefore, another method to design the reactors has to be found where it is possible to compensate for the reactive power and for the phase currents to have the same size when a change in power factor happens.
Through simulations it was determined that the size of reactor 1 should be 30

MVAR and reactor 2 should be 87 MVAR for the best response and to ensure that the amount of current running through the cable does not exceed the maximum current rating of the cables used in this model. The results can be seen in figure 2.4. It should be noticed that the jump presented in the simulation is due to the change of the power factor in the system.

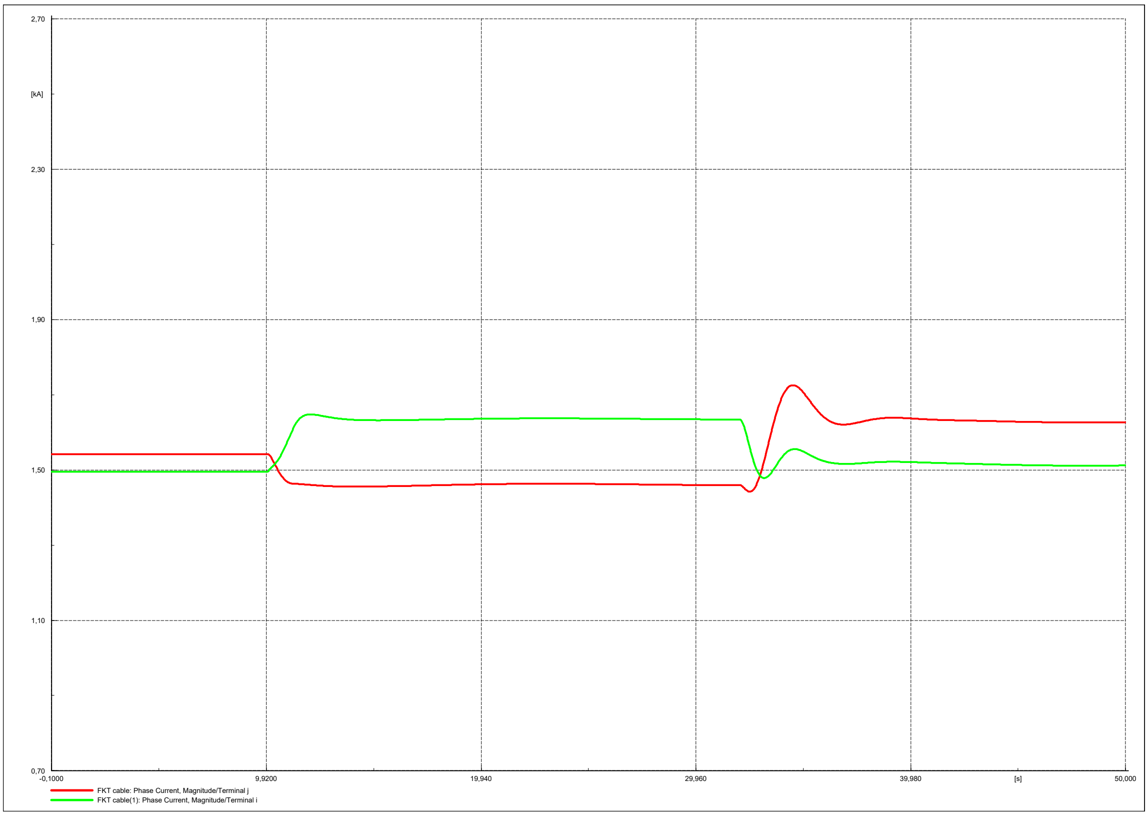


Figure 2.4: Phase current measured at terminal j bottom cable (red) and phase current measured at terminal i top cable (green) and their response to change of power factor.

Design of substation

Following the new EU requirements for transformers, it has been stated that transformers with a bigger size than >100 MVA by 2021 should have a minimum efficiency of 99.770%. However, bigger transformers have a higher efficiency of around 99.91% resulting in the transformers having a no-load current of 0,1-0,09% and no-load losses of 150 kW [10]. These values are implemented and used in the PowerFactory model of the transformer.
Other parameters such as copper losses, the saturation flux (knee flux), saturation exponent, and saturated reactance should also be defined in the design process of the transformer.

In the technical reference for transformers in PowerFactory [11] the saturation exponent, has been giving in the range of 9, 13, or 15 and gives the exponent of a polynomial representation. In this study it has been set to 13. For large power transformers, the saturation flux is usually in the range of 1,1-1,3 p.u. so in this study, it has been assumed that the saturation flux is 1.2.
As mentioned the copper losses have to be stated in the model and therefore it is needed to calculate it. The copper losses have been calculated based on the efficiency of the transformer and the load [12].

$$P_{load} = S \cdot PF = 442MVA \cdot 0.95 = 419.9MW \tag{2.1}$$

$$P_{loss} = \frac{P_{load} - (1 - eff)}{eff} = 378.25kW \tag{2.2}$$

With eff being the efficiency of the TRF given as 99.91%.
The saturated reactance has to be calculate next and it is depending on the saturated inductance. Before it is possible to calculated the saturated reactance, the saturated inductance has to be found from the base value and nominal value.
The impedance for the TRF is determined from short circuit voltage in %, the voltage base value, and the apparent power base

$$z = \frac{U_{base}^2 \cdot U_{sc,pro}}{S_{base}} = \frac{155^2 kV \cdot 0.12}{442MVA} = 5.523\Omega \tag{2.3}$$

And the resistance is given as

$$R = \frac{U_{base} \cdot P_{loss}}{S_{base}^2} = 0.047\Omega \tag{2.4}$$

Based on the impedance and resistance the reactance can be calculated

$$x = \sqrt{z^2 - R^2} = 6.522\Omega \tag{2.5}$$

Next the base value of the impedance is calculated

$$L_{base} = \frac{U_{base}^2}{S_{base}} \cdot \frac{1}{\omega_{base}} = 0.173H \tag{2.6}$$

With ω given by $2\pi \cdot 50Hz$.
The nominal impedance is given by

$$L = \frac{x}{\omega} = 0.021H \tag{2.7}$$

Now the saturated impedance can be calculated based on the above calculated values for the base and nominal impedance

$$Lsat = \frac{L}{L_{base}} = 0.12 \tag{2.8}$$

It is then possible to calculated the saturated reactance based on the saturated inductance

$$R_{sat} = 1.5 \sim 2 \cdot L_{sat} = 0.18 p.u. \quad (2.9)$$

These values are all implemented in the PowerFactory model for the substation which it uses to describe the output of the transformer.

2.2 Calculation of loadflow and short circuit of the offshore wind power plant

In this part the calculation of loadflow and short circuit made in PowerFactory will be presented.
In figure 2.5 the loadflow calculation has been conducted for the entire system. It can be seen how the current and voltage results do not exceed the stated values presented in the design requirements in table 2.1. From HV side the maximum current rating from the loadflow is 1,522 kA and in the table the maximum current rating the system can operate with is 1,647 kA. On the MV side the maximum current rating from the loadflow is 3,494 kA and in the table the maximum current rating is 3,867 kA.
Through the system a power loss of around 17 MW is present which is due to losses through the substation and the transportation of electricity through the cables.

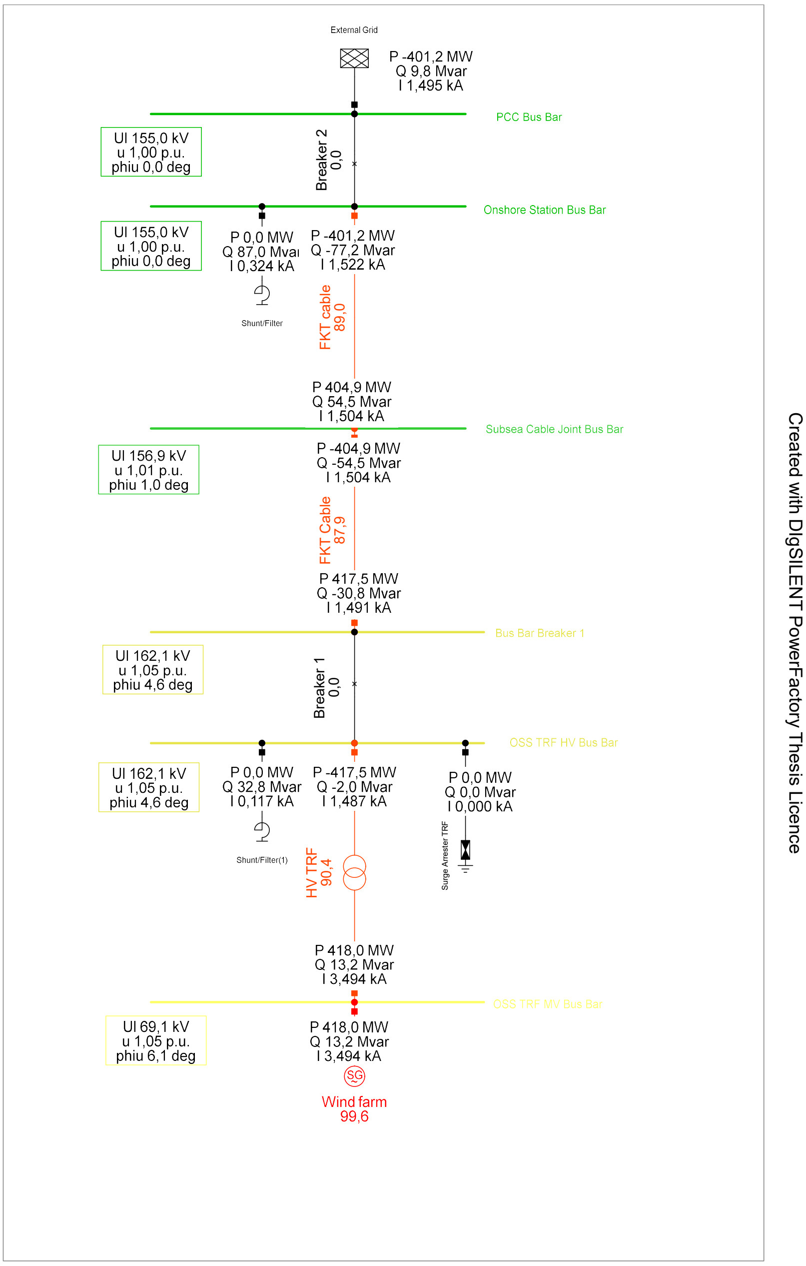


Figure 2.5: Calculation of loadflow in PowerFactory.

In figure 2.6 the short circuit calculation for the entire system is represented.

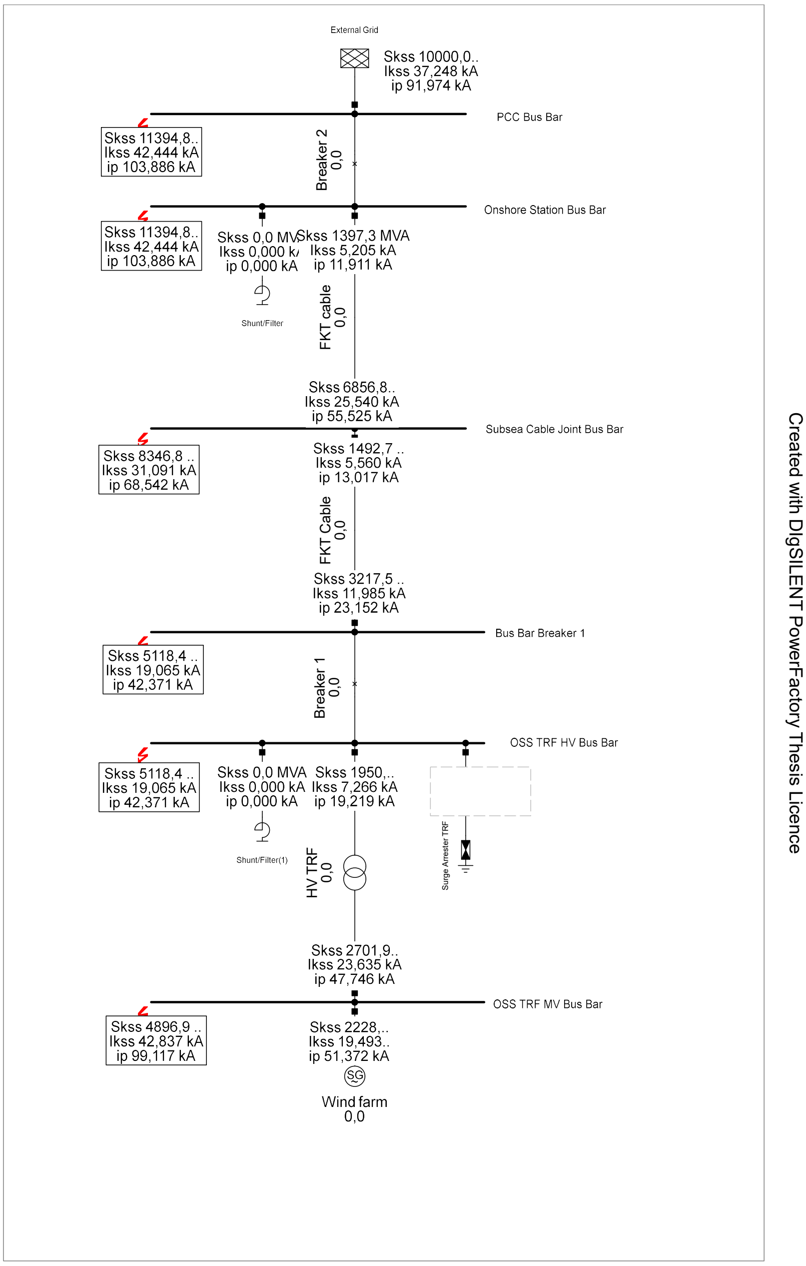


Figure 2.6: Calculation of short circuit in PowerFactory.

In the coming chapters, this model will be used to implement a model of the electric arc based on mathematical models to obtain a transient analysis of the offshore wind power plant.

Chapter 3

Modelling of electric arc for circuit breaker

In this chapter, the modeling of the electric arc for an offshore circuit breaker will be explained and presented based on Cassie- and Mayr- models. The models will be implemented in Simulink so simulate the arc's behavior during transients in switching conditions. The electric arc models will later be implemented in Power-Factory to make a model which can be used for transient analysis.

3.1 Circuit breaker

Circuit breakers are used in power systems to interrupt the current in case of a fault in the grid or a short circuit in the the electrical components in an offshore wind farm. Circuit breakers are also used to connect or disconnect part of the network and the wind turbines.

Circuit breakers consist of a plug that is connected to a contact where the current can flow through when the breaker is closed. To interrupt the current through the circuit breaker the plug and the contact has to be separated fast. During this switching action the breaker changes from operating as a conductor to an insulator, and the current will flow through the arc channel between the plug and the contact resulting in the electric arc. Comprehending the electric arc phenomenon and analyzing what happens under the arc is a key factor in understanding how the circuit breaker functions. This phenomenon of the arc is represented in a simplified version in figure 3.2.

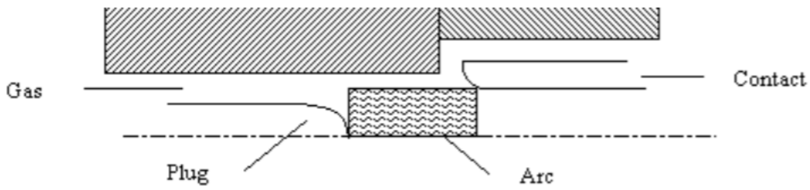


Figure 3.1: Simplified representation of the electric arc between the plug and contact [13].

If the arc is cooled sufficiently in the circuit breaker, at the time where the current goes through zero, the circuit breaker will be able to interrupt the current since the electrical arc power input into the arc will be zero. However, it is also possible for the circuit breaker to interrupt the current at any other point of the current wave, this will, however, lead to overvoltages that can damage the system.

3.2 Capacitive and inductive current switching

One way of conducting a transient analysis of the circuit breaker can be by interruption of capacitive and inductive current switching.
Capacitive switching happens when de/energizing of unloaded cables, overhead lines, and capacitor banks and inductive switching happens when de/energizing the transformer or shunt reactor at no-load or at current in-rush flow.

Interruption of Capacitive circuits

During the breaking of capacitive current, the main concern is overvoltages produced due to possible arc re-ignition which can happen for example as the capacitor bank de-energizes. When breaking the current the voltage remains constant at the capacitor bank terminal which can exceed the dielectric withstand of the contact gap leading to the circuit breaker not being able to break successfully. This is due to the fact that the dielectric withstand is not being sufficiently restored [8]. A representation of the breaking of capacitive current can be seen in figure 3.2.

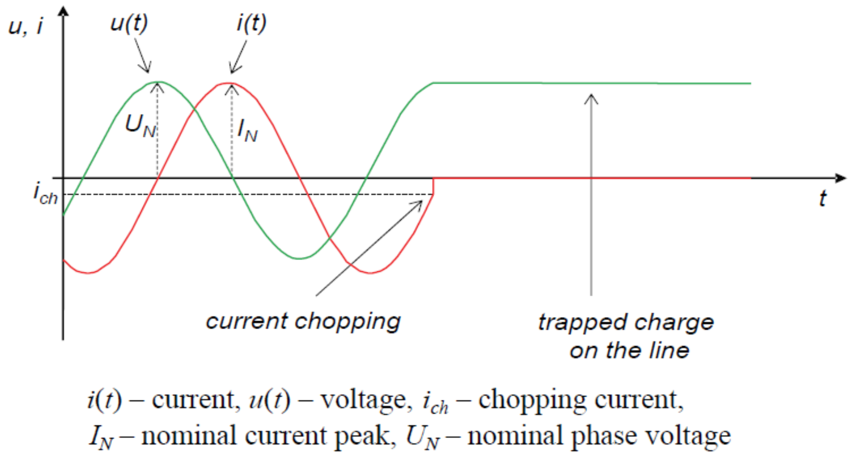


Figure 3.2: Breaking of capacitive current in the circuit breaker [8].

Interruption of inductive circuits

In inductive circuits there is a large phase angle between voltage and current since the resistance in inductive circuits is small. In these cases zero current no longer occurs at the point where the voltage is reaching zero but at the point when the voltage reaches its maximum value. Breaking of inductive current can lead to high-frequency overvoltages which can lead to high transient overvoltage peaks due to the oscillation of the energy trapped [3]. This phenomenon can be seen in figure 3.3.

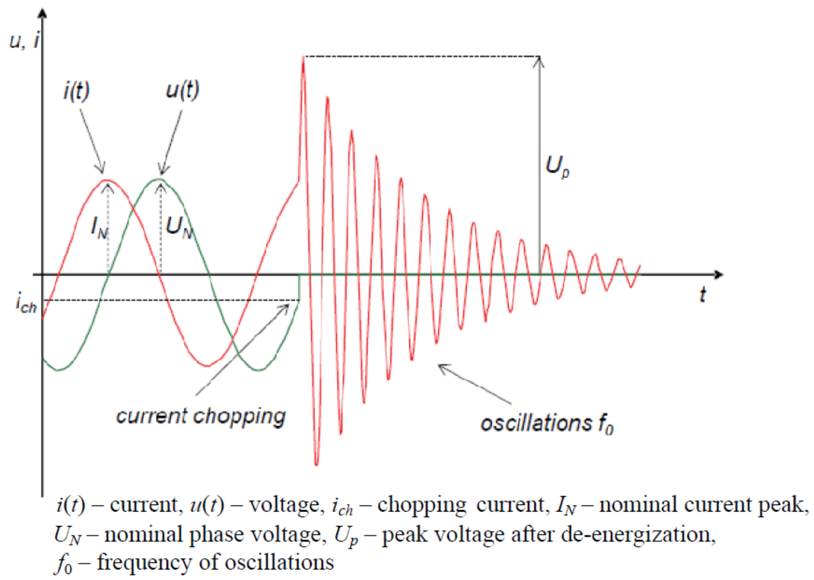


Figure 3.3: Breaking of inductive current in the circuit breaker [8].

During the interruption of the inductive current, the recovery voltage is expected to reach its maximum value at the same time current is interrupted. However, due to the capacitance present in the system from the transformer coils, the recovery voltage does not reach its peak at the same instant that current is interrupted and therefore a transient response can be observed in the circuit [3].
As shown in figure 3.2 and figure 3.3 current chopped before its natural zero-crossing leads to produced overvoltage in the system. The generated overvoltages can lead to overstressing of the insulation systems installed in the offshore wind power plant. It is, therefore, desired to design a mathematical electric arc model to predict the dangerous effects of switching transient, since it is difficult to ensure that the circuit breaker breaks exactly at the current's natural zero crossings.

3.3 Mathematical modelling of the Electric arc for a circuit breaker

With the use of software such as Simulink and Powerfactory an analysis of switching transient states can be made by implementing mathematical models of the electric arc. In this section, multiple complex mathematical models are presented which describe the electric arc behavior during switching operation in high voltage circuit breakers.
The modeling of the arc is based on a more simplified version without including information about the geometry of the circuit breaker, magnetic field, or by fluid

flowing at high pressure.
Many different values affect the parameters used in the models depending on how the circuit breaker has been build and designed. Circuit breakers are made of many different materials depending on the voltage range the system is working in. In figure 3.4, the different materials used depending on the voltage is shown. For an offshore wind farm Air compressed, Oil or SF6 suits the voltage range working with offshore.

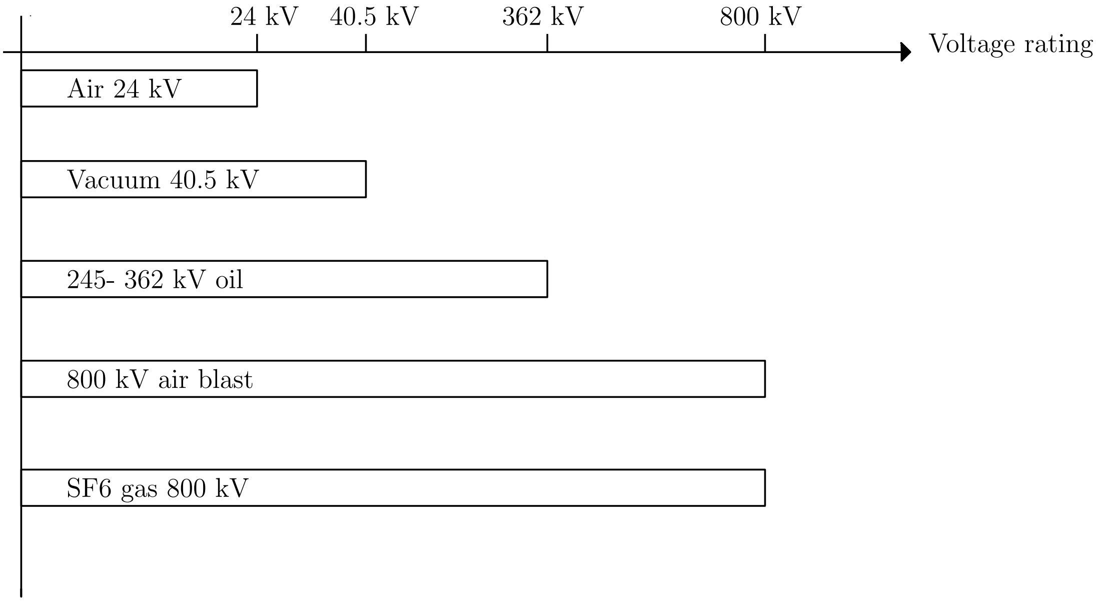


Figure 3.4: Overview of the different materials used for the design of circuit breaker, depending on the system's voltage range [14].

The material the circuit breaker is made from has an impact on the parameters used in the model. However, exemplary values of constant parameters will be used based on parameters stated in [15].

3.3.1 Cassie model

The Cassie model was the first mathematical model derived to provide a better representation of the electric arc for large values of current. The mathematical model for Cassie is presented as a differential equation which describes the arc conductance during current interruption processes and is represented in equation 3.1 [16] [6] [8].

$$\frac{dg_c}{dt} = \frac{1}{\tau_c} \cdot \left(\frac{i_a^2}{u_s^2 \cdot g_c} - g_c \right) \tag{3.1}$$

Where g_c is the arc conductance [S], τ_c is the time constant of the arc [s], u_s is the steady-state arc voltage [V], and i_a is the arc current [A].

The Cassie equation includes many parameters which have to be determined, however, those parameters are strongly depending on the type of material used for the circuit breaker. An estimation of the required parameters used for the equation can be found in table 3.1.

Table 3.1: Constant parameter values for the Cassie model [15].

Circuit breaker	Arc voltage	Time constant of the arc tau	Arc conductance g
	[kV]	[μs]	[S]
	3.85	1.2e-6	1.e4

3.3.2 Mayr model

The Mayr model was derived to represent the phenomena of the electric arc for small values of current. The mathematical model for Mayr is presented as differential equations which describe the arc conductance. It is represented in equation 3.2 [16] [6] [8].

$$\frac{dg_m}{dt} = \frac{1}{\tau_m} \cdot \left(\frac{i_a^2}{P_0} - g_m \right) \tag{3.2}$$

Where g_m is the arc conductance [S], τ_m is the time constant of the arc [s], P_0 is the steady-state cooling power of the arc [W].
The Mayr equation includes many parameters which has to be determined but it allows using constant parameters given in table 3.2.

Table 3.2: Constant parameter values for the Mayr model [15].
*P the value for the arc cooling power has been found from interpolation since no value was found for the voltage level worked with in this project.

Circuit breaker	Arc cooling power P_0	Time constant of the arc tau	Arc conductance g
	[MW]	[μs]	[S]
	105 *	0.3e-6	1.e4

3.3.3 Cassie-Mayr model

The overall representation of the arc model can be represented by combining the Cassie and Mayr model working simultaneously. By combining them an improved accuracy of the mathematical model of the electric arc can be obtained. For high condition current the Cassie model is the main part of the total arc voltage whereas for the condition where current is close to zero the Mary model describes the behavior more accurately. The total arc conductance of the Cassie-Mayr model is described in equation 3.3

$$r_{arc} = \frac{1}{g_{arc}} = \left(\frac{1}{g_c} + \frac{1}{g_m}\right) \tag{3.3}$$

Where g_c is the arc conductance calculated according to the Cassie equation 3.1 and g_m is the arc conductance calculated according to the Mayr equation 3.2.
This equation gives an accurate representation of the electrical arc for both low and high value of current. Based on the values given in table 3.1 and table 3.2 [6] it is possible to calculate the arc conductances for Cassie and Mayr.

3.3.4 Schwarz-Avdonin model

The Schwarz-Avdonin model is a modified version of the Cassie-Mayr model which describes the behavior of the electrical arc using the same structure as the Cassie-Mayr model. However, in the Schwarz-Avdonin model some of the parameters such as the cooling power P_g and the thermal time constant τ_g are conductance-dependent parameters. This can be seen in equation 3.4 represent the Schwarz-Avdonin model [8].

$$\frac{dg}{dt} = \frac{1}{\tau(g)} \cdot \left(\frac{i_a^2}{P(g)} - g\right) \tag{3.4}$$

Where g is the arc conductance [S], i is the arc current [A], $P(g)$ is the arc cooling power dependent on the electric arc conductance [W], and τ_g is the thermal time constant dependent on the electric arc conductance [s].
The values of the P_g and τ_g can be defined as a function of conductance $f(g)$ according to the following expressions

$$P_g = P_o \cdot g^{\beta} \tag{3.5}$$

$$\tau_g = \tau_0 \cdot g^{\alpha} \tag{3.6}$$

Where β and α are free parameters $[S]^{-1}$.
Combining equation 3.4 with equation 3.5 and equation 3.6 the following expression for the Schwarz-Avdonin model is obtained.

$$\frac{dg}{dt} = \frac{1}{\tau_o \cdot g^{\alpha}} \cdot \left(\frac{i^2}{P_o \cdot g^{\beta}} - g\right) \tag{3.7}$$

In table 3.4 constant values used for HV circuit breakers for the Schwarz-Avdonin model can be found.

Table 3.3: Constant parameter values for Schwarz-Avdonin model [15].

Circuit breaker	Arc cooling power P_o	Time constant of the arc τ_o	α coefficient	β coefficient	Arc conductance g
	[MW]	[μs]	-	-	[S]
	100	6.e-6	0.17	0.68	1.e4

3.4 Implementation of arc models in Simulink

Based on the mathematical models derived in the previous section the models will now be implemented in Simulink to simulate the arcs responses. The models will hereafter be implemented in PowerFactory to use the models for transient analysis. The Simulink arc model developed by P. H. Shavenmaker and L. Van Der Sluis in 2002 will be used in collaboration with the Matlab command $power_{arcmodels}$ and figure 3.5 represents a general overview of the system for each electric arc model, but in this figure the Mayr model is presented. The model has been implemented together with a transmission line.

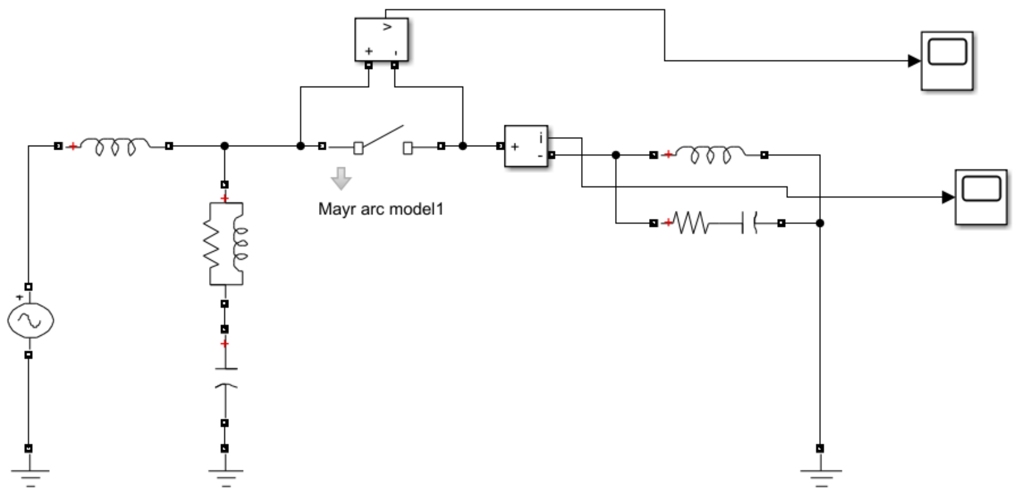


Figure 3.5: Representation of the Mayr model in Simulink used to simulate the phenomena of the electric arc.

From figure 3.5 both Cassie and Schwarz-Avdonin are implemented in the same way but with different differential equations and parameter values. An overview of the Mayr arc equation in Simulink can be seen in figure 3.6.

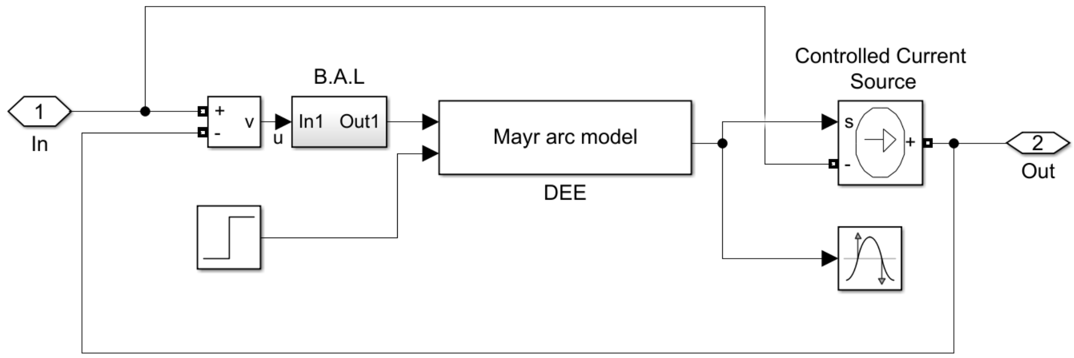


Figure 3.6: Representation of the implemented Mayr equations in simulink.

The input to the Mayr arc model system is voltage and the output of the system is current. The input signal is added through the B.A.L. block and hereafter it goes into the DEE block together with a step response. The step response is used to control the contact separation of the circuit breaker. The step is defined from the value of zero to the specified contact separation time. When the contact is closed the differential equation for Mayr is

$$\frac{dg_m}{dt} = 0 \tag{3.8}$$

When it is open the Mayr differential equation, described in equation 3.2, in the DEE block can be solved. In the block it differentiates for the arc conductance and for each new value found for the arc conductance, current is calculated based on

$$i_a = g \cdot v \tag{3.9}$$

Where g is the arc conductance and v is the voltage across the circuit breaker.
The output from the DEE block goes into a controlled current source and a Hit crossing block. The Hit crossing block detects when the current crosses the zero value. This is needed when the stepsize is being adjusted so the simulation will continue to find a zero-crossing point.
The controlled current source converts the Simulink signal into an equivalent current source.
The parameters used in these simulations are based on table 3.1 for Cassie, table 3.2 for Mayr, and table 3.3 for Schwarz-Avdonin.
The results of the simulations for Cassie, Mayr and Schwarz-Avdonin can be seen in the following figures. It should be noticed that the circuit breaker contact separation starts at t= 0s.
The following results for the Mayr simulation can be seen in figure 3.7 for voltage

and figure 3.8 for current.

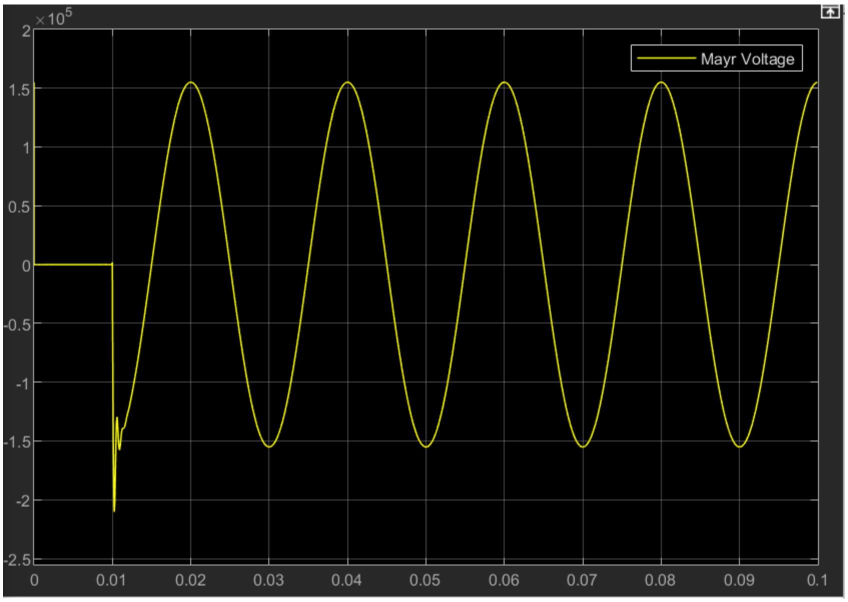


Figure 3.7: Voltage simulation of the circuit breaker for the Mayr Model when current interruption takes place.

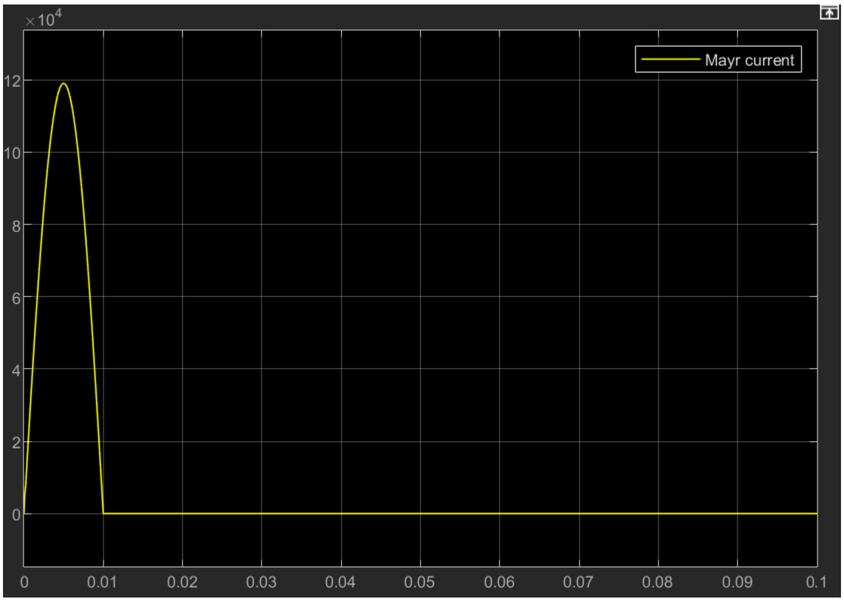


Figure 3.8: Current simulation of the circuit breaker for the Mayr Model when current interruption takes place.

In figure 3.8 it can be seen how the current is interrupted at 0.01 s and that it remains constant during the rest of the simulation. In figure 3.7 it can be seen how the voltage has a peak when the interruption of current takes place which results in the presence of transient recovery voltage (TRV). In can be concluded that the Mayr model successfully interrupted the current in this simulation.
The following results for the Cassie simulation can be seen in figure 3.9 for voltage and figure 3.10 for current.

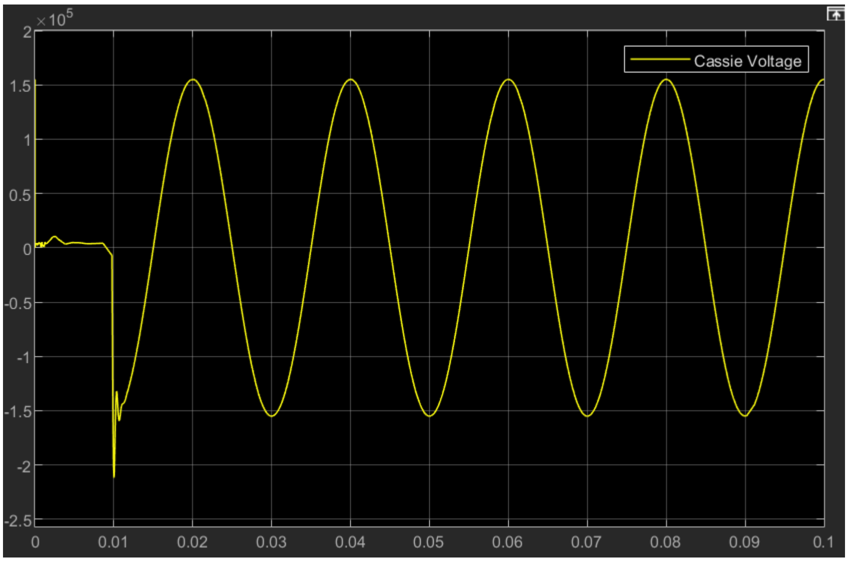


Figure 3.9: Voltage simulation of the circuit breaker for the Cassie Model when current interruption takes place.

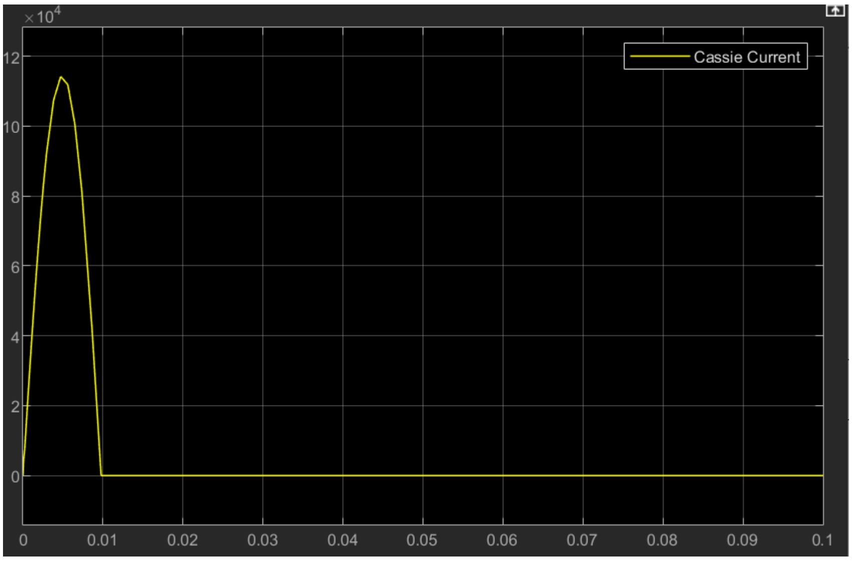


Figure 3.10: Current simulation of the circuit breaker for the Cassie Model when current interruption takes place.

In figure 3.10 it can be seen how the current is interrupted at 0.01 s and that it remains constant during the rest of the simulation. In figure 3.9 it can be seen how the voltage at the beginning of the simulation has some small peaks but around 0.01 s when the current is interrupted a TRV takes place. In this simulation the Cassie model successfully interrupted the current.
The following results were obtained for the Schwarz-Avdonin model and the figures for the simulation of voltage and current can be seen in figure 3.11 and figure 3.12.

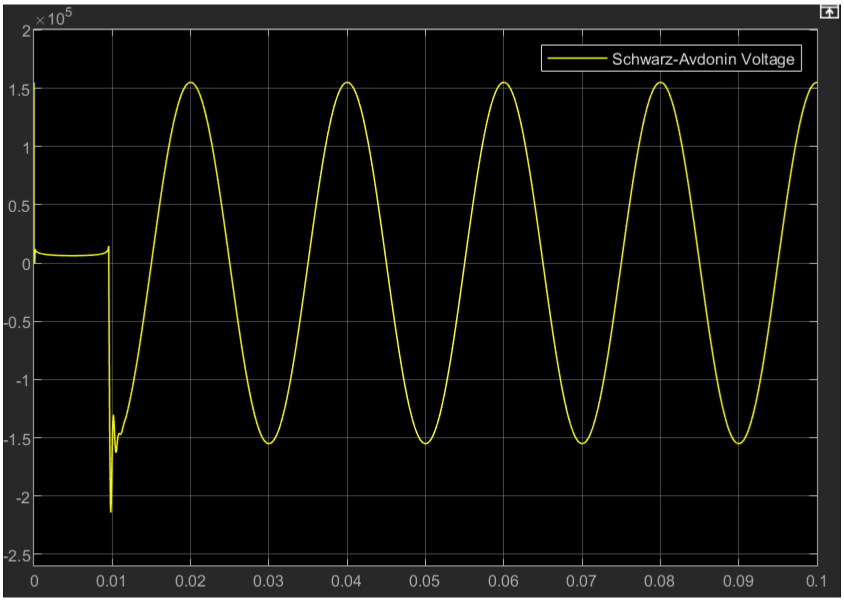


Figure 3.11: Voltage simulation of the circuit breaker for the Schwarz-Avdonin Model when current interruption takes place.

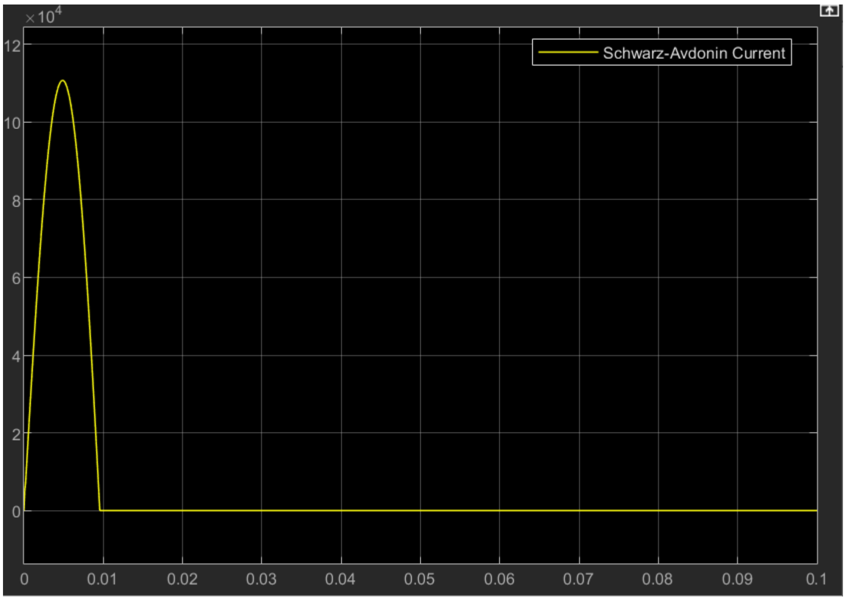


Figure 3.12: Current simulation of the circuit breaker for the Schwarz-Avdonin Model when current interruption takes place.

In figure 3.12 it can be seen how the current is interrupted at 0.01 s and that it remains constant during the rest of the simulation. In figure 3.11 it can be seen how the voltage, in the beginning, is arching a bit until it goes down when the

current is being interrupted at 0.01 s. Again it can be seen how a TRV takes place where after the voltage simulation returns to normal.
In general it can be seen how all three simulations have a similar response in both the voltage and current simulations. However, it can be noticed how the current level differs from each of the three arc models. The Mayr model has the highest current response of 120 kA and a smooth curve whereas the Cassie model has a current response of 113 kA and the Schwarz-Avdonin model a current response of 111 kA.
A close up of the TRV for all three models can be seen in the following figures

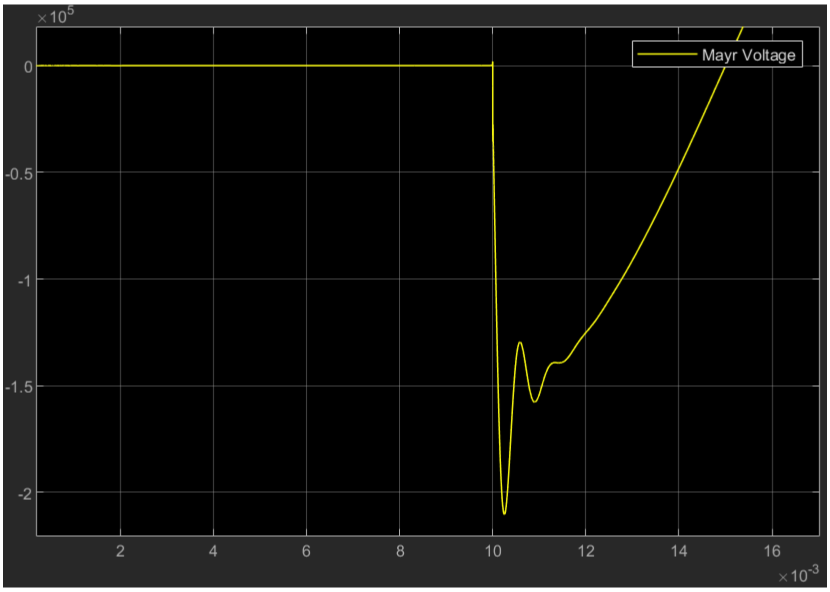


Figure 3.13: Close-up of the transient recovery voltage for the Mayr model.

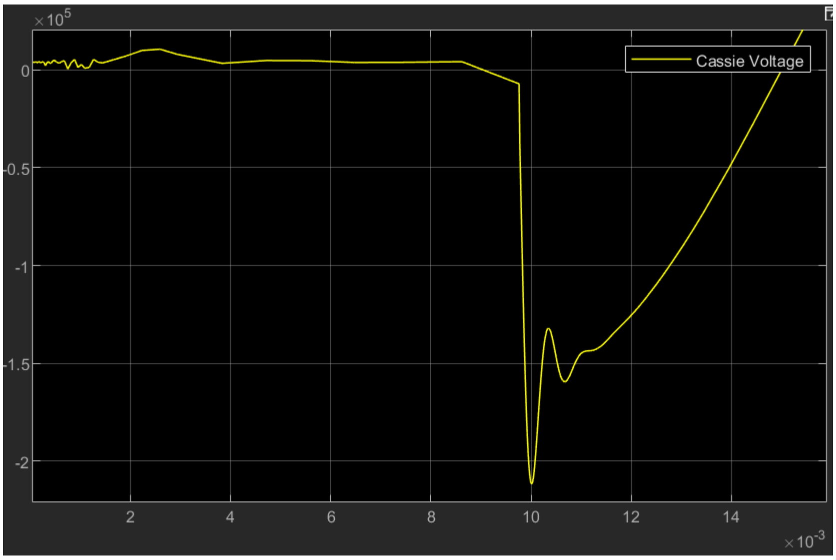


Figure 3.14: Close-up of the transient recovery voltage for the Cassie model.

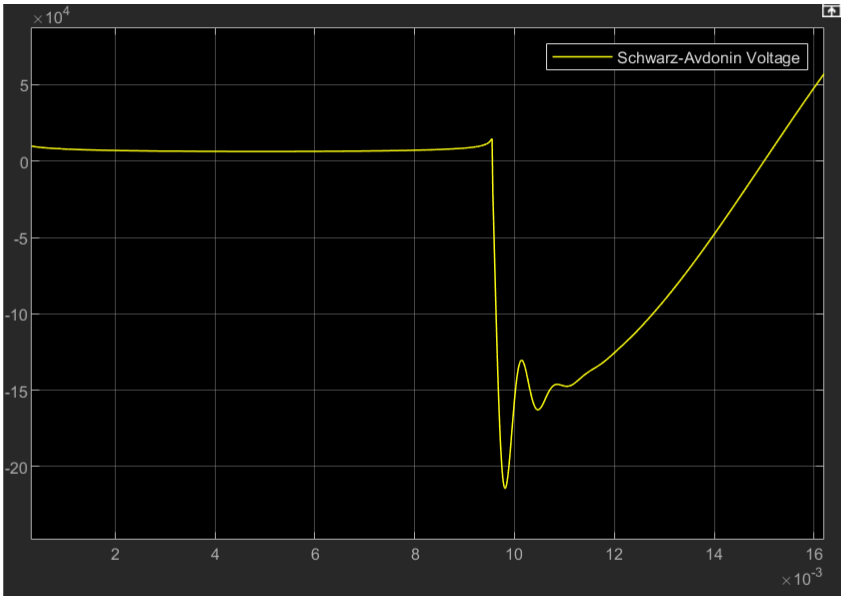


Figure 3.15: Close-up of the transient recovery voltage for the Schwarz-Avdonin model.

The TRV for all three models are similar but each model differs a bit in the hight of the peaks.
The Mayr model first peak has the value of -210 kV going up to -130 kV to -157 kV before it becomes stable.
The Cassie model first peak has its value of -210 kV going up to -132 kV and at last -160 kV before it becomes stable.

The Schwarz-Avdonin model's first peak of -220 kV going up to -130 kV and thereafter to -163 kV.
In the coming chapter the following models will be implemented in PowerFactory to conduct a transient analysis of the circuit breaker in an offshore wind farm system.

Chapter 4

Implementation of the circuit breaker arc models in the offshore wind farm

In this chapter, the Mayr-, Cassie- and the Schwarz-Avdonin model will be implemented into the offshore wind farm. The implementation will be based on the parameters and equations stated in the last chapter and an explanation of the implementation will be elaborated. The implementation of the models will be implemented in the areas marked in figure 4.1.

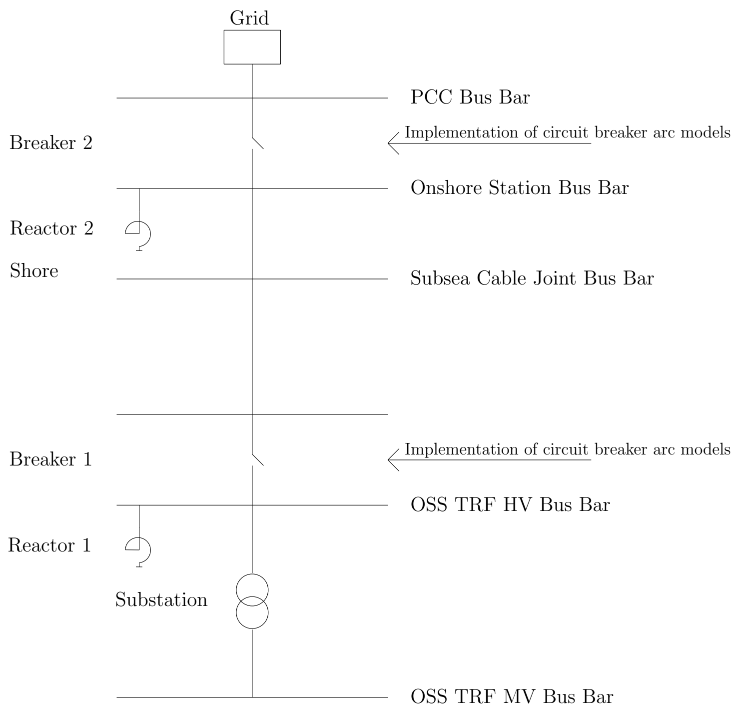


Figure 4.1: Representation of the offshore wind farm and where the models will be implemented.

4.1 Implementation of arc models in PowerFactory

Each of the arc models has been implemented in PowerFactory based on the equations from section 3.3. Each arc model has its own composite model in PowerFactory based on the equation. The equation has been divided into different blocks for simplicity and been written using DPL programming. An overview of the implemented Mayr arc model can be seen in figure 4.2. A representation of the Cassie-Mayr model implemented together can be found further in the section.

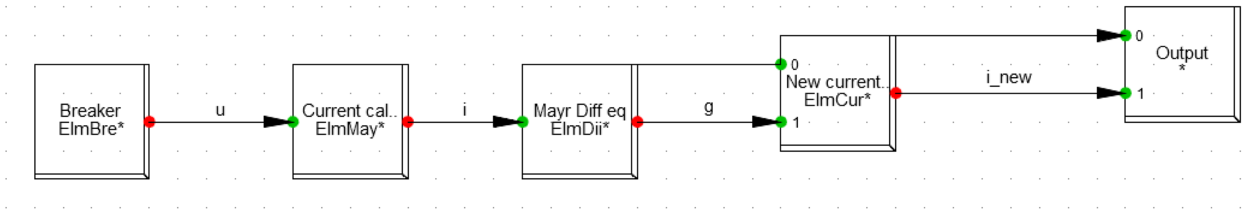


Figure 4.2: Representation of how the Mayr arc equation has been implemented in PowerFactory.

From figure 4.2 it can be seen how the circuit breaker works as the input to the blocks. It uses the voltage u which goes into the current calculation block and calculates the current based on the predefined arc conductance. The calculated current values go hereafter into the Mayr Diff. eq. block which calculates a new value of the arc conductance g. The newly calculated value for arc conductance goes into New current calculation block which calculates a new value for current based on voltage and the arc conductance.
Each block has its own common model which contains all the parameters given in the tables in section section 3.3. A representation of the commons models can be found in figure 4.3.

Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
1	Breaker	Breaker 1
2	Current calculation	dsl Mayr eq
3	Mayr Diff eq	dsl Differential equation
4	New current calc	dsl New current calc
5	Output	

Figure 4.3: General overview of the composite model and the different common models containing the parameters used in the equations.

The Cassie-Mayr model implemented together can be found in figure 4.4. The Cassie model has been implemented the same way as described for the Mayr model.

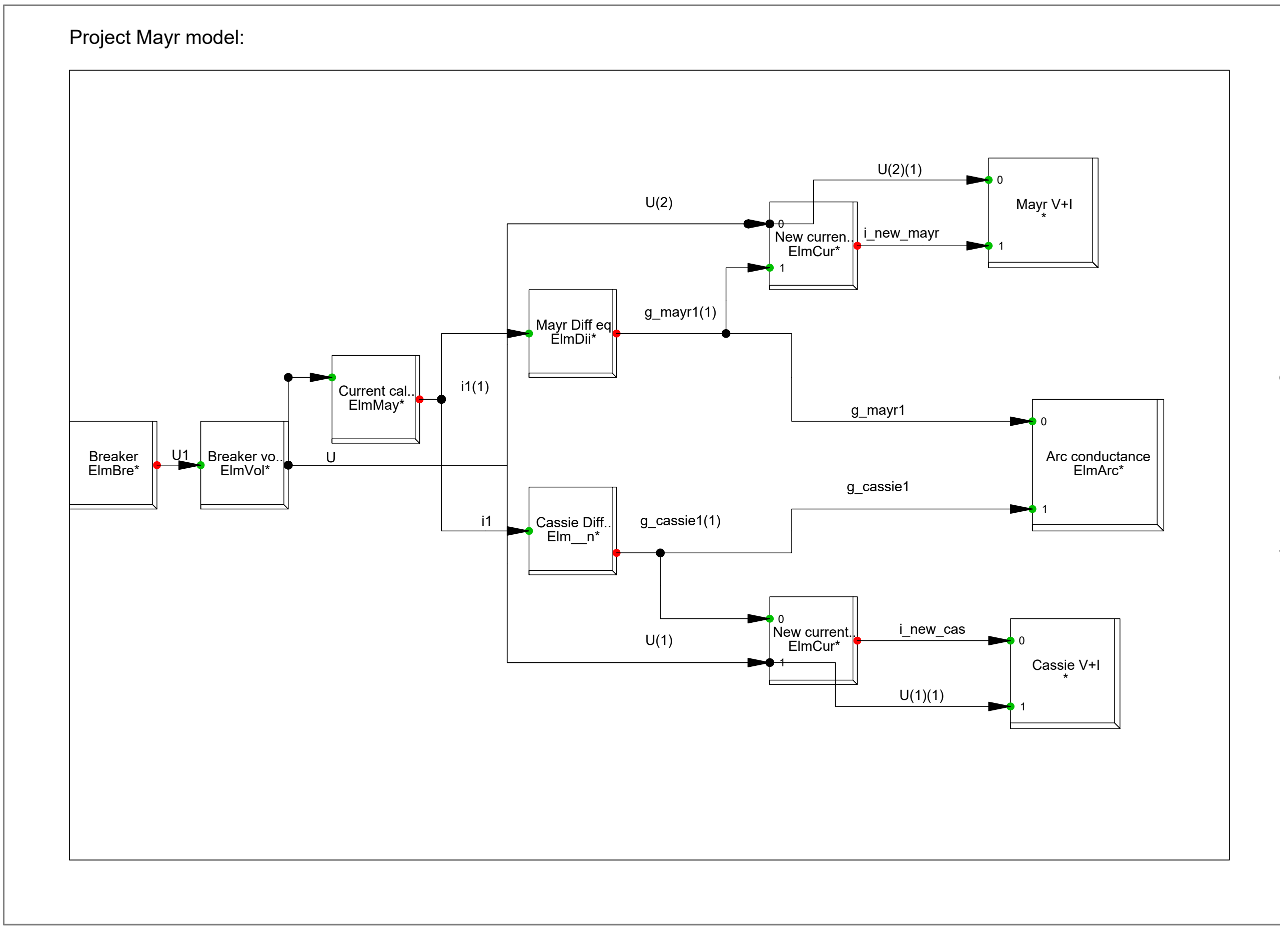
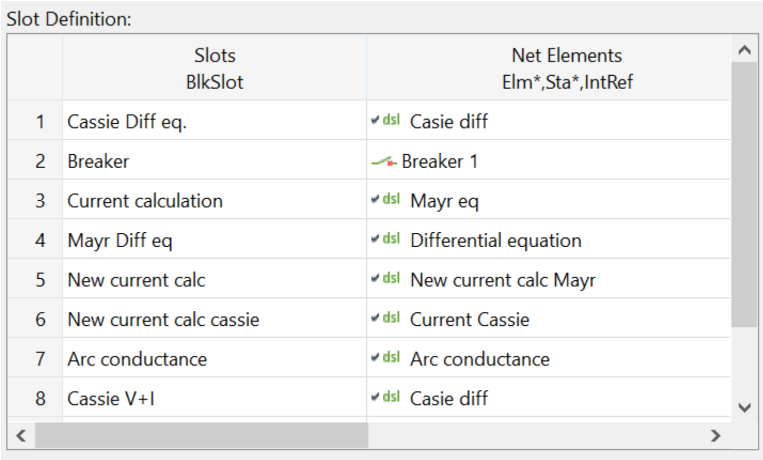


Figure 4.4: The fully implemented Cassie-Mayr model in PowerFactory based on the equations given in section 3.3.

From figure 4.4 it can be seen how both the Cassie- and Mayr- model are receiving the same voltage input from the Breaker voltage block. This block is receiving its input signal from the Breaker block where the voltage level of the system is stored. In the breaker voltage block the voltage across the circuit breaker is calculated and this voltage value is used in the other blocks.
From the Breaker voltage block the current of the circuit breaker is calculated and this value is used in both of the models since the arc conductance is the same value for both models. Hereafter is a new value of the arc conductance calculated for both models based on the differential equations. There are a total of three output blocks: Mayr $V + I$, Arc conductance, and Cassie $V + I$.
The Mayr $V + I$ and the Cassie $V + I$ output block consists of the arc current and voltage.
The Arc conductance block consists of the total arc conductance calculated based on equation 3.3 in subsection 3.3.3.

In figure 4.7 the content of the composite model can be seen. The composite model consisting of all the common models for both Cassie and Mayr used to describe the different blocks in the full model.



Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
1	Cassie Diff eq.	dsl Casie diff
2	Breaker	Breaker 1
3	Current calculation	dsl Mayr eq
4	Mayr Diff eq	dsl Differential equation
5	New current calc	dsl New current calc Mayr
6	New current calc cassie	dsl Current Cassie
7	Arc conductance	dsl Arc conductance
8	Cassie V+I	dsl Casie diff

Figure 4.5: General overview of the composite model and the different common models containing the parameters used in the equations and blocks for the Cassie-Mayr model.
It should be noticed that the composite models consists of more common models then represented on the figure.

The Schwarz-Avdonin model has also been implemented in PowerFactory. This can be seen on figure 4.6.

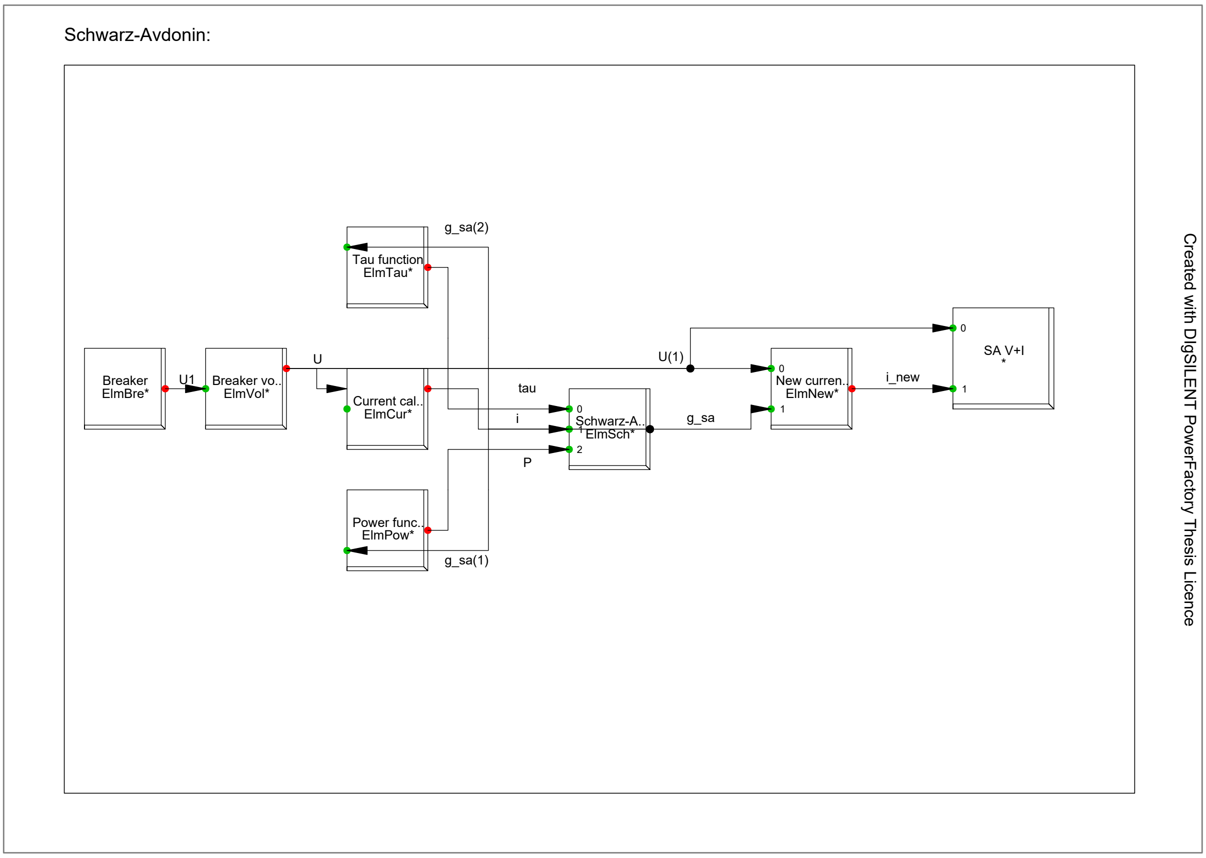


Figure 4.6: The implemented Schwarz-Avdonin model in PowerFactory based on the equations given in section 3.3.

The implementation of the Schwarz-Avdonin model is similar to the way the Cassie-Mayr model has been implemented, however, it should be noticed that it consists of two new blocks; Tau function block and Power function block. These two blocks are implemented since the time- and cooling power constant depends on the newly calculated value of the arc conductance.
In figure 4.7 the content of the composite model can be seen consisting of all its common models describing the different blocks in the model.

Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
1	Breaker	Breaker 1
2	Current calculation	dsl Current calc
3	Schwarz-Avdonin	dsl SA diff
4	New current calc	dsl New current SA
5	SA V+I	
6	Breaker voltage	dsl Voltage across breaker
7	Tau function	dsl Tau func
8	Power function	dsl Power func

Figure 4.7: General overview of the composite model and the different common models containing the parameters used in the equations and blocks for the Schwarz-Avdonin model.

Due to some problems described in the next chapter it was not possible to obtain any useful simulations yet for the transient analysis, this is due to initialization problems inside the blocks. However, it was possible to get an output response of each blocks through simulation.

Chapter 5

Project results, problems, and limitations

During this project the main focus has been on designing a mathematical model that can describe the behavior of a circuit breaker's electric arc when breaking. This is a useful tool to have when conducting a transient analysis of offshore wind power plants to ensure that the components in the system will not be damaged from the power disturbance.
In this chapter a summary of the obtained results, problems, and limitations during this project are presented and discussed. A future work perspective will also be concluded as well as suggestions for possible simulations to make a transient analysis of the wind power plant.

5.1 Project results

The mathematical model obtained during this project has been implemented into a previously developed wind power plant by the author to conduct a full transient analysis of the system.
The first part of the project focused on the development of the mathematical model and implementation into Simulink.
Mathematical models describing the behavior of the arc were made based on Cassie-Mayr and the modified version of Cassie-Mayr, Schwarz-Avdonin. These models were then implemented into Simulink. Predefined models were already available in Simulink and have worked as the base for the implemented mathematical models. Some changes had to be done to suit the requirements of the wind power plant, such as the voltage level, which resulted in finding and using other constant parameters in the base models.
The Schwarz-Avdonin model also had to be updated to match the 2020 version of Matlab/Simulink. Many of the arc models were developed in 2002 and do there-

fore not work in the newer versions of Simulink.
After the base models were updated and changed simulations were conducted for breaking of current at t=0s. The simulations were conducted for different scenarios to look at the output responses of the models based on a successful and unsuccessful interruption of current. In the report the simulation results of a successful interruption can be found. The output responses obtained from the simulations have been compared to other researchers' results to see if similar results were obtained, which was the case.
The next step of the project was to implement and build the models in PowerFactory. The first model build was the Mayr model which later on was combined with Cassie to obtain the full Cassie-Mayr model.
The models implemented were written in DPL which led to some troubles which will be described in the coming section.
In the end it was possible to implement the model and run it without errors in the block consisting of the equations defined in section 3.3. Hereafter the Schwarz-Avdonin model was implemented as well and run without errors.
Unfortunately it was not possible to obtain any simulations in PowerFactory yet due to problems which will be discussed in the next section. However, as a beta model of something never completed before, the model has the potential to be further developed and used as a tool for transient analysis.

5.2 Problems and limitations during the project

It was experienced during the project progress that the goal of this project has not been completed before and therefore no guidelines or help could be found from other people's research.
During this thesis multiple problems and challenges were encountered. The first problem was for the determination of the constant parameters used in the models. Most available information is given for medium voltage circuit breakers which made it challenging to find the correct values which could be used for this project. Some of the parameters such as cooling power and arc voltage can only be found from the manufactures through datasheets and these are often not public. It has therefore been necessary to use trial and error to determine the cooling power size for the Mayr model. It was observed that if the cooling power was not sufficiently large enough, the model was not able to interrupt the current. Based on interpolation of the value from the known cooling power of MV circuit breakers to the size of the voltage range used in this system it was determined that the size of 105 MW would be a realistic guess. Through simulation it was possible to interrupt the current at this size. It was also experienced that if a cooling power size less than 105 MW was used interruption of current was no longer possible.
The next problems encountered in the thesis occurred in the implementation of

the models in PowerFactory. First the equations had to be written in DPL which showed some complications. Another part was for the differential part of the equation which had to be written in its own block by using macro equations.
After ensuring that all the models could be run without errors occurring in the equations another problem occurred. Each block's input and output had to be initialized before it was possible to get an output response in the simulations. It has been hard to set a correct initialization in the models which is one of the things that need more work. Through research different initialization points have been chosen and simulated to see the impact on the simulation.
During this thesis, Coronavirus has also put its imprint on it. It has made some parts more difficult to solve and find solutions due to a lack of personal interactions. A day with a person who has more knowledge with the software PowerFactory would have shortened the amount of time used for building the models in PowerFactory and with the initialization problems. However, in general it was possible to implement the models and receive an output of the simulations, but the model still has parts that need to be improved to obtain a useful output.

5.3 Future work

During this thesis several obstacles had to be overcome as explained in the above section. Especially two points need more work to complete the model.
The first part is regarding the parameters. To ensure the right response of the model parameters from a circuit breaker manufacture could be helpful. It was experienced from simulations the importance and impact the value of the parameters had on the interruption of current. The parameters used in this thesis has been based on values stated in the base model as well as from other researchers' papers. In general the same values were used again and again and there is a lack of information regarding the modeling of HV circuit breakers.
Another part is regarding the initialization of the different blocks in PowerFactory. As mentioned above it has been challenging to state the correct initialization points.
Another idea could be to check the interface between each block to make them collaborate better. As the model is now it can run and give a simulation output, however, the blocks could be better at working together and using each other's signals and results.

For the analysis part of the circuit breaker, different scenarios have been conceived and would be interesting to look further into. The scenarios are regarding the circuit breakers' materials as well as for capacitive and inductive current.
Regarding the circuit breakers' material it would be interesting to do a comparison of the arc's behavior with different materials to see what sort of impact it might

have on the output response. In the study made by [8], parameters were given for different medium voltage circuit breakers and parameters such as cooling power, the time constants, and steady-state arc voltage changed depending on the material. However, no analysis was conducted regarding the difference between the output responses.

A way to simulate and analyze the transient behavior of the circuit breaker would be by interrupting capacitive and inductive current. These cases would be interesting to analyze due to the difficult conditions of the current interruption process as described in section 3.2. During this interruption the dielectric withstand of the contact gap can be exceeded after the arc quenching process and this can lead to the generation of arc-reignition which will lead to an unsuccessful breaking of the current. It could, therefore, be good scenarios to simulate these cases in PowerFactory and see if it is possible to interrupt the current.

Chapter 6

Discussion

During this project the main goal has been to analyze the transient behavior of a circuit breaker in an offshore wind farm using a mathematical model describing the behavior of its electric arc.
Describing the behavior of the electric arc has proven to be complicated in many ways. One of the complications has been regarding the constant parameters used in the simulations. Finding values for the parameters matching the voltage level working within this project has been difficult. Most of the pre-defined models in Simulink use a voltage level of 59 kV which has resulted in the need for interpolating and trial and error to find a value for the cooling power in the Mayr model. However, the value found in the end gave an expected output response of the mathematical model. However, some uncertainties are still present with all the constant parameters since it has not been possible to find other values or a specific explanation for chosen values for especially the arc conductance and τ.

When implementing the models into PowerFactory multiple problems were presented. The first problem was related to the implementation/expression of the equations. The error *parser failure* and *expression for this variable not convenient* was shown multiple times but was solved in the end by rewriting all of the equations into DPL programming. The models also have difficulty choosing the correct input into the model but after changing the composite model for the different block this problem was solved.

One of the focus areas trying to achieve which was to make a transient analysis of the circuit breakers, in this thesis was not met due to problems in PowerFactory. However, it was possible to implement all models without any errors present and to make simulations. There is however space for improvement before the model will be ready for use for transient analysis.

Another factor that has played a role during this thesis has been the coronavirus. Due to the unexpected situation caused by coronavirus it has made some problems difficult to solve. Especially problems related to PowerFactory can be difficult to explain and find solutions for when it has to be done online. However, my supervisor Amin Hajizadeh has been good at supervising me over Microsoft Teams and tried to guide me through some of the issues I have been having in this project.

Chapter 7

Conclusion

The scope of this project was to make a transient analysis of circuit breakers in an offshore wind power plant based on the Cassie-Mayr model.
The first step in the project was to build the base model of the wind power plant in PowerFactory, which will later be used for the implementation of the high voltage circuit breaker model.

Hereafter, the mathematical model of the electric arc was derived. It was desired to make a model that describes the behavior of the electric arc in the Circuit Breaker. This has been derived based on the Cassie-Mayr model as well as for the modified version of Cassie-Mayr; Schwarz-Avdonin's model. Based on the mathematical models a Simulink model was made to conduct simulations to see how the different models responded when interrupting current.

The next step was then to implement the models into PowerFactory. In conclusion it was possible to develop mathematical models to describe the behavior of the electric arc, however, more work needs to be conducted before it is possible to make a transient analysis in PowerFactory. This has been further explained in section 5.3.

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