Doubly Fed Induction Generator Fault Simulation

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Foreword

The present work represents my 4th semester master project at Aalborg University Denmark (AAU). The project was proposed by Vestas who also funded my studies at the Institute of Energy Technology of Denmark. I wish to thank the company and our contact person Remus Teodorescu.

I wish to thank my supervisor Ewen Ritchie who guided me through three semesters of my masters study; Jorge Martinez who proposed the project and took the time to discuss the stage of the project with us.

Special appreciations to Lascu Cristian and Alin Argeseanu for the support rendered and also to my friend Anca Julean for her help.

I want to thank my friends and colleagues for their kind thoughts and moral support.

Last but by no means least I want to thank my parents for getting me where I am now. I want to dedicate the effort done in this project to my late father who always believed in me and stood by my decisions.

The report is divided into chapters and subchapters. Appendices render additional information about the main body of the text.

Every chapter starts with a summary of the topics discussed in that particular section. To make reading easier, the summaries were collected in a table. For specific terms used in this report, please refer to the dedicated section where definitions are given. The purpose of this is to familiarise the reader with notions not insisted on in the main text. For a more detailed set of information, available references guide to a complex documentation.

Krisztina Leban

Abstract

This project focuses on modelling a wind turbine system. The machine used was a doubly fed induction generator (DFIG). Two fault ride through situations were investigated. As protection against short circuit transients, the dump resistor and the crowbar protection were modelled.

An equivalent model was constructed for each case. Simplifications were made so as to have a system composed of grid, transformer, line and generator represented by elementary circuit elements (R, L, C and voltage sources). Equivalent circuit models were simplified so that the fault models may be used for synchronous machine parameters. The assumption that the mechanical system cannot respond during the short time of a three phased short circuit.

The simplified crowbar and dump resistor models were compared to simulations constructed with complex library subsystems. The SimPower Systems Simulink library was used for this purpose.

Premises for a space state model and transfer function of the system was made. Step and impulse response of the fault model are documented. This model is the first step towards stability analysis.

Keywords: Wind generator, DFIG, modelling, equivalent system, fault, crowbar

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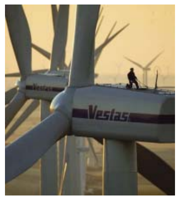
Presentation of Chapters

In this section contents of the chapters and appendix are presented. A suggestive picture is associated to facilitate finding desired information in the project.

Chapter 1: Introduction

In this chapter the project formulation is presented. Objectives, the work structure and motivation as well as limits of the project are listed.

Chapter 2: Background and State of the Art



In the following, a brief background and status of wind generators is presented. This chapter considers only DFIG and Synchronous generators for wind turbine applications. The study of the present technology represents a starting point for identifying the simulation model requirements. A detailed outline of the subject may be found in the indicated references.

Chapter 3: Understanding of DFIG

In this chapter, basics of the Doubly Fed Induction Generator are presented. Functioning, applications and mathematical model are stated. The chapter concludes on the features a fault model should focus on. Simplification criteria are also devised based on the functioning of the DFIG.

Chapter 4: Understanding of the Synchronous Machine

In this chapter, functioning and mathematical model of the synchronous machine are presented. As the fault process has a small time constant compared to the time constant of the system, the slip does not vary during the fault. Because of this, the DFIG may be considered to behave like a synchronous machine. In other words, synchronous machine parameters may be applied to a DFIG fault simulator. To argue for this possibility being valid, one must be familiar with the function of the synchronous generator.

Chapter 5: DFIG System Description

In this chapter, the modelled drive system having a DFIG is described. Function of the DFIG is analysed and the basic elements of the drive are presented. The aim is to represent the drive using an equivalent circuit in all three cases: normal operation, fault-dump resistor active, and fault-crowbar active. To allow for fault models fitted for both induction and synchronous machines, the circuits must be simplified. Grounds for the simplifications are argued in the chapter.

Chapter 6: Simulation Model

In this chapter the simulation of the DFIG applied to a wind turbine system is presented. With this, an idea of the validity of the simplified model may be tested. Models presented in this report are detailed. Normal duty and fault ride through models are described. Results are documented and conclusions drawn.

Chapter 7: Model Validation

In this chapter, the validation method and the validation of the model are presented. Consequences of simplified assumptions implemented in the models are shown. Acceptability of the simulation results is discussed.

Chapter 8: Conclusions

In this chapter overall conclusions are presented. A bridge is built between the initial objectives and the project results.

Chapter 9: Future Work

In this chapter, future work ambitions are presented. Present state of the development is summarised. The tasks are valid for this evolution point of the project. As work goes on, other tasks will emerge.

Appendix 1: Symbols

In this appendix symbols used in this project may be found. Alphabetical ordering of elements makes browsing fast and easy.

Appendix 2: Terminology

In this appendix, simple definitions of basic concepts may be found. The information is provided with references for further follow-up.

Appendix 3: Matlab Initialisation Code

The code used to initialise the simulation parameters for all models is presented in this appendix.

References

Chapter 1: Introduction

In this chapter the problem formulation of the project proposal is presented. Objectives, the work structure and motivation and the limits of the project are listed.

A. Problem Statement

The Doubly Fed Induction Generator (DFIG) is widely used in wind energy power generation. To connect the turbine or turbines to the mains, specifications listed in the national Grid Code must be respected. Voltage and power characteristics and fault ride through (see the terminology chapter) are handled by the control system of the turbine. To analyse a DFIG system a simulation model is useful.

This project deals with the simulation of a wind turbine system comprising the generator, transformer, transmission line and the mains. Two fault models are to be constructed for two protection types: converter blocked and crowbar activated. Simplifying assumptions have to be considered to obtain simple models.

For each case, equivalent circuits should be built to model the fault response of the DFIG system. Simplifications were made so as to have models which can be used for the DFIG as well as for synchronous machine parameters. The assumption is made that the mechanical system cannot respond during the short time of a three phased short circuit.

A compromise must be reached between the simplicity of the model and its accuracy.

B. Motivation

This simplified approach of DFIG system study facilitates the integration of the model into models of more complex systems, like wind farms. In that case, simulation speed and comprehendability of the model are essential features.

As the fault is handled at generator level, the effects of grid disturbances are reduced.

Models compatible with both induction and synchronous machines would be a great advantage in fault ride through analysis as they would on one hand facilitate understanding of the phenomena by comparison and on the other hand present a flexible solution for analysis.

C. Objectives

<u>Tasks:</u>

- Understanding the synchronous machine
- Build a simplified fault model of a DFIG wind turbine system
- Simplify the DFIG models further to enable the use of synchronous generator type parameters.
- Prepare the model for integration in a higher level system(e.g. a wind farm)
- The simulation should be able to be used for synchronous machine fault modelling as the fault time is so short that the slip may be considered

constant (the inertia of the system prevents the slip from varying instantaneously)

- Verify the models

Motivation:

- To increase the understanding of the effects of faults and protection systems on DFIGs.

Target group:

- The model is oriented towards fault effect prediction and is intended for use by engineers engaged in wind turbine system monitoring.

Method:

- Implement the model in Matlab-Simulink using SimPower Systems Library
- Construct a transfer function for the fault model
- Test the model by applying different inputs (voltage and slip)

D. Project Limitation

As control of the system has not been studied, normal functioning of the wind turbine system was not modelled. The reason for this is that without control, the machine would be unstable

Practical experiments were not performed as no experimental arrangement was available for a fault test experiment.

Only the machine, transformer and line models were simulated. Because of this, the machine is modelled working as a motor (consumer). For the machine to work in generator mode, the mechanical system, aerodynamics and power system must also be modelled. To engage in constructing a complex model, one must make sure that all the subsystems function correctly. In this project the simplified arrangement comprising transformer - line – machine was focused on. Modelling the machine as a motor is acceptable, because the direction of power flow does not change the structure of the equivalent system.

The mechanical components (gearbox and torque equation) have not been taken into account in the developed model. This was done under the consideration that during the fault time, the mechanical system will not have time to react.

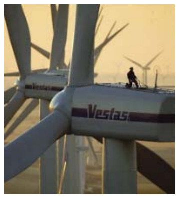
As no system parameters were supplied by the proposer of the project, parameters used in the simulation do not come from measurements from a real system. Their origins are from papers but numbers have been adjusted.

Conclusions:

By combining the objectives and the limitations, the project was carried out to meet the project expectations stated in the project statement

Chapter 2:

Background and State of the Art



In the following, a brief background and state of the art of wind generators is presented. This chapter considers only DFIG and Synchronous generators for wind turbine applications. The study of the present technology represents a starting point for identifying the simulation model requirements. A detailed outline of the subject may be found in the indicated references.

Wind energy is a popular renewable energy source. Doubly-fed induction generator (DFIG) wind turbines are used widely by all the wind generator manufacturers [1], [2].

DFIGs are variable speed generators with advantages compared to other solutions [3]. They are used more and more in wind turbine applications due to easy controllability, high energy efficiency and improved power quality. Fixed speed generators and induction generators had the disadvantage of having low power efficiencies at most speeds. To improve the efficiency, controlled power electronics converters are commonly used. Voltage source inverters are used to convert the voltage magnitude and frequency to match the grid values.

As power converters in a DFIG system only deal with rotor power, electronics costs are kept low, about approximately 20-25% of the total generator power. This is due to the fact that the rotor voltage is lower than the stator voltage. This implies that the converter is dimensioned to suit the rotor parameters. This makes the system more economical than using a full power rated converter in a series configuration. [4], [5], [6], [7].

Turbines are commonly installed in rural areas with unbalanced power transmission grids. For an induction machine an unbalanced grid imposes negative effects like overheating and mechanical stress due to torque pulsations.

For example for an unbalance of 6% the induction generator is stopped from generating to the grid. By control of the rotor currents of a DFIG, the effects of unbalanced stator voltages may be compensated for. [1]

The drive system operates in four quadrants. This implies that a bidirectional flow of power is possible. The possibility of supplying and consuming reactive power enables the generator system to act as a power factor compensator. By the control of the back to back inverters, the slip may be controlled. In the case of the squirrel cage induction machine, for example, as the rotor cannot be driven, the slip only depends on the stator and load inputs. As for synchronous machines, a relatively large torque may cause the machine to oscillate [8], [9]. The DFIG does not pose any synchronisation problems.

To observe the system and the flow of active and reactive power, a dynamic model is needed. The machine may be simulated as an induction machine having 3 phase supply in the stator and three phase supply in the rotor.[10]

In Figure 1 a basic layout of a DFIG wind turbine system is shown. The rotor circuit is connected through slip rings (see Appendix 2 for definition) to the back to back converter arrangement controlled by PWM strategies. The voltage magnitude and power direction between the rotor and the supply may be varied by controlling the switch impulses that drive the IGBTs [11], [12], [13].

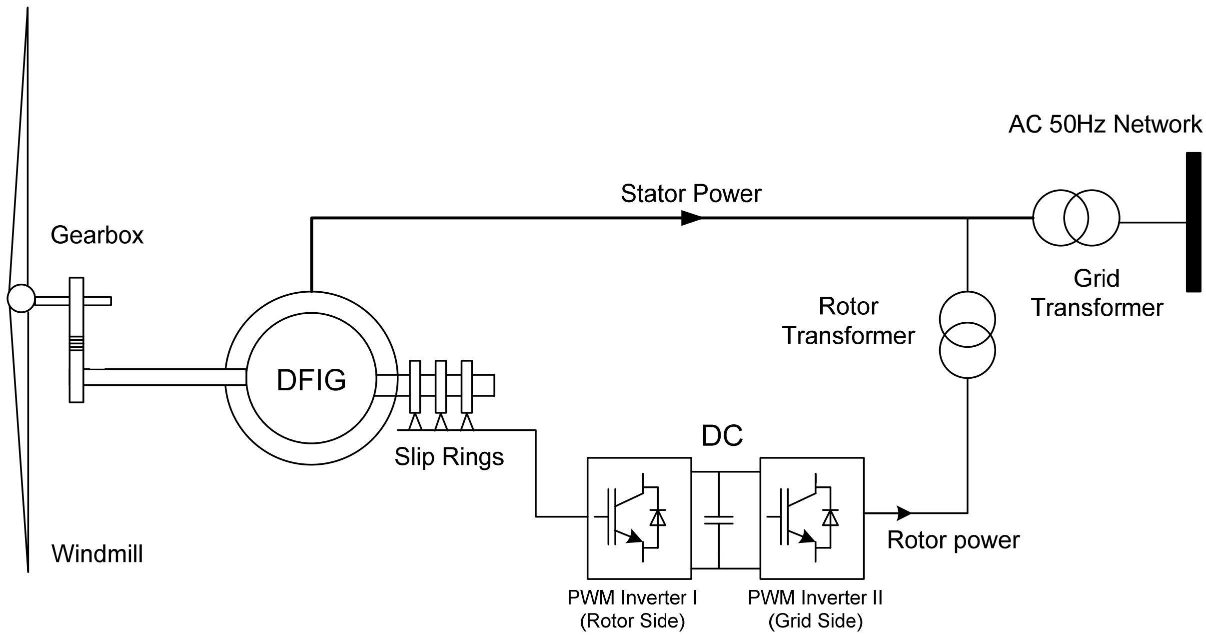


Figure 1: DFIG wind turbine System

Back to back converters consist of two voltage source converters (ac-dc-ac) having a dc link capacitor connecting them. The generator side converter takes the variable frequency voltage and converts it into dc voltage. The grid side converter has the ac voltage from the dc link as input and voltage at grid parameters as output [3], [14].

The gearbox has the role of matching the speed between the blades and the rotor. The transformer couples the generator to the grid adjusts the voltage of the machine to that of the grid. [10] This is only a typical example of the DFIG system layout.

The stator is connected directly to the grid. The rotor on the other hand needs a step down transformer in order to connect to the grid [19], [20], [21]. For a normal generation regime, the energy obtained by processing the wind speed as an input is fed into the network by both the stator and the rotor.

Wind turbine systems have two major control areas: electrical control of the converters and mechanical control of the blade pitch angle.

Like all drive systems wind turbines need to be protected against electrical transients that might damage the layout components. In the literature, implemented protective strategies are referred to as 'fault ride through capability'. [22]

According to [23] the machine may be simplified down to a series reactance and resistance (see Figure 2). This is a possibility not explored in the present project because it would oversimplify the simulation.

Mainly simulations were done on basis of equivalent systems ether by using simulation blocks or implementing code. Simplifications depend on the functioning modelled and on the purpose of the model.

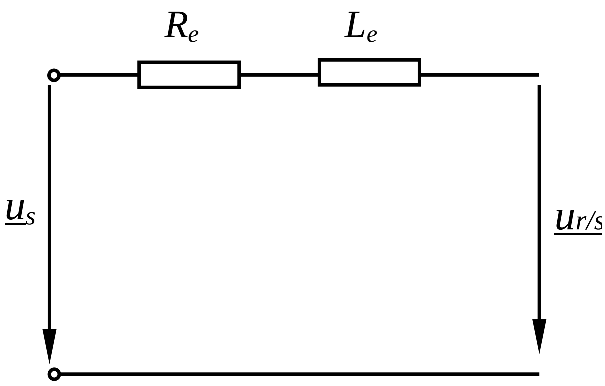


Figure 2: Simplified DFIG Model

Conclusions:

In the present project, the equivalent circuits of the system presented in Figure 1 were modelled. Fault handling, namely by inserting dump resistors and applying crowbar protection were analysed and discussed. A simplified circuit was aimed for. The machine, transformer and parasitic transmission line parameters were included.

This chapter gives and overview on the DFIG analysed in this project and also represents a summary of the biography investigated for the projects. As it is a form of an introduction, no details have been specified. Highlights of the information are delivered to prepare the reader for the next chapters.

Chapter 3: Understanding of DFIG

In this chapter, basics of the Doubly Fed Induction Generator are presented. Functioning, applications and mathematical model are stated. The chapter concludes on the features a fault model should focus on. Simplification criteria are also devised based on the functioning of the DFIG.

The DFIG system is also referred to as the Scherbius drive **[11]**. In Figure 3 a layout for a DFIG drive system is shown. In the following, the system function is explained.

The DFIG has windings on both the stator and the rotor. The stator is connected to the 3 phase supply - the mains. To match the stator voltages with the ones of the mains a 3 phase transformer could be used. [24]The shaft of the generator receives mechanical power through a coupling. For the practical case of wind application, the mechanical power originates from the wind powered blades of the turbine. To emulate the mechanical input, in laboratory testing, an electrical machine may be used in motoring regime [9]. Often DC machines are used as their speed may be controlled by controlling the voltage. Torque received from DC machine emulates the wind speed transmitted through the blades of the wind turbine. In order feed the DC machine a rectifier and current control are used.

The rotor is connected through an inductance to the rotor side inverter. The back to back inverter system is commonly used in such systems. Both inverters are PWM driven and vector controlled. [25], [26]. Measurement blocks are needed to acquire elements needed for the control. An encoder is needed to obtain the position of the rotor. From this, the speed of the shaft is obtained. [29][30]

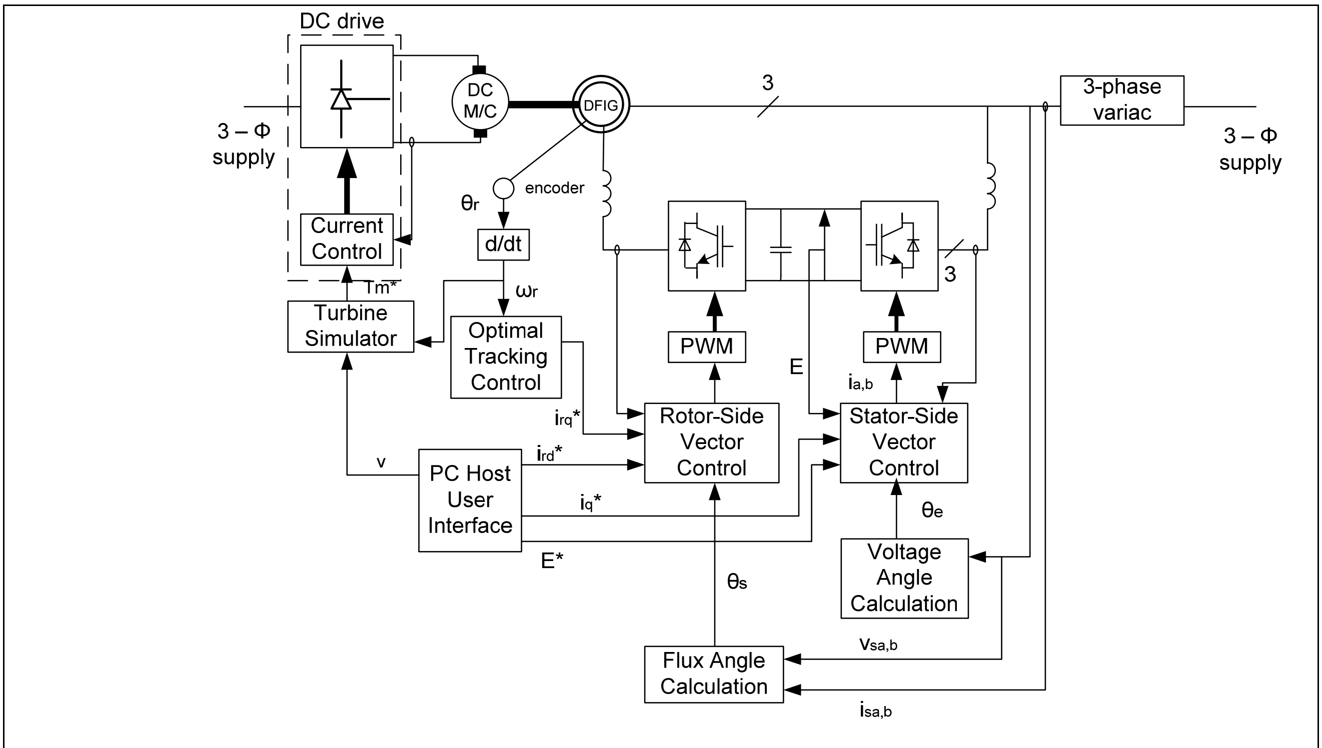


Figure 3: Scherbius Drive Block Diagram

Operation of the machine is set by control of the two converters. The vector control strategy used allows for generation at speeds from below to above synchronous speed.

Power factor is controlled by regulating the displacement angle between the current and voltage of the supply converter.

In the following, an example is presented for a better understanding of the system. Figure 3 presents a test layout of a DFIG having a controlled shaft torque. For a wind turbine, the shaft torque is never constant as the aerodynamics of the wind-blade system is independent of the implemented control.

The converters are rated with respect to the desired maximum speed. This depends on the rotor supply voltage. For a 6 pole machine a nominal modulation of 0.75 is implemented for the grid side converter and 0.76 for the rotor side converter. This strategy would give a speed range of 0 to 2000rpm. The actual maximum speed used depends on the rotor side inverter rating. Design requirements take the cut-in speed (see Appendix 2: Terminology) into consideration when setting the speed range. The gear box ratio is chosen in accordance with the rated speed of the generator and wind velocity. To obtain maximum efficiency of the system, the operating speed should be set above synchronous speed corresponding to the generator area as can be seen in (Figure 4 – where s is the slip; n is the speed and Me is the electromagnetic torque). The slip should not be allowed to increase over a certain limit as the efficiency of the system starts to decrease because of rotor losses and friction

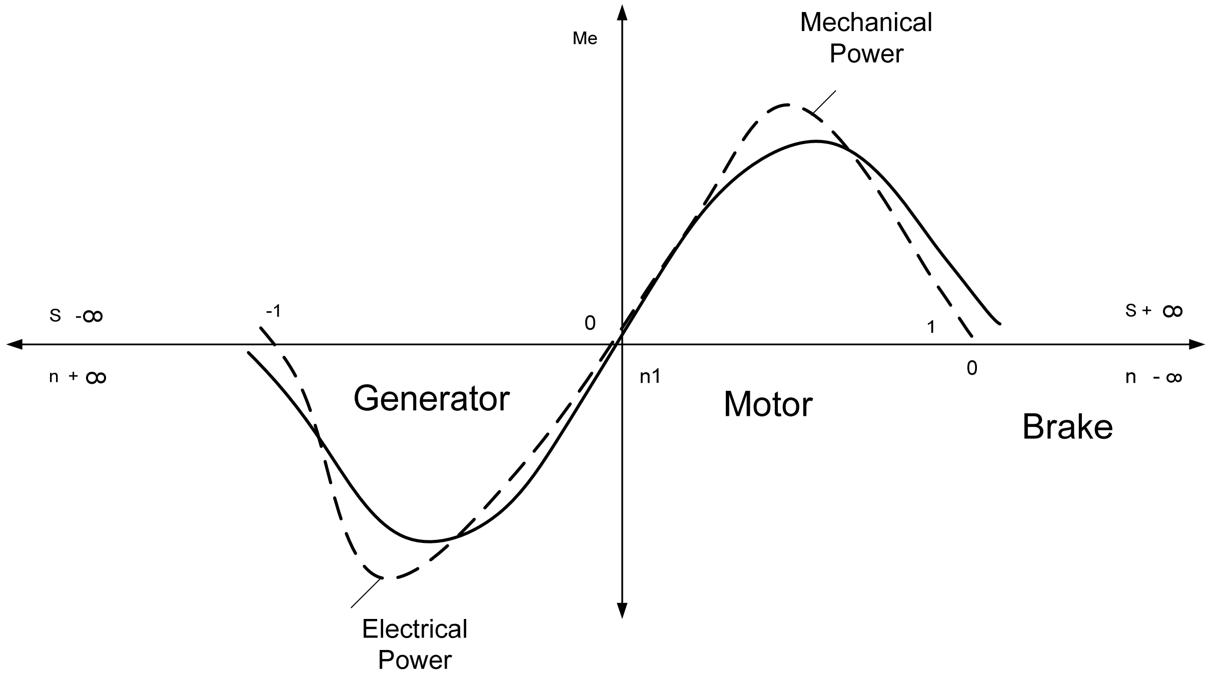


Figure 4: Induction Machine Characteristic[9]

The converter fed DC machine is used to emulate the turbine having a variable wind speed between 4m/s and 10 m/s. the generator speed is 1500 rpm, rated value. The switches in the converters are IGBTs. The DC link voltage may have values from 550V but not over 700V.

In the following a detailed description of the machine, grid side and rotor side converters is presented.

3.1 DFIG Equivalent Circuit and Equations

The arbitrary reference frame is used to present the general equations. ω_e can be replaced with the speed of the considered coordinate system.

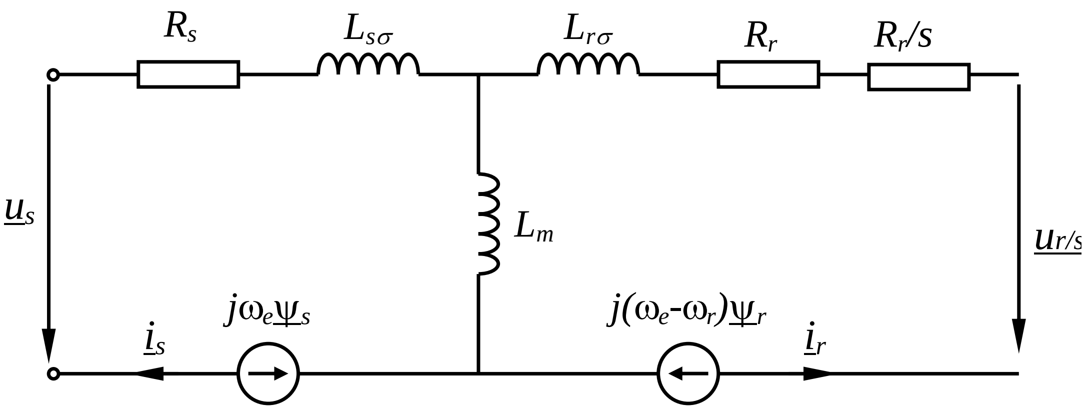


Figure 5: Space vector equivalent circuit for the arbitrary reference frame [25]

Equations of the machine are presented in the arbitrary reference frame ω_e [21]. The equations can be rewritten in the desired reference frame by replacing ω_e with the reference frame speed.[25], [26], [27]

The stator equation is presented below:

$$\underline{u}_s = R_s \underline{i}_s + \frac{d\underline{\psi}_s}{dt} + j\omega_e \underline{\psi}_s \tag{1}$$

Where

$\underline{u}_s$ - the stator voltage space vector,

$\underline{i}_s$ - the stator current space vector,

$\underline{R}_s$ - the stator resistance,

$\psi_{\underline{s}}$ – stator flux,

ω_e - the reference frame speed (arbitrary),

j – complex operator.

The stator voltage may be expressed as a sum of the stator d and q voltage components:

$$\underline{u}_s = u_{sd} + ju_{sq} \tag{2}$$

$\underline{i}_s$, $\underline{i}_r$ the stator and rotor current space vectors are also expressed in d and q components:

$$\underline{i}_s = i_{sd} + ji_{sq} \qquad \underline{i}_r = i_{rd} + ji_{rq} \tag{3}$$

Ψ_s, Ψ_r the stator and rotor flux space vectors,

$$\underline{\psi}_s = \psi_{sd} + j\psi_{sq} \qquad \underline{\psi}_r = \psi_{rd} + j\psi_{rq} \tag{4}$$

$\underline{u}_r$ is the rotor voltage space vector equation is written for the rotor circuit.

$$\underline{u}_r = R'_r \underline{i}_r + \frac{d\underline{\psi}_r}{dt} + j(\omega_e - \omega_r)\underline{\psi}_r \tag{5}$$

R'_r is the rotor equivalent resistor and ω_r is the rotor speed,

$$\underline{u}_r = u_{rd} + ju_{rq} \tag{6}$$

$$\underline{\psi}_s = L_s \underline{i}_s + L_m \underline{i}_r \qquad \underline{\psi}_r = L_r \underline{i}_r + L_m \underline{i}_s \tag{7}$$

where

L_m	the magnetizing inductance,
L_s, L_r	the stator and rotor inductances

$$L_s = L_m + L_{s\sigma} \qquad L_r = L_m + L_{r\sigma} \tag{8}$$

Where

$L_{s\sigma}$ is the stator leakage inductance and $L_{r\sigma}$ is the rotor leakage inductance

The mechanical equation comprising the rotor inertia J, load torque T_L, electromagnetic torque T_e and the rotor speed ω_r is written as follows:

$$J\frac{d\omega_r}{dt} = T_e - T_L \tag{9}$$

The electromagnetic torque is a function of the machine pole pairs (p) and stator currents and fluxes:

$$T_e = \frac{3}{2}p(\psi_{sd}i_{sq} - \psi_{sq}i_{sd}) \tag{10}$$

Space vector representation of the machine is preferred due to the fact that control strategies involve managing the d and q components of the system.

To write machine equations, equivalent circuits for both d and q axis must be drawn.

3.2 Grid - Side and Rotor - Side Converter

The stator of the DFIG is directly connected to the grid. The rotor is fed using two PWM converters (rotor side and stator side) through slip rings (Figure 6).

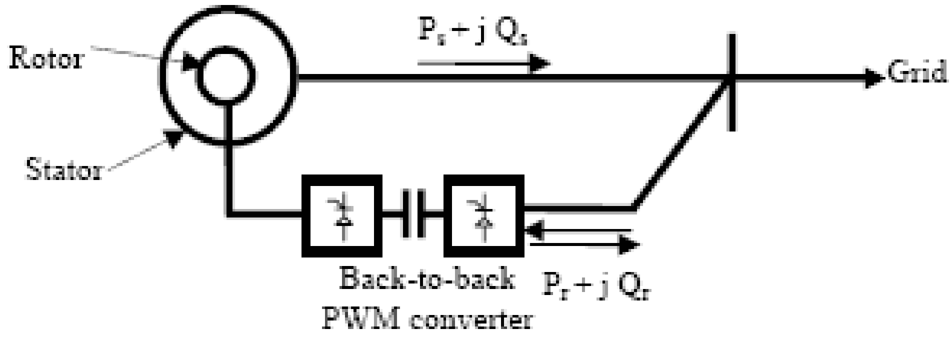


Figure 6: Doubly Fed Induction Generator Wind Turbine System

The role of the converters is to allow for a variety of speeds dictated by the wind speed at one specific time. The converters adapt the frequency of the wind speed to the frequency of the grid. The DC link capacitor has the role of storing energy in the conversion process. To enable complete control over the generation process, the voltage in the DC link must be greater than the line to line amplitude of the grid voltage. [11], [29], [30]

The role of the supply side converter is to maintain the voltage in the dc link constant for every magnitude and direction of rotor power. The control is achieved by driving the switches with a PWM strategy (vector-control in stator coordinates). An additional current regulator is commonly used for the converters.

The speed of the generator may be determined by controlling the rotor and stator side converters. Functioning may be set for both below and above synchronous speed. With this, function a four quadrant operating mode is obtained [31]. In other words, when the slip power is used to supply the rotor windings, functioning at synchronous speed is achieved. The DFIG is seen like a synchronous generator from the outside system.

3.3 Speed controller

Speed control is implemented to reduce torque ripple and consequently increase output power quality; attenuate of mechanical stress; reduce noise, mainly at low speeds; and increase turbine efficiency for a range of wind speeds. Power vs. speed characteristics influence the speed of the rotor by enabling control of the torque with respect to a power vs. speed chart. The speed is the measured quantity. An example of a speed control curve may be viewed in Figure 7, [11], [29], [30] .

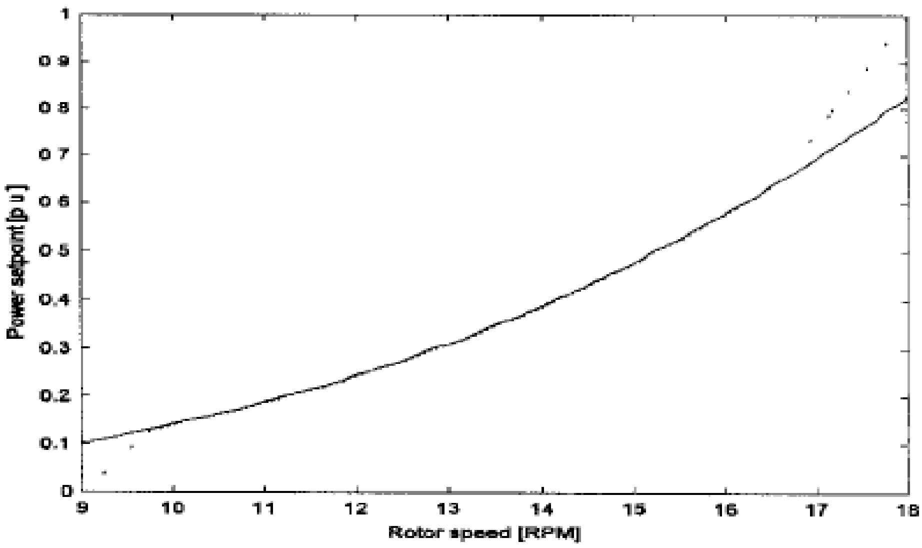


Figure 7: Optimal (full line) and implemented (dotted line)rotor speed characteristic

3.4 Pitch control

The role of the pitch control is to regulate the speed of the rotor in order to avoid overloading the machine and converter when the wind speed is too high. In actual fact, the angle of the blades is changed gradually to avoid faults arising [32].

Simplifying assumptions are usually made to implement pitch control. The main assumptions are presented in the following:

- The entire rotating mass is represented by one element -'lumped-mass'
- quasi static model of the aerodynamic part [33]
- sinusoidal flux distribution in the generator
- neglecting dynamic phenomena of the mechanical system

Conclusions:

The DFIG is a complex system. In order to create a simulation model the machine and the additional drive elements must be subjected to simplifications. If operating in specific regimes, for example fault or no load regimes, additional assumptions may be made. Chapter 5 presents the simplified model for the short circuit fault ride through handling.

Beside the fact that understanding the DFIG was a requirement in the project proposal, before modelling it, the functioning and equations of the subject must be investigated.

Chapter 4: Understanding of the Synchronous Machine

In this chapter, the function and mathematical model of the synchronous machine are presented. As the fault process has a very small time constant compared to that of the system, the slip does not vary during the fault. Because of this, the DFIG may be considered to behave like a synchronous machine. In other words, synchronous machine parameters may be applied to a DFIG fault simulator. To argue for this possibility being valid, one must be familiar with the function of the synchronous generator.

A synchronous machine is fed from a three-phase voltage source in the stator exactly like the induction machine. The difference is in the rotor, where the synchronous machine has a constant magnetic field generator. The source may be either permanent magnets or windings fed with DC voltage. The three-phase stator voltages produce a rotating field which interacts with the constant field of the rotor. Unlike the case of the induction machine, the synchronous machine has no slip (the rotor field leads the stator field in a generator).

Starting the synchronous machine working as a generator(wanting to connect to the consumer) or a motor requires special attention. To start the machine, a stronger field is needed because the windings are not magnetised and the mechanical inertia which tends to keep the rotor in stand still state. The starting field cannot be obtained by the stator and rotor alone. As a consequence, the machine will start in an asynchronous manner. A synchronisation procedure is needed. For this, power electronics are used to control the field. To assist at start up by creating a surplus field, an amortisation winding is used. After the machine had started, the amortisation circuit is taken out as the machine is fully magnetised. [9]

To understand, analyse and control the synchronous motor, an equivalent circuit is most useful. For control purposes, a dq representation of the stator and rotor is needed. Two circuits are employed: one in the q axis and one in the d axis. (Figure 8, Figure 9).

As depicted in Figure 8 and Figure 9 the machine is represented as a stator resistor, inductor and flux modelled as a voltage source (Ls, L1, and φ (q or d)). The magnetisation is represented by the inductance Lm (q or d) [34]

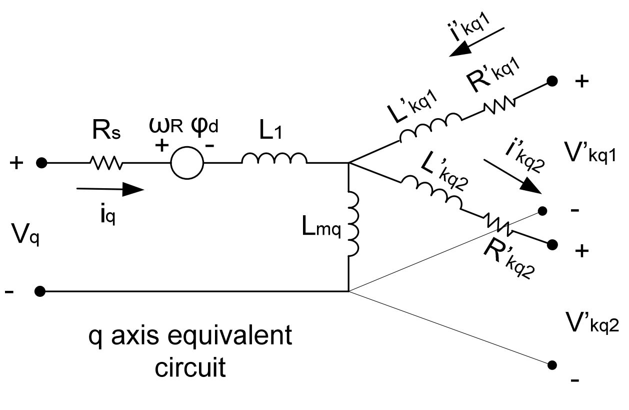


Figure 8: Synchronous Machine – q axis Equivalent Circuit

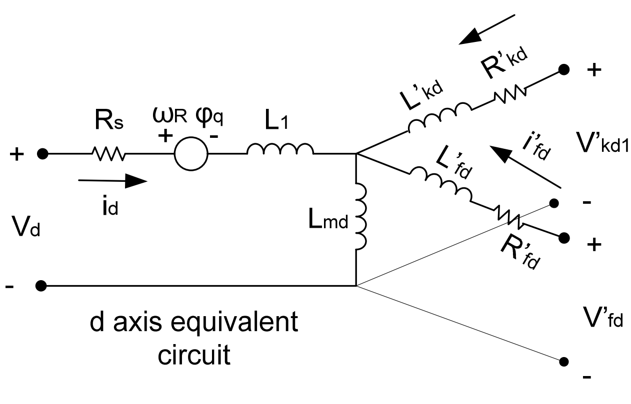


Figure 9: Synchronous Machine – d axis Equivalent Circuit

In Figure 8 and Figure 9 the subscript k stands for the amortisation circuit and the subscript f for the field winding.

Stator voltage equation:

$$V_q = R_s i_q + \frac{d}{dt}\Phi_q - \omega_R \Phi_d \tag{11}$$

V_q – q axis voltage

R_s – stator resistance

i_q – q axis current

Φ_q – q axis flux

Φ_d – d axis flux

ω_R – rotor speed

$$V_d = R_s i_d + \frac{d}{dt}\Phi_d - \omega_R \Phi_q \tag{12}$$

V_d – d axis voltage

i_d – d axis current

The flux equations show a dependency of inductances (L_d, L_q-leakage inductances, L_{md}, L_{mq}-magnetisation inductances) and currents (i'_{fd}-field circuit current in d axis, i’fq-field circuit current in q axis, $i'_{kd(q)}$- amortisation circuit current in d(q) axis).

$$\Phi_d = L_d i_q + L_{md}(i'_{fd} + i'_{kd}) \tag{13}$$

$$\Phi_q = L_q i_q + L_{mq} i'_{kq} \tag{14}$$

Flux equations are presented in the following

$$\Phi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i'_d + i'_{kd}) \tag{15}$$

$$\Phi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i'_d + i'_{fd}) \tag{16}$$

$$\Phi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \tag{17}$$

$$\Phi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \quad (18)$$

Field circuit voltage equation:

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt} \Phi'_{fd} \quad (19)$$

Amortisation circuit voltage equation:

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt} \Phi'_{kd} \quad (20)$$

where R'_{kd} is the resistance of the amortisation circuit.

For the diagram presented in Figure 8, the amortisation q voltages

$$V'_{kq1} = R'_{kd1} i'_{kq1} + \frac{d}{dt} \Phi'_{kq1} \quad (21)$$

For the diagram presented in Figure 8

$$V'_{kq2} = R'_{kd2} i'_{kq2} + \frac{d}{dt} \Phi'_{kq2} \quad (22)$$

[35], [36], [37], [38]

In Figure 10 the synchronous machine control system is presented. The back to back full power converter system enables the stator circuit voltage to be controlled. Measured quantities (e.g. voltages, currents, speed, and torque) calculated (speed) and estimated values (flux) are needed by the control system.

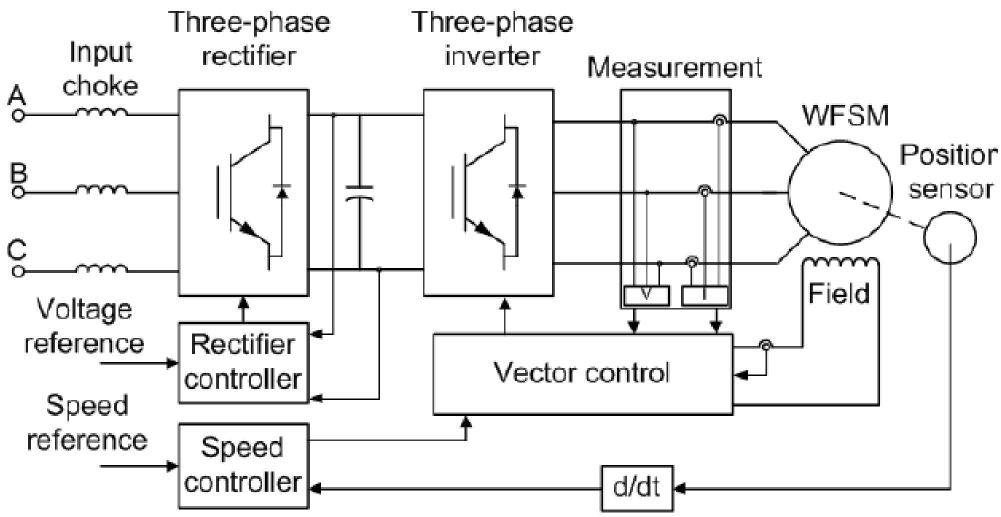


Figure 10: Synchronous Machine Control System [36], [37]

Conclusions:

Compared to the DFIG, the synchronous machine needs an auxiliary winding and power supply to magnetise the machine [9]. At steady state, the basic difference between the induction machine and the synchronous machine is the slip. The assumption can be made that the slip is constant during short periods of time. In other words, as the electrical time constant is considerably smaller than the mechanical time constant, the mechanical response is considered constant during an electrical transient. Based on this, the slip is considered constant during a short circuit.

As the problem statement asks for the DFIG model to be suitable for synchronous machine parameters two, an overview chapter of the synchronous machine is needed to justify an support simplifying assumptions on the simulation model.

Chapter 5: System Description

In this chapter, the modelled drive system having a DFIG is described. Function of the DFIG is analysed and the basic elements of the drive are presented. The aim is to represent the drive using an equivalent circuit in all three cases: normal operation, fault-dump resistor active, and fault-crowbar active. To allow for fault models fitted for both induction and synchronous machines, the circuits must be simplified. Grounds for the simplifications are argued in the chapter.

The objective of this chapter is to describe the circuits modelled in Matlab Simulink. Before presenting each actual simulation, the idea behind it must be clearly stated.

In Figure 11 the basic normal duty diagram for the wind turbine is presented. T_w represents the driving torque produce by the wind. From the blade and shaft, the rotor of the generator receives the torque. The energy is fed to the grid through the back to back inverter system and the three phase transformer. The initial model of the transmission line consisted of a pi diagram containing the parasitic elements of the conduction cable. According to [38] lines under 100 km are considered short lines and may be modelled as an inductance. The grid was modelled as a three-phase voltage source.

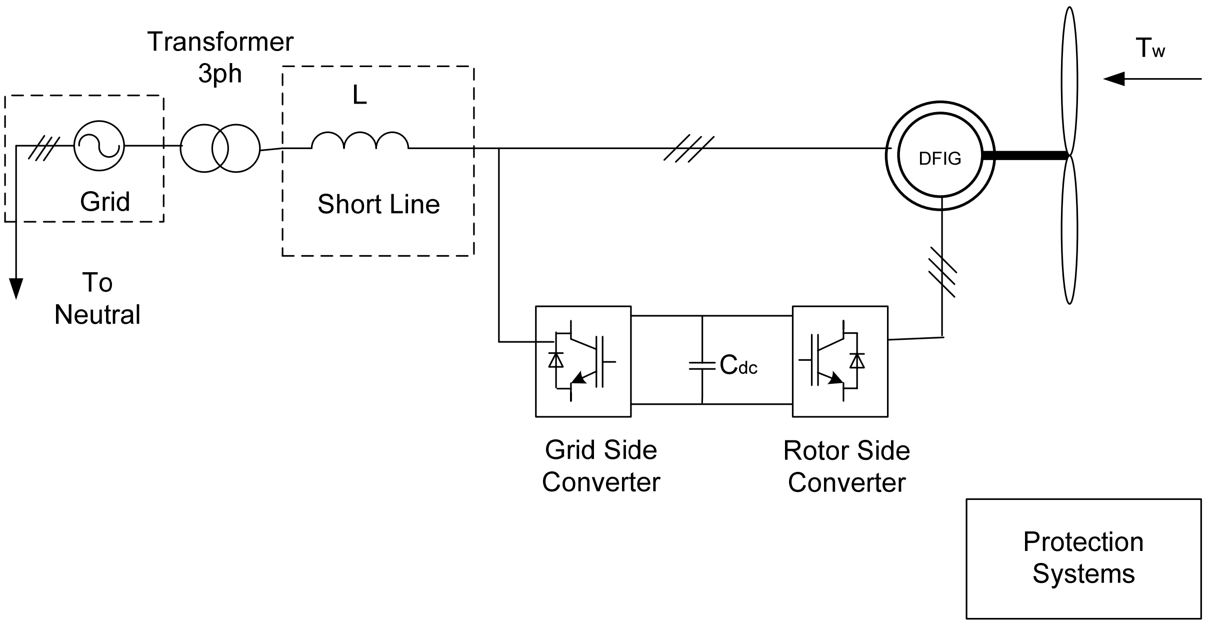


Figure 11: Basic Normal Duty Diagram

5.1 Normal Duty

In Figure 12 the normal duty connection diagram of the generator system is shown. The rotor of the generator is connected to the rotor side converter through switch K. in the actual setup, K is a switch converter.

The crowbar protection is also depicted in Figure 12. By switch K, the resistor bank may be connected to the rotor windings. This is activated when a fault occurs and transients are so high that the generator must be protected by short-circuiting the rotor [38]. Details of the function are presented in the third section of this chapter.

R_{dump} is used as an alternative fault protection. If the dump resistor is connected into the circuit the rotor converter is disconnected from the circuit (by switching the K1 comutators). For charging/discharging the dc link capacitor C_{dc} a dedicated circuit is used.

The grid side converter is connected to the transmission line through a three-phase step down transformer. The grid is modelled as a three-phase voltage source.

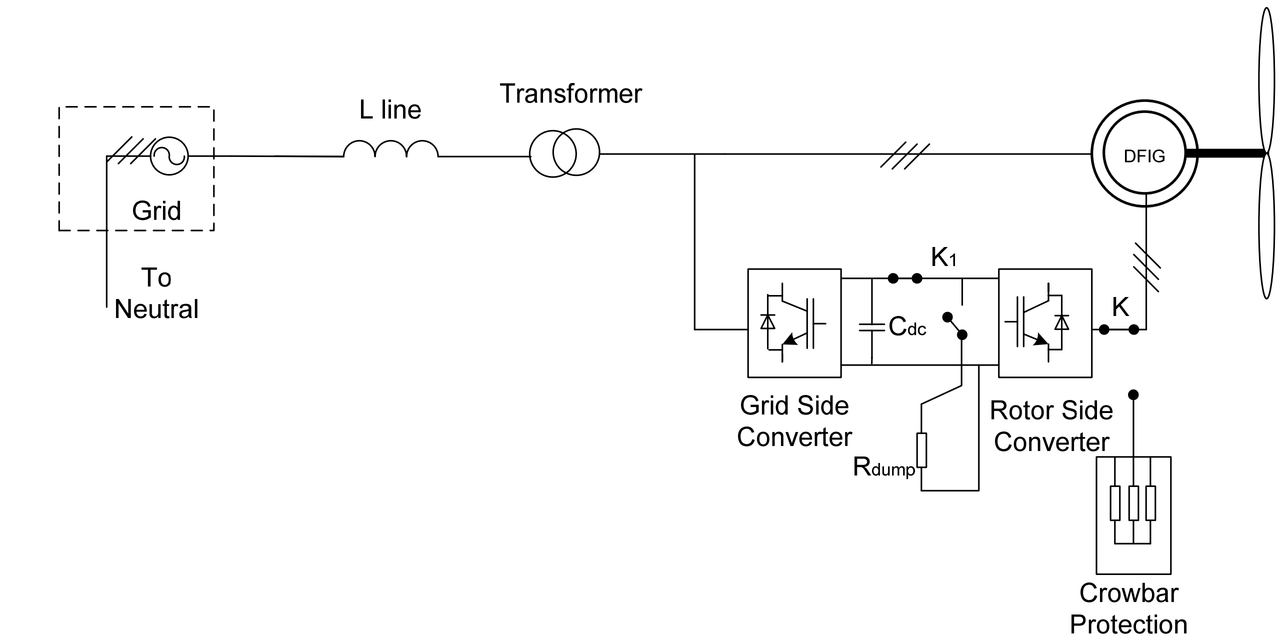


Figure 12: Normal Duty Diagram

In Figure 14 the equivalent circuit of the system is presented. The grid was represented as an alternating voltage source. For the transmission line, a pi equivalent circuit was used [38] and for both the transformer and the machine was modelled as a T equivalent circuit [40].

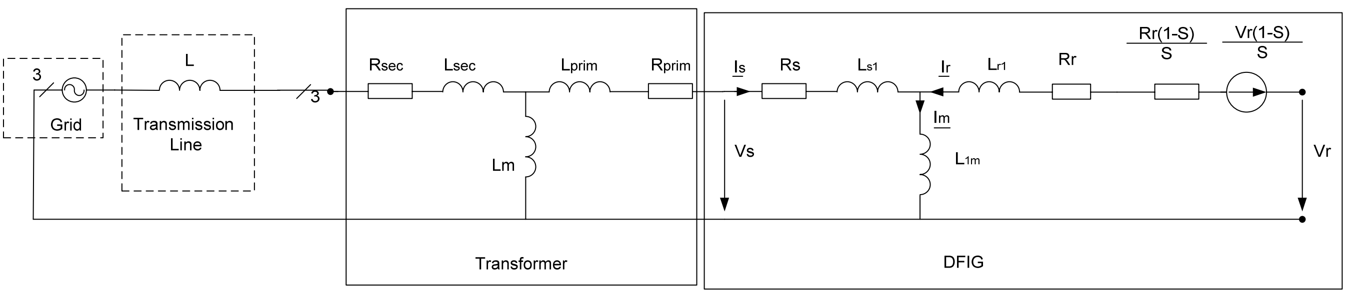


Figure 13: Normal Duty Equivalent Circuit

In order to simplify the equivalent circuit and consequently the mathematical model derived from it, a set of simplifying assumptions were considered. Arguments are provided for each assumption to show their validity.

As the line is considered to be short (< 100km [41]), the model may be simplified to a single parasitic inductance. The magnetisation branch of the transformer was neglected ([38]). This is done under the assumption that the current is too small in that branch and the reactance is small compared to the series branch reactance.

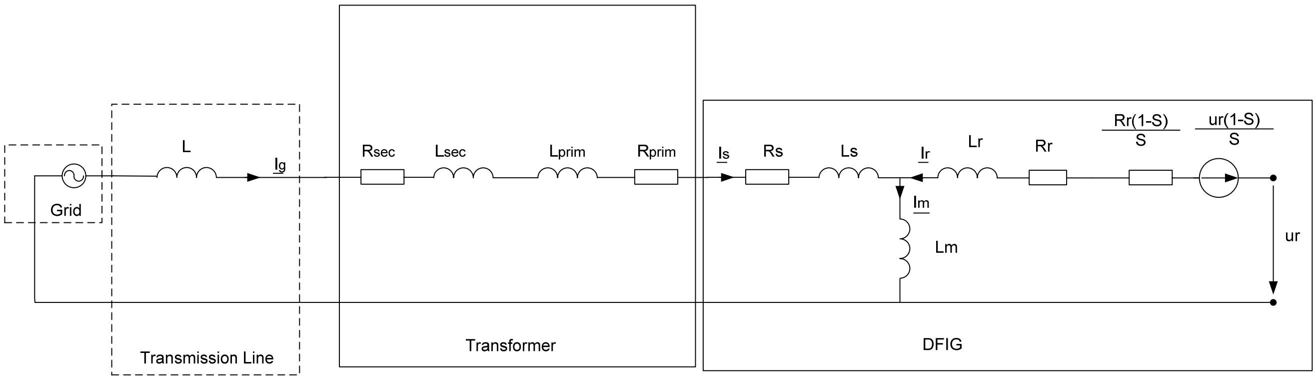


Figure 14: Normal Duty Simplified Equivalent Circuit

Equations derived from, Figure 14 are presented in the following:

The first circuit loop comprising the grid voltage u_g the equivalent inductance L_{ech} and resistance $R_{ech.}$ By omitting the magnetising branch of the transformer, the primary and secondary elements being connected in series may be reduced to equivalent components below.

$$\underline{u}_g = R_{ech}\underline{i}_g + \frac{dL_{ech}}{dt}\underline{i}_g + \frac{dL_m}{dt}\underline{i}_m \quad (23)$$

The detailed formulas for the equivalent resistance and inductance are presented in the following

$$R_{ech} = R_{sec} + R_{prim} + R_s \quad (24)$$

Where

R_{sec} – resistance of the secondary side of the transformer

R_{prim} – resistance of the primary side of the transformer

R_s – stator resistance of the machine

$$L_{ech} = L_{sec} + L_{prim} + L_{line} + L_s \quad (25)$$

Where

R_{sec} – resistance of the secondary side of the transformer

R_{prim} – resistance of the primary side of the transformer

Lsec – inductance of the secondary side of the transformer

Lprim – inductance of the primary side of the transformer

Lline – line parasitic inductance

L_s – stator inductance

The second circuit loop equation comprises the rotor voltage and the slip dependent elements

$$\underline{u}_r = R_a \underline{i}_r + \frac{d\underline{\psi}_r}{dt} - \frac{u_r(1-S)}{S} \qquad (26)$$

where

Ra - rotor equivalent resistor. See equation below

S-slip

$\underline{\Psi}_r$ – rotor flux

$$R_a = R_r + \frac{R_r(1-S)}{S} \qquad (27)$$

The rotor flux is:

$$\underline{\psi}_r = L_r \underline{i}_r + L_m \underline{i}_s \qquad (28)$$

If the slip is considered constant, the rotor resistor value would incorporate the slip value component for a given slip. This assumption is acceptable for the fault situations presented in the following.

5.2 Converter Blocked

When a fault occurs on a transmission line, over-currents flow in the system. The protection system of the wind generator has the role to limit the short circuit current. The converter is disconnected from the circuit and connected to a load resistor (R_{load} [40]).The diagram of the fault and protection is depicted in Figure 15

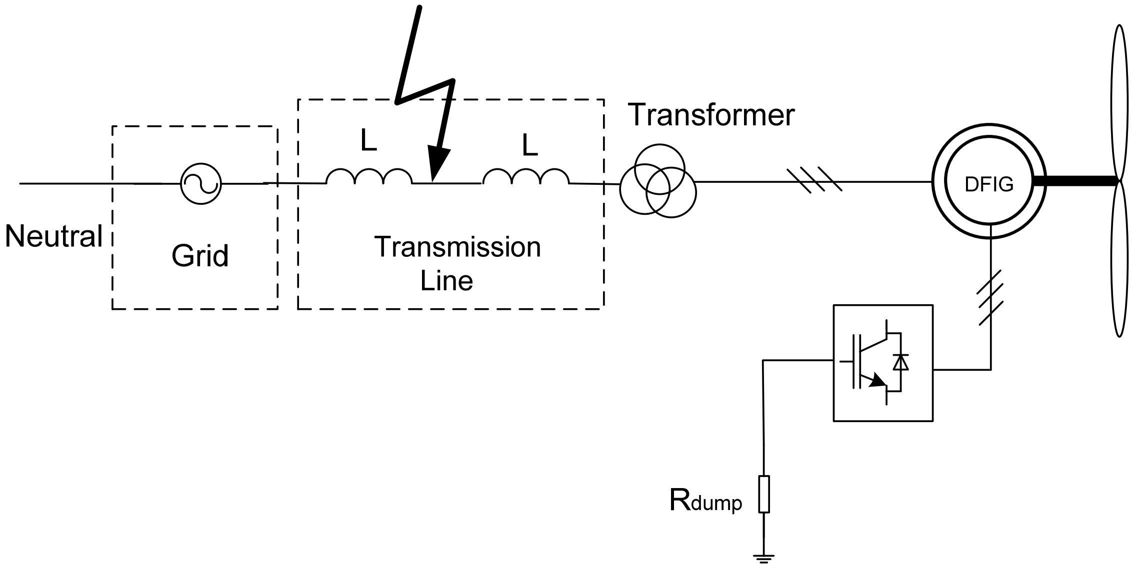


Figure 15: Converter Blocked Diagram

When a short circuit occurs and the current rises, the voltage drops at constant power. Based on this, capacitors in the circuit may be neglected. The simplified equivalent circuit is presented in Figure 16. The rotor is no longer supplied from the voltage source inverter. Instead, it is connected to the dump resistor through a commutator.

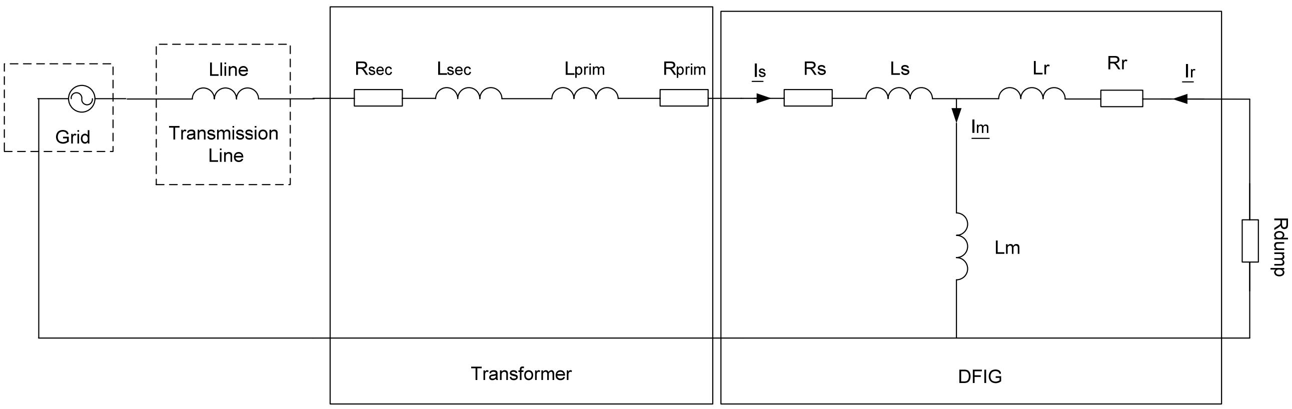


Figure 16: Converter Blocked Equivalent Circuit

The magnetisation branch of the transformer was neglected on the grounds that the current flowing through it is low. The series inductances and resistances cannot be neglected as values of the corresponding impedances rise with the current.

Equations derived from Figure 16 represented in the following:

In the first circuit loop, the equation is written as:

$$\underline{u}_g = R_{ech}\underline{i}_g + \frac{dL_{ech}}{dt}\underline{i}_g + \frac{dL_m}{dt}\underline{i}_m \quad (29)$$

The equivalent elements are written as sums of series components are given below:

$$R_{ech} = R_{sec} + R_{prim} \quad (30)$$

$$L_{ech} = L_{sec} + L_{prim} + L_{line} \quad (31)$$

For the second circuit loop, as the rotor is disconnected from the voltage source, only the energy stored in the motor magnetising branch intervenes. This is the main reason why the magnetising element may not be neglected in this case.

$$\underline{0} = R_a\underline{i}_r + \frac{d\underline{\psi}_r}{dt} + (R_{dump} + \frac{R_r}{S})\underline{i}_r \quad (32)$$

If the slip is assumed to be constant, the resistor value of the rotor resistor will remain constant.

$$\underline{0} = R_a\underline{i}_r + \frac{d\underline{\psi}_r}{dt} + (R_{dump} + R_r^{'})\underline{i}_r \quad (33)$$

$$\underline{\psi}_r = L_r\underline{i}_r + L_m\underline{i}_s \quad (34)$$

In the simulation, as the entire system was not modelled, the machine was modelled as a consumer (motor). To insert the model into a complex system, extra voltage sources (to simulate the stored energy) must not exist in the simplified subsystem.

5.3 Crowbar Activated

Another protection for a short circuit is called the crowbar (see Appendix 2). This fault handler is a set of resistors used to short circuit the rotor windings in case of a severe fault. In literature it is also called ‘beak resistor’ because it has a electrical breaking effect on the accelerating rotor. [38]. The role of the circuit is to contribute to system stability during transients. The extra resistance introduced in the circuit dissipates the surplus energy generated during the fault in extremely high current conditions. The rotor of the generator is disconnected from the back to back inverter system and short-circuited with resistors (see Figure 17).! Automatically disconnect after the fault is cleared. K is a symbolical switch representing the connection apparatus and control.

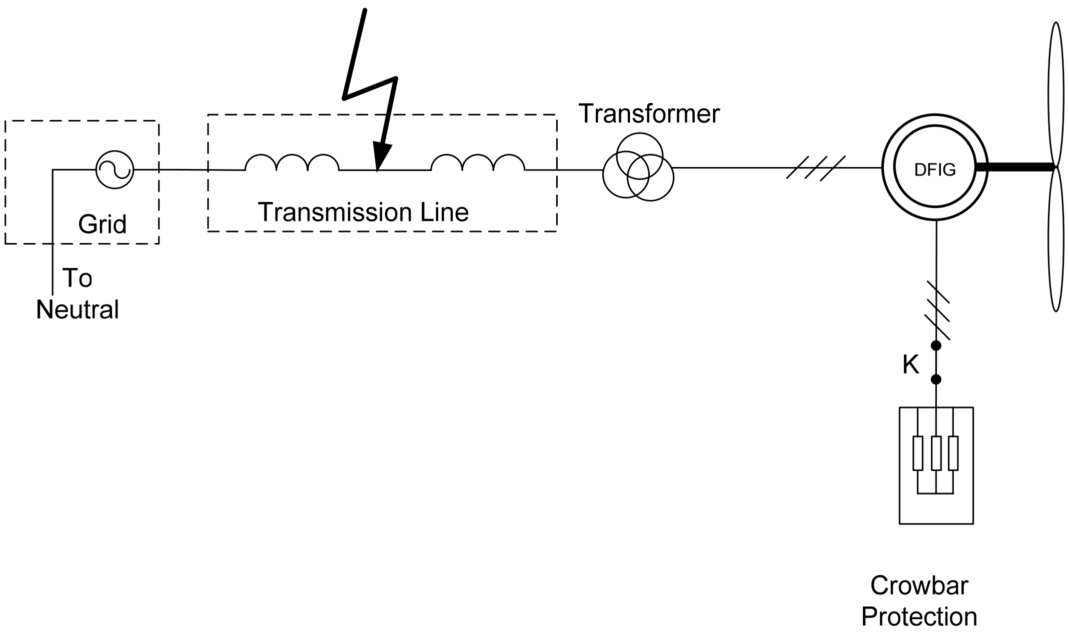


Figure 17: Crowbar Activated Diagram

The equivalent circuit of the crowbar activated diagram is shown in Figure 18. Simplifications by neglecting capacitors where made on the same considerations stated in the previous subchapter.

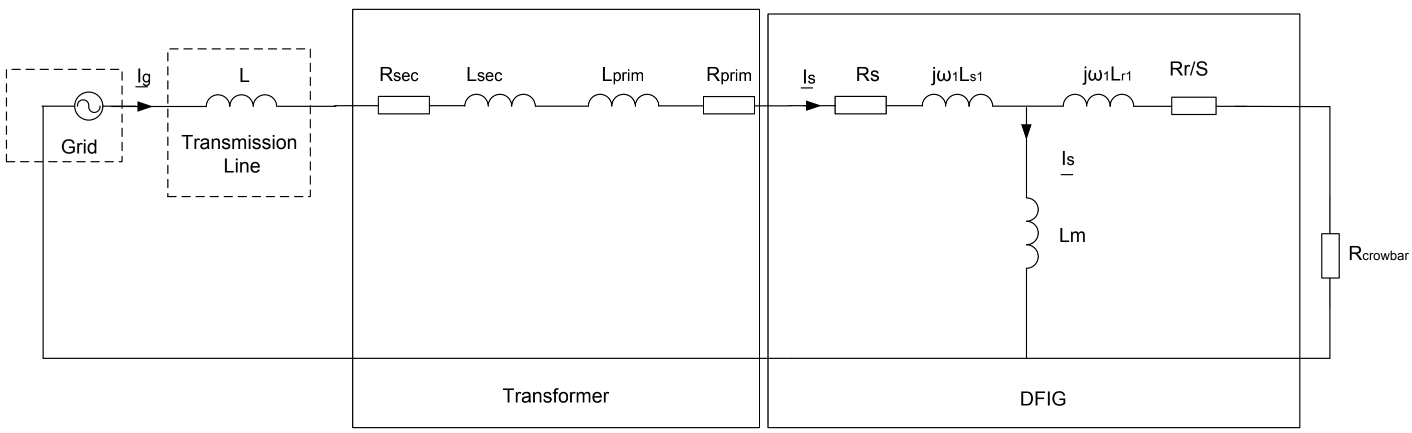


Figure 18: Crowbar Activated Equivalent Circuit

Equations derived from Figure 18 are presented in the following:

In the first circuit loop, the equation is written as:

$$\underline{u}_g = R_{ech}\underline{i}_g + \frac{dL_{ech}}{dt}\underline{i}_g + \frac{dL_m}{dt}\underline{i}_m \quad (35)$$

The equivalent elements are written as sums of series components:

$$R_{ech} = R_{sec} + R_{prim} \quad (36)$$

$$L_{ech} = L_{sec} + L_{prim} + L_{line} \quad (37)$$

For the second circuit loop, as the rotor is disconnected from the voltage source, only the energy stored in the motor magnetising branch intervenes. This is the main reason why the magnetising element may not be neglected in this case.

$$\underline{0} = R_a\underline{i}_r + \frac{d\underline{\psi}_r}{dt} + (R_{crowbar} + \frac{R_r}{S})\underline{i}_r \quad (38)$$

If the slip is considered to be constant, the resistor value of the rotor would remain constant.

$$\underline{0} = R_a\underline{i}_r + \frac{d\underline{\psi}_r}{dt} + (R_{crowbar} + R_r^{'})\underline{i}_r \quad (39)$$

$$\underline{\psi}_r = L_r\underline{i}_r + L_m\underline{i}_s \quad (40)$$

The inductance of the straight wire conductor may be calculated, knowing the diameter and the length [41]:

$$L = l(\ln\frac{4l}{d} - 1)\cdot 200\times 10^{-1} \quad (41)$$

$$L = 5.0\cdot l(\ln\frac{4l}{d} - 1) \quad (42)$$

where

L = inductance (H) ; *l* = length of conductor (m) ; *d* = diameter of conductor (m)

Conclusions:

The circuits presented above were used as a basis for the fault simulation models of later chapters. Each circuit was simulated and analysed separately as shown in the next chapter. the separation has been made in order to facilitate the basic understanding of the model and to reduce computing time.

Chapter 6: Simulation Model

In this chapter the simulation of the DFIG included in a wind turbine system is presented. With this, an idea of the validity of the simplified model may be tested. Models developed in this project are detailed. Normal duty and fault ride through models are described. Results are documented and conclusions drawn.

As the objective of the project is to build a transient model and test it, special simulation measures where taken to highlight the desired features. The simulation time was chosen intentionally large to observe clearly the response of the system. The half of the fault time has been left without protection. In the second half of the fault time, the effects of the protection systems were added, and may be observed.

The model behaves like a motor and not as a generator in the simulation because the system was partially constructed. The response of the simplified system may be evaluated in a motoring regime without introducing additional errors from this point of view. This is due to the fact that the direction of the power flow does not modify the structure of the circuit.

A. Detailed DFIG System Model

6.1 Dump resistor protection

Figure 19 shows the main simulation level for the dump resistor protected system. The three phase fault is placed after the transformer. The line was modelled as an RL equivalent circuit. Parasitic capacitances were neglected in the line [39]. The short-circuit time depends on the rotor parameters [42].

$$T_r = \frac{L_r}{R_r + R_{crowbar}} \tag{43}$$

Parameters are loaded automatically (like in all the presented models) from the model properties initialisation window (see code in Appendix 4)

Voltage and current measurement blocks were used to view stator and rotor transients.

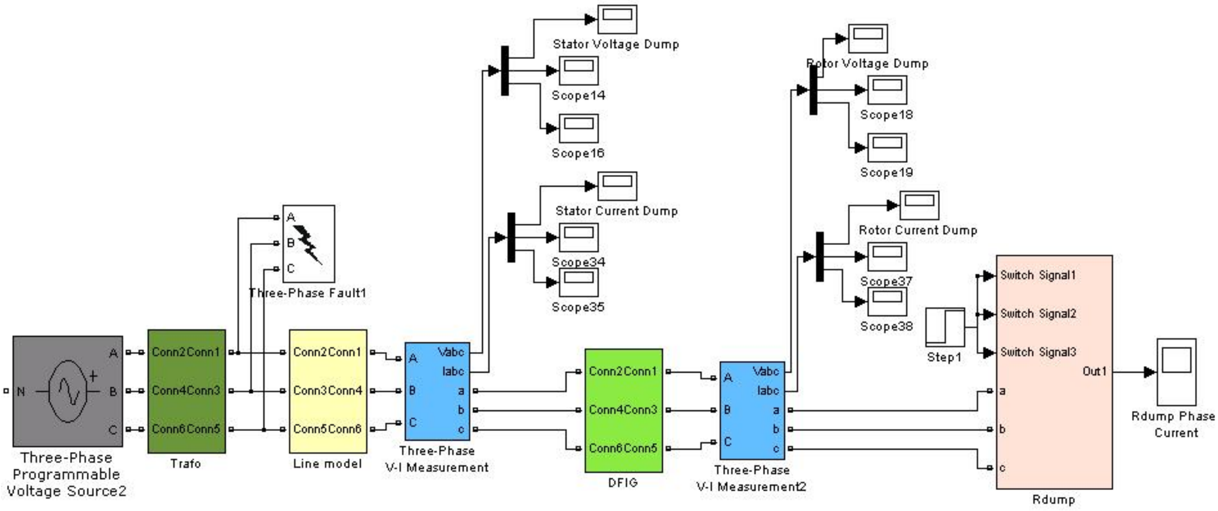


Figure 19: Dump Resistor Protection – Main Simulation Level

Figure 20 depicts the DFIG subsystem. The slip was considered to be constant during the fault time. The slip dependent value of the rotor resistor [40], was integrated in the Rs variable. The simplification was made on the assumption that the mechanical part of the turbine will not change during the fault because the inertia phenomena.

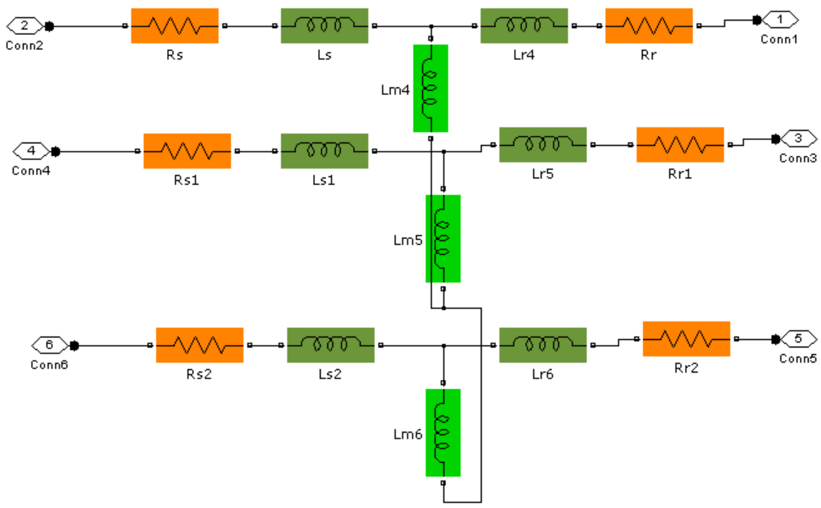


Figure 20: DFIG equivalent circuit

The fault was applied between 0.2 and 0.3 seconds by setting the fault block to generate a short-circuit between all 3 phases [45]. The protection was switched on at 0.25 seconds by applying a signal to the Dump resistor switch (see Figure 21).

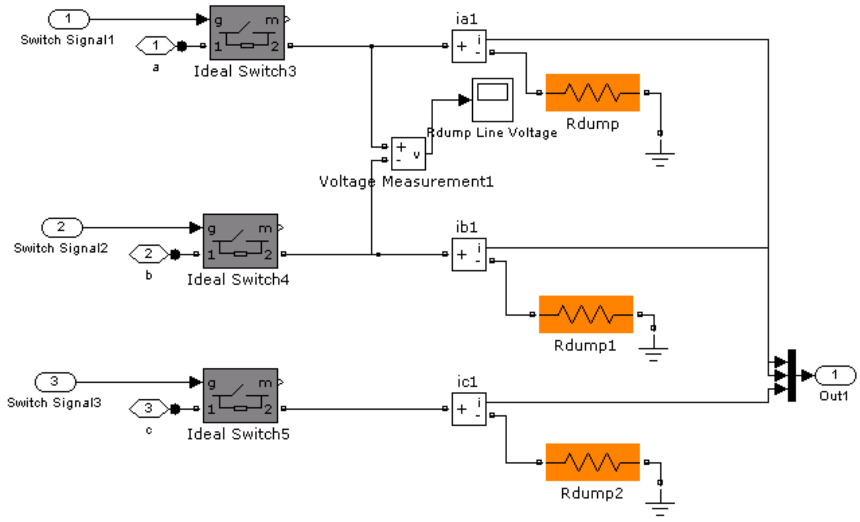


Figure 21: Dump Resistor Block

In Figure 22 and Figure 23 the transformer and line subsystems are detailed. Parameters for the circuit elements are initialised in the model property code.

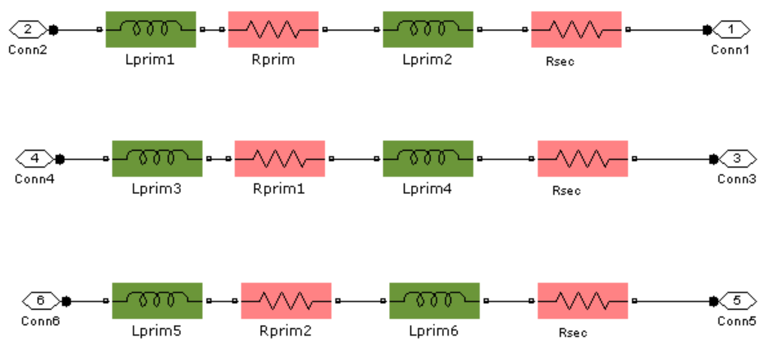


Figure 22: Transformer Block

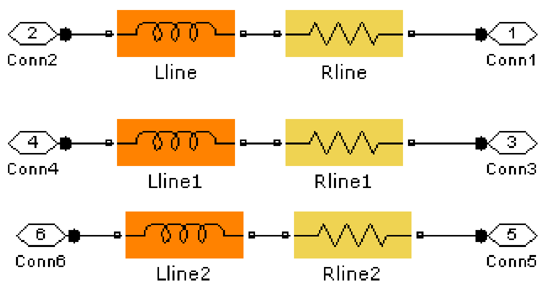
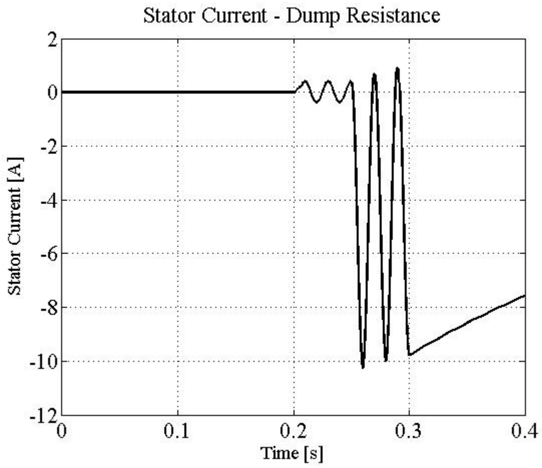
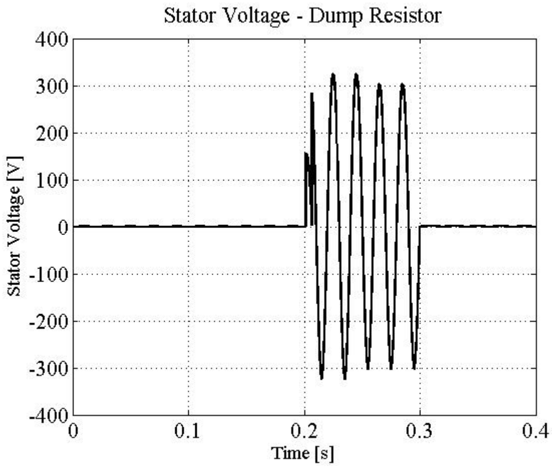


Figure 23: Transmission Line

In Figure 24, stator current of phase A and phase to ground voltage are presented. The protection response may be viewed during the second half of the fault. This applies to all fault modelling simulations in this report.



(a) Stator Current vs. Simulation Time

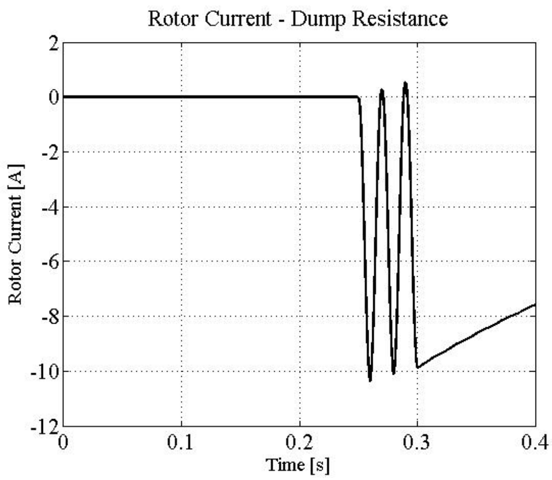


(b) Stator Voltage vs. Simulation Time

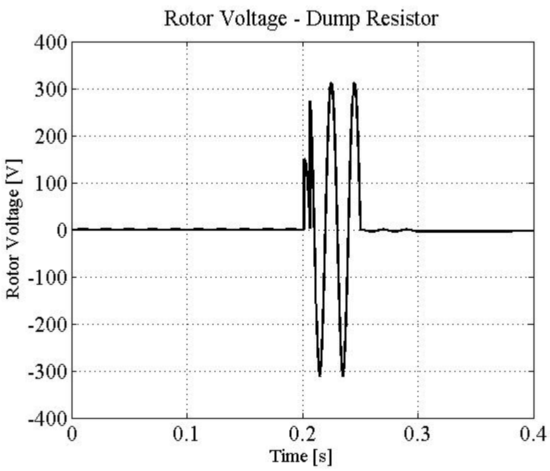
Figure 24: Dump Resistor Simulation Results-Stator Measurements

The stator current increases when the additional resistors are connected. The voltage is decreasing as shown in Figure 24 (b).

The rotor current and voltage are shown in Figure 25**.** One may observe that after connecting the protection, the voltage is greatly reduced. However, residual voltage may still be seen until the fault subsides at 0.3s.



(a) Rotor Current vs. Simulation Time



(b) Rotor Voltage vs. Simulation Time

Figure 25: Dump Resistor Simulation Results-Rotor Measurements

Conclusions:

The model presented in this chapter is working in a consumer mode. Results are validated Chapter 7 by comparing the results to others obtained by simulating the system using library subsystems.

6.2 Crowbar protection

Figure 26 shows the main simulation level of the crowbar fault response. The system resembles the dump resistor protection model (Figure 25). The difference lies in the protection block.

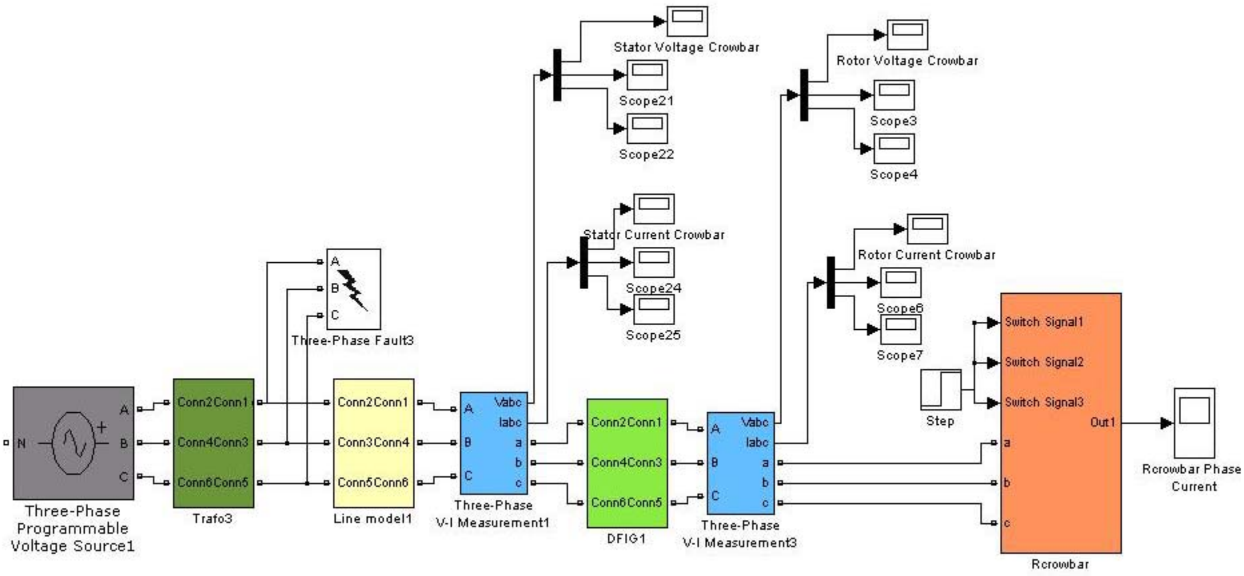


Figure 26: Crowbar Protection – Main Simulation Level

In Figure 27 the detailed Crowbar protection block is shown. As in the previous model, the protection is activated at 0.25s via ideal switches driven by a step signal. The value of the crowbar resistor is half the value of a dump resistor (see values in Appendix 4).

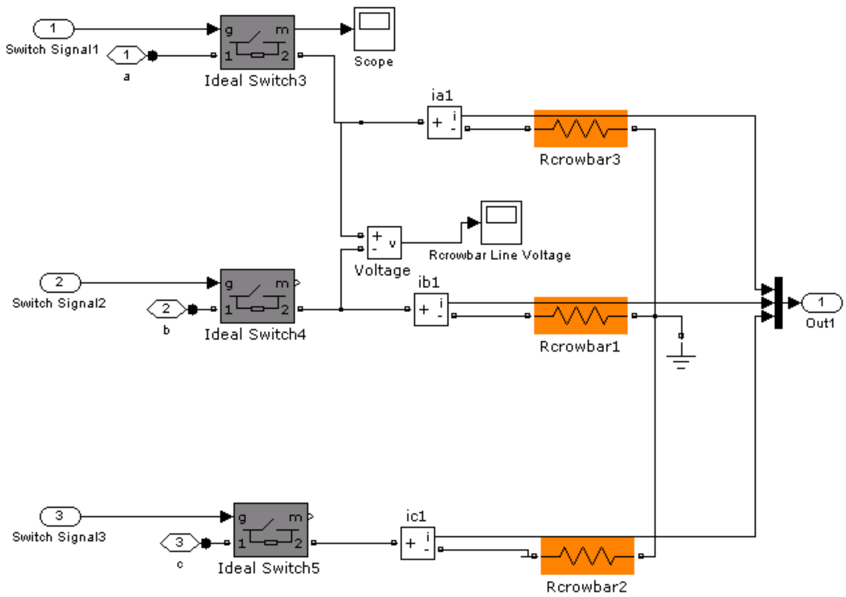
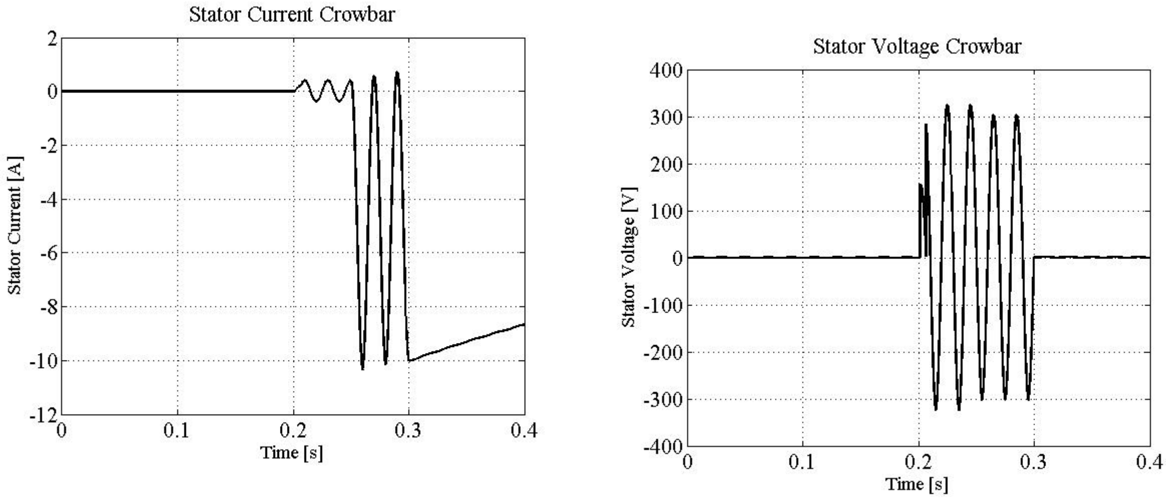


Figure 27: Crowbar Resistor Block

The rest of the subsystems are tows presented in the previous subchapter

The effects on the stator voltage and current are shown in Figure 28. As in the previous case, the current needs a longer time to reach zero because of the inductances in the system.

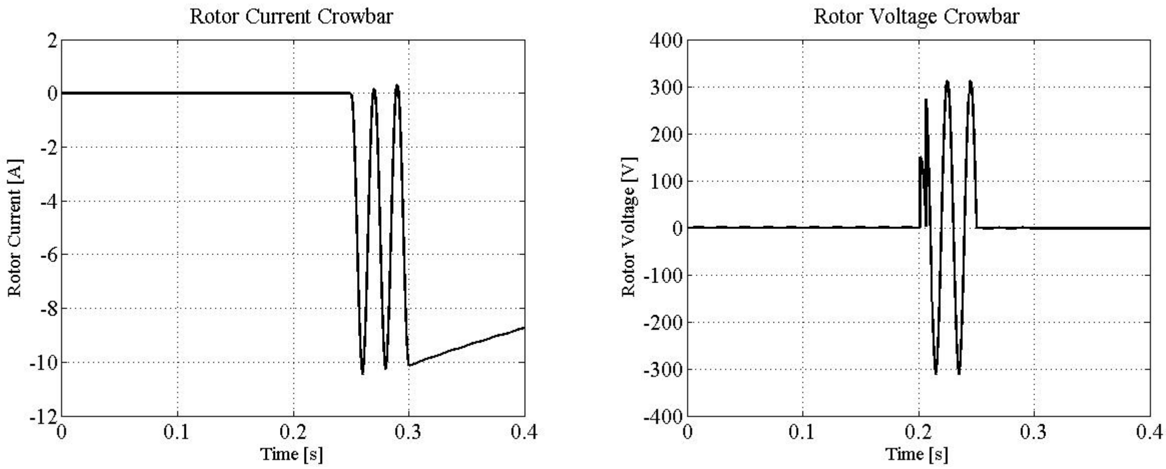
These prevent the current to have sudden variations. As capacitances were ignored, the voltage variation is rapid as it may be observed in Figure 28 (b)



(a) Stator Current vs. Simulation Time (b) Stator Voltage vs. Simulation Time

Figure 28: Crowbar Protection Simulation Results

Rotor measurements are shown in Figure 29



(a) Rotor Current vs. Simulation Time (b) Rotor Voltage vs. Simulation Time

Figure 29:Crowbar Protection Simulation Results-Rotor Measurements

As it can be seen in Figure 29 (b), the voltage is zero after applying the protection unlike in the case of the dump resistor Figure 25 (b) where residual voltage is present.

Conclusions

The crowbar protection is employed to attenuate severe faults. The excess energy of the rotor (from high currents due to fault) is to be dissipated in the resistors. Compared to the dump resistor system response, the response of the crowbar system is more intense.

B. Transfer Function Model

To analyse the stability and response of a system, a transfer function and a state space model is useful. As the circuit has been reduced to the simplified form shown in Figure 26, the analysis models were obtained. The circuit was explained in subchapter 305.3 of Chapter 5.

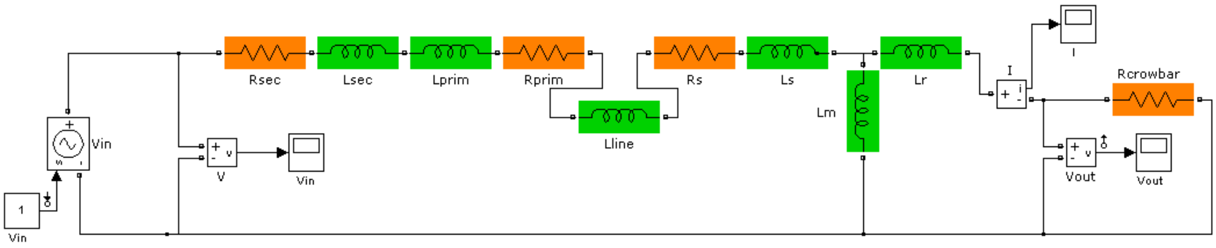


Figure 30: U_r/U_g transfer Function – Main Simulation Level

To obtain the transfer function of a system, one must have an equivalent circuit composed of R L C and voltage sources (like in Figure 30). Kirchhoff equations must be written for the circuit. The Laplace transform is applied to the equation to express them in operational instead of time domain. Input and outputs are to be chosen. They may be ether currents or voltages. By mathematical substitution an output/input expression is obtained [42]. This is called the open loop transfer function.

The state space model is a mathematical expression of input, output and state variables. It may be obtained from the transfer function. Both models differ with respect to the chosen inputs and outputs. More details about obtaining the functions may be found in [42].

As obtaining the transfer function and space state coefficient matrices by manual calculation is both time consuming and subjective to error, the automatic method of using Simulink was chosen. The input and output signals were chosen by right-clicking the connection line and selecting the linearisation point option. After setting the inputs and outputs, by selecting the *Tool* element from the Simulink menu and *Control Design-Linear Analysis* both models are generated.[45] The operation point of the linearisation is 1 p.u.

The transfer function for the system in Figure 30 is shown below. Coefficients were calculated automatically from the values given in the simulation.

$$\frac{U_r}{Ug} = \frac{4.886s - 3.39e - 16}{s^2 + 5.655s + 0.1995} \tag{44}$$

The state space matrix coefficients are presented below:

$$A = \begin{bmatrix} & x_1 & x_2 \\ x_1 & -5.142 & -0.4989 \\ x_2 & -4.886 & -0.5128 \end{bmatrix} \tag{45}$$

$$B = \begin{bmatrix} x_1 & 4.886 \\ x_2 & 5.023 \end{bmatrix} \quad (46)$$

$$C = \begin{bmatrix} x_1 & x_2 \\ 1 & 0 \end{bmatrix} \qquad D = [0] \quad (47)$$

The GUI can also generate among other things the step and impulse response. Results from the function generated for the circuit in Figure 26 are shown in Figure 31

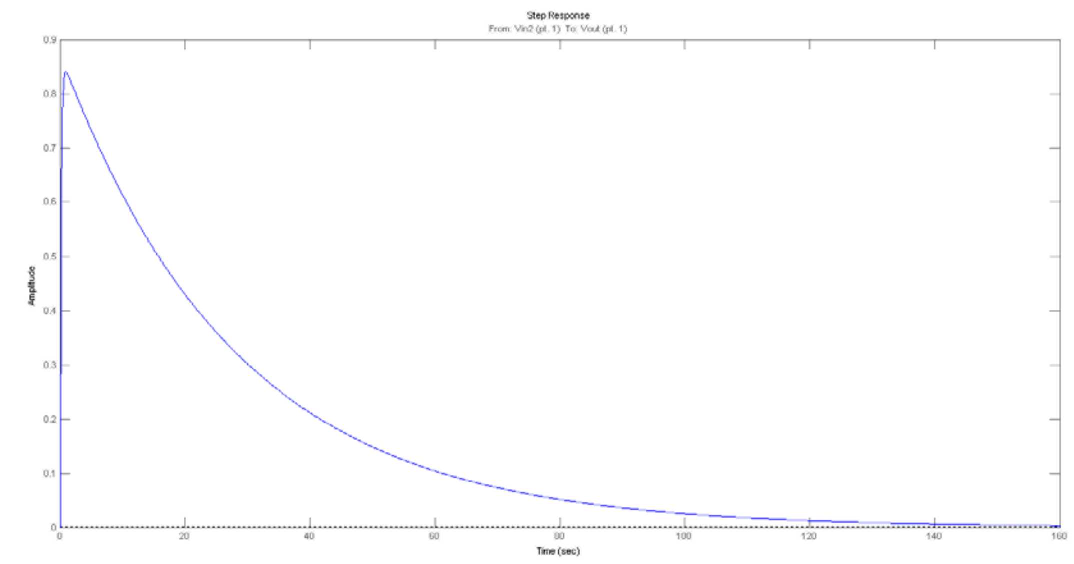


Figure 31: Ur/Ug transfer Function Simulation Results - Step Response

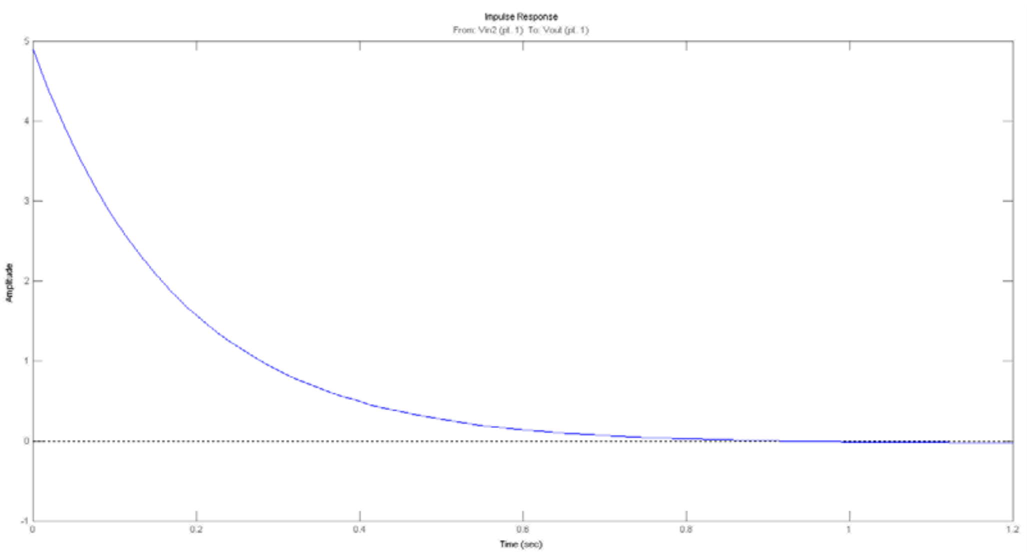


Figure 32: U_r/U_g transfer Function Simulation Result - Impulse Response

The step and impulse response of the open loop transfer function is the basic step towards analysing the stability of the system. From this more complex tests may be performed [43]. Also the system may be further developed adding control. As stability tests were not the subject of this project, the transfer function model was left at this state. It is to be further investigated in future work.

Conclusions:

This model enables stability analysis. This is important for analysing system response to various inputs. The main advantages of using the Simulink tool are that transfer function and state space coefficients may be calculated quickly for every input and output required.

Chapter 7: Model Validation

In this chapter, the validation method of the model is presented. Consequences of simplified assumptions implemented in the models are shown. Acceptability of results is discussed.

To validate the simplified model an additional system has been simulated. In the following, the results of the simulations are presented and discussed. Two fault ride through protections were implemented: dump resistor and crowbar. The difference between the following model and the detailed model is that the SimPower System blocks used in the verification model are more complex than the circuits modelled in the detailed model.

7.1 Dump Resistor Protection Fault Ride Through - SimPower Systems Blocks

The main window of the validating model may be viewed in Figure 33. The three phase programmable voltage source and protection blocks are identical to those used in the detailed simulations (see Figure 19, Figure 26 and simulation models on the CD). The transformer block used is a SimPower Systems library model. Initialisation values are those stated in Appendix 4. The same approach was used in the case of the library asynchronous machine. No torque was input to enable a valid comparison grounds between the simplified model and the validating one.

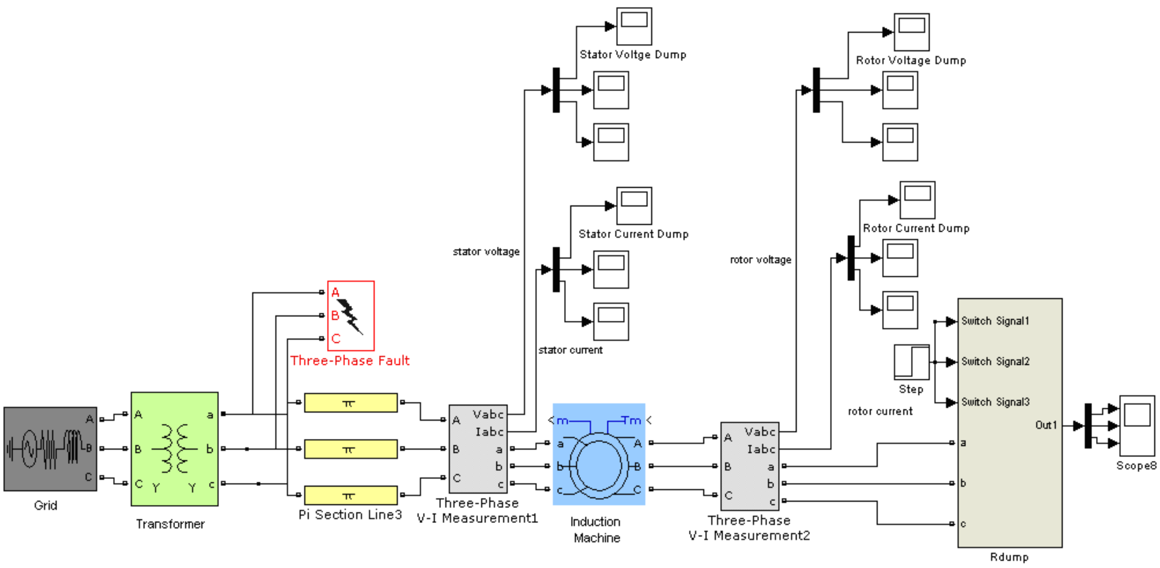
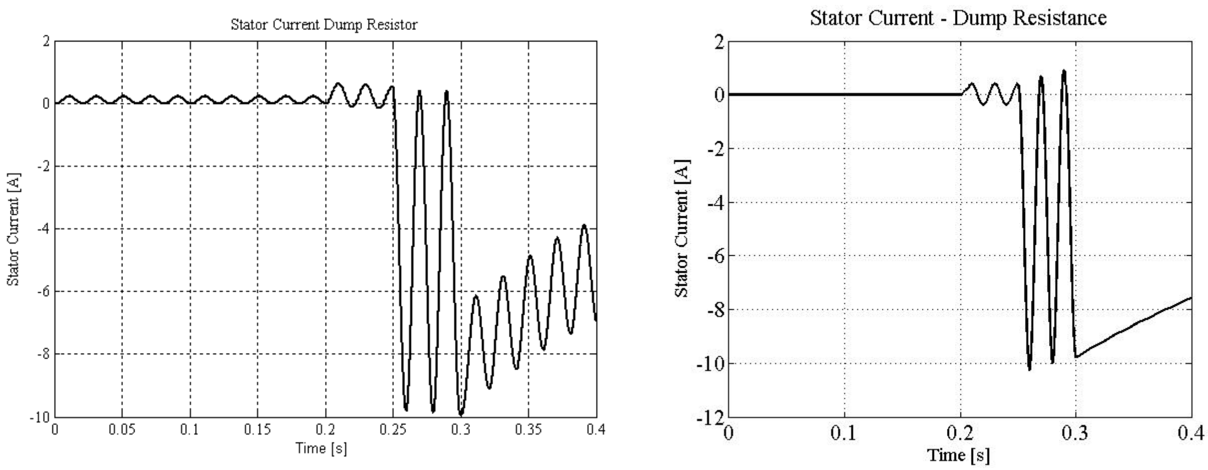


Figure 33: Dump Resistor Protection – Main Simulation Level

The measurement blocks are placed both at the rotor and stator side as in the detailed models. The fault time is [0.2, 0.3] and the protection is active from 0.25. In other words, the same simulation settings were used for the compared models.

In the following, simulation results are presented and compared. Discussions on the validity of the simplified model compared to the validation model are presented. The goal is to get similar responses to the same input signal from models with same parameters.

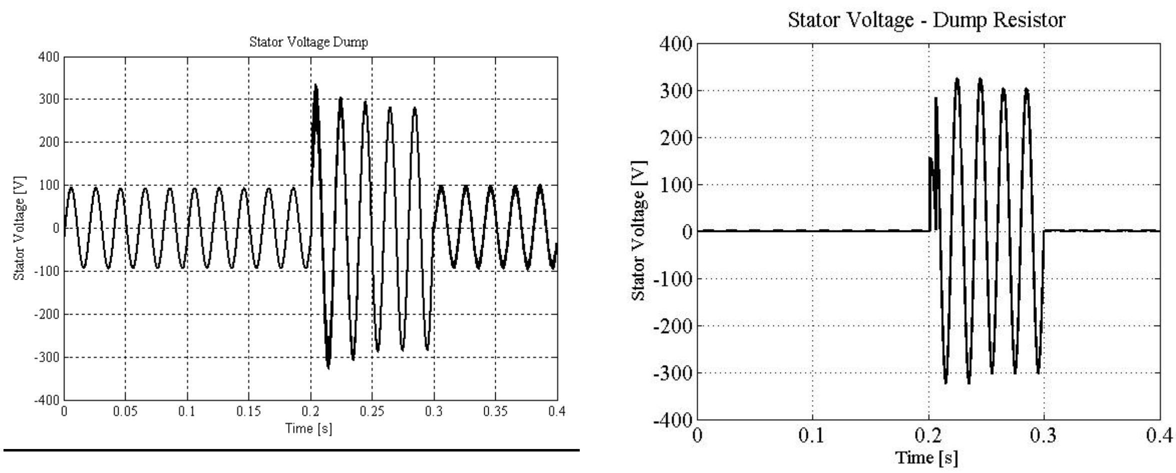
In Figure 34 dump resistor simulation results from the detailed model and the library model are presented. The area of interest is between 0.2 and 03 seconds. This is the time interval in which the fault is active. As can be observed, the response is similar in both cases. This proves that during the fault, the neglected components in the detailed model did not introduce unacceptable errors. The difference between the two graphics lies in the time intervals outside the fault region. Due to the extra elements considered, the library model stator current presents fluctuations outside the fault area. Nevertheless the average value follows the simplified model response.



(a) Library Model (b) Detailed Model

Figure 34: Dump Resistor Simulation Results - Stator Current vs. Simulation Time

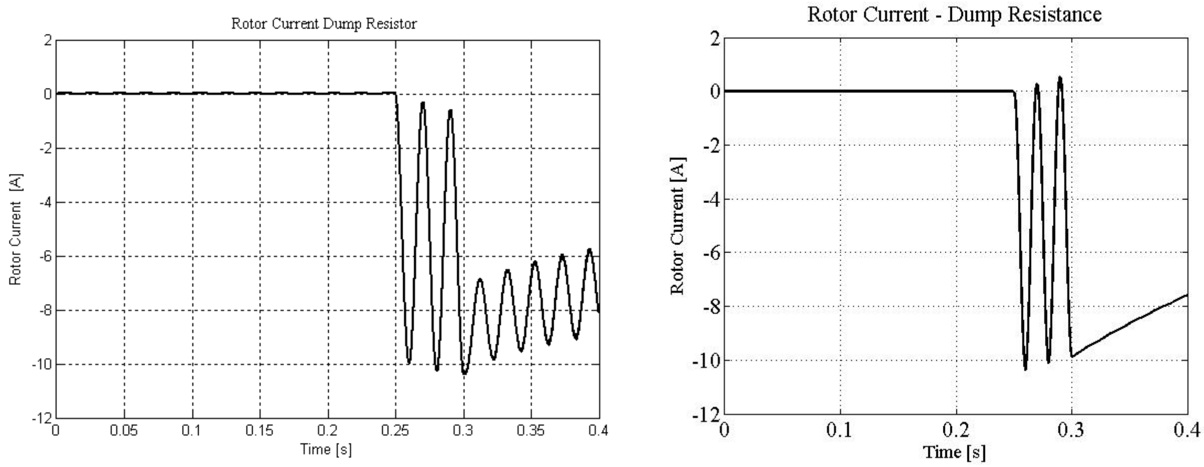
In Figure 35 the stator voltage of both models are compared. In the area of interest, the amplitude of the first spike differs significantly. The other spikes are comparable.



(a) Library Model (b) Detailed Model

Figure 35: Dump Resistor Simulation Results - Stator Voltage vs. Simulation Time

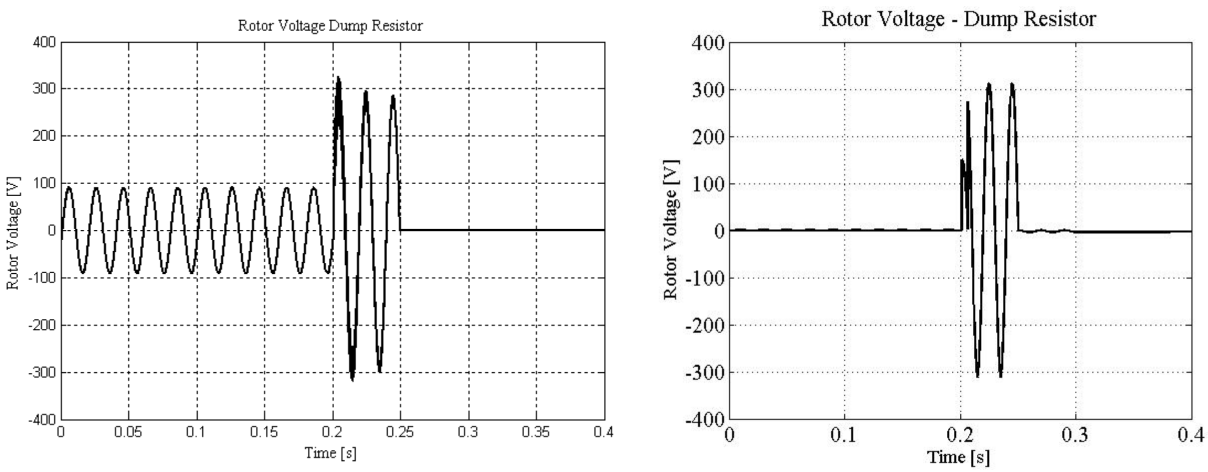
The rotor currents are depicted in Figure 36. The magnitudes during the fault is different between the two models.



(a) Library Model (b) Detailed Model

Figure 36: Dump Resistor Simulation Results - Rotor Current vs. Simulation Time

The rotor voltages (Figure 27) present the same difference as stator voltages (see Figure 35), namely that of the first spikes at 0.22s (positive)



(a) Library Model (b) Detailed Model

Figure 37: Dump Resistor Simulation Results - Rotor Voltage vs. Simulation Time

The magnitude of the negative spikes may be considered acceptable my comparison.

Conclusions:

Due to simplifications, the detailed model has lower voltage consumption. As the capacitor in the line model, the voltage peak is not as high. Voltage on a capacitor cannot vary suddenly. Nevertheless a relationship between the input and the first peak voltage may be expressed. (Reference is made to the positive spikes.) This is reserved for future work on the models as stated in Chapter 9.

7.2 Crowbar Protection Fault Ride Through – Library Model

In Figure 38 the model main level is presented. All settings are similar to the previously described model. The difference lies in the protection subsystem. Instead of the dump resistor block, the crowbar protection was inserted. The same Crowbar Resistor block was used as in the detailed model. Stator and rotor measurements are depicted in Figure 39, Figure 40, Figure 41 and Figure 42.

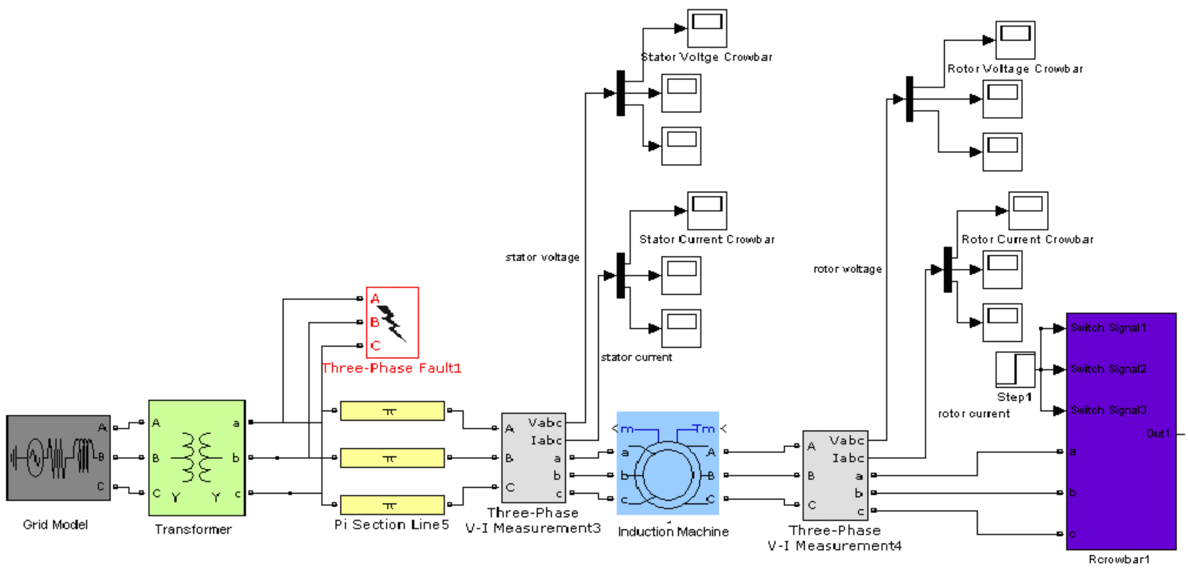
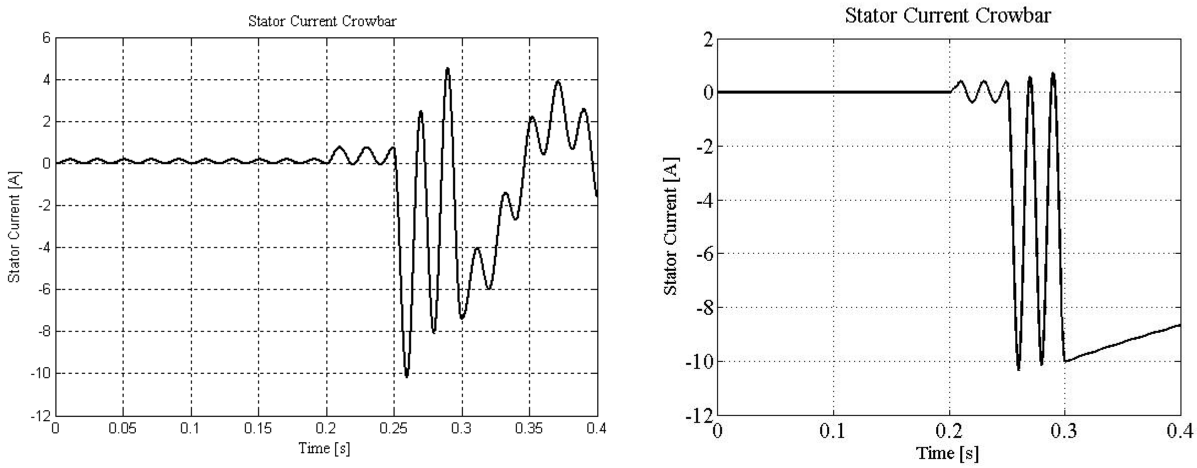


Figure 38: Crowbar Protection – Main Simulation Level

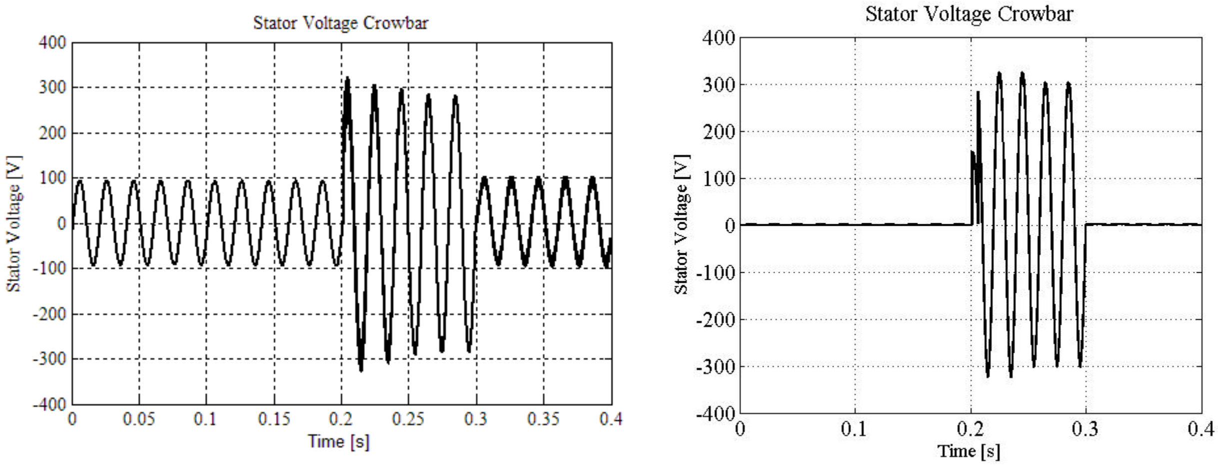
In Figure 39 stator currents are presented. Although similar, the library model responds with a larger magnitude and slope after the fault had passed. The main area of interest as in the previous models is [0.2; 0.3] seconds. The maximum negative values match for the first spike, but not for the negative ones.



(a) Library Model

(b) Detailed Model

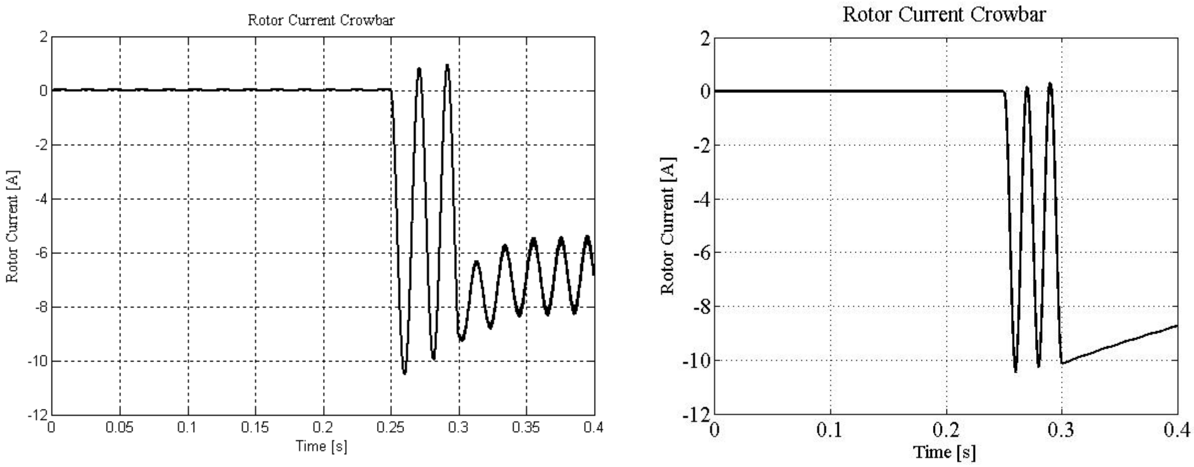
Figure 39: Crowbar Resistor Simulation Results - Stator Current vs. Simulation Time



(a) Library Model (b) Detailed Model

Figure 40: Crowbar Resistor Simulation Results - Stator Voltage vs. Simulation Time

Voltages in Figure 40 show the same magnitude problems at the beginning of the fault as the previous model. Other than that the -300V and 300V magnitudes inside the fault interval are validated by comparing the results.

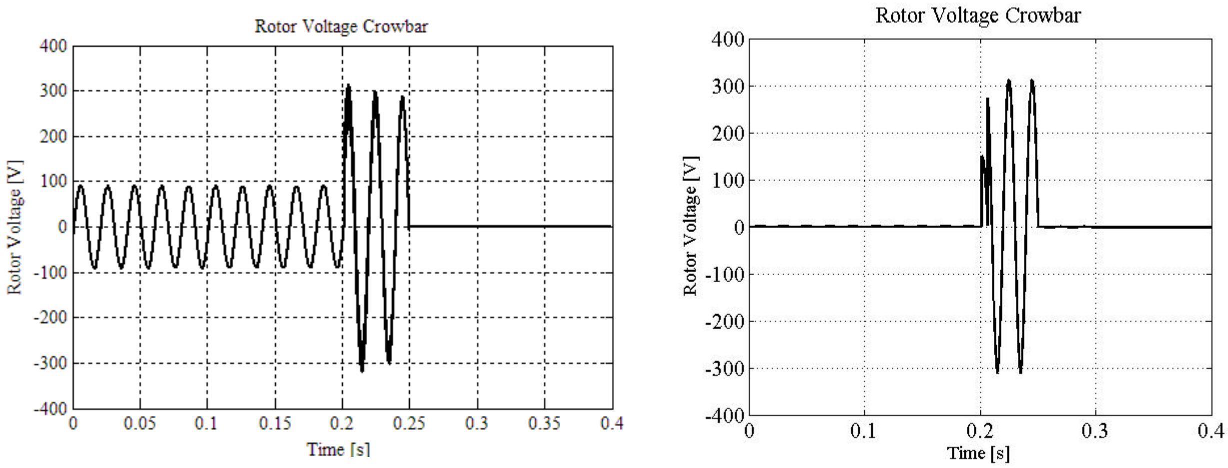


(a) Library Model (b) Detailed Model

Figure 41: Crowbar Resistor Simulation Results - Rotor Current vs. Simulation Time

As can be observed in Figure 41 the detailed model is verified.

The rotor voltages from both models are presented in Figure 42. During the fault period the models behave in a similar fashion. At the first part of the fault interval, a difference in voltage magnitude may be observed. The negative spikes have matching magnitudes.



(a) Library Model (b) Detailed Model

Figure 42: Crowbar Resistor Simulation Results - Rotor Voltage vs. Simulation Time

Conclusion:

In this chapter two conceptually different models were compared. A simplified system and a complex one were compared side by side. Similarities and differences were pointed out. To shine a better light on the differences, other the models should be tested with different inputs (power levels and parameters). Testing is to be done in future work.

Chapter 8: Conclusions

In this chapter overall conclusions are presented. A bridge is built between the initial objectives and the project results.

In this project the synchronous and the doubly fed machines were introduced. Functioning, equivalent circuits and mathematical models were presented for both machines.

For the doubly fed induction machine, a simplified system was developed to simulate fault situations. The simplified transformer-transmission line-machine model was built. The model obtained may be used for both synchronous and asynchronous machines. This may be done due to the fact that the slip is not considered in the simulation. Fault behaviour of the system was analysed. Crowbar and dump resistor protection systems were studied. Both s-function and a time function models were documented.

To validate the simplified model, the same simulation parameters were put into a model built using SimPower Systems elements. These elements are complex blocks which take into account losses more rigorously than the project model. Results were proved to be comparable.

To make possible integration of the model in a complex system possible, no extra blocks were introduced in the simulation to emulate to emulate network components.

The constructed models were verified using a test model. The purpose of the verification was to observe the consequences of the applied simplifying assumptions. The crowbar and dump resistor models were verified. Differences between the verification model and the studied model are to be investigated in future work.

Understanding of the effects of faults and protection systems on DFIGs was increased by observing the model behaviour.

From the simplified equivalent circuit of the fault system, the transfer function and state space models were obtained. This opens up the path to stability analysis.

Chapter 9: Future Work

In this chapter, future work ambitions are presented. Present state of the development is summarised. The tasks are valid for this evolution point of the project. As work goes on, other tasks will emerge.

- Stability study
- Inputting real parameters-a complete set of values was not obtained for this project
- Construction of the mechanical system
- Construction of the aerodynamically system-wind mode
- Quantify the error introduced by simplifications
- Determine error level acceptability
- Consider saturation
- Building of complex power system including progressive step –down transformers filters and consumers.
- I Integrated the simplified model in an existing complex model
- test the present model against other existing models
- further test short

Appendix 1:

Symbols and Abbreviations

In this appendix symbols used in this project may be found. Alphabetical ordering of elements makes browsing fast and easy.

1.1. Symbols

f - the field winding indice

B – friction coefficient

C - DC-link capacitance

d - diameter of conductor (m)

F - Combined rotor and load viscous friction coefficient

H - Combined rotor and load inertia constant

$i'_{kd(q)}$- amortisation circuit current in d(q) axis

I1-equivalent outer loop current

i_d – d axis current

I_g-grid voltage

$L_{s\sigma}$ - stator leakage induction

$L_{r\sigma}$ - rotor leakage induction

i_q – q axis current

$\underline{i}_r$ - the rotor current space vectors

$\underline{i}_s$ is the stator current space vector,

J - Combined rotor and load inertia coefficient

j – complex operator

k - amortisation circuit indice

L - inductance

l - length of conductor (m)

L_d, L_q- q and d leakage inductances

L_{ech} – equivalent inductance

L_{line} – line parasitic inductance

L_m - magnetizing inductance,

L_{md}, L_{mq}-magnetisation inductances

L_{prim} – inductance of the primary side of the transformer

L_r - the rotor and rotor inductances

L_s – stator inductance

L_{sec} – inductance of the secondary side of the transformer

p - Number of pole pairs

P, Q - active and reactive power

P_m - Mechanical power captured by the wind turbine and transmitted to the rotor

P_r - Rotor electrical power output

P_s - Stator electrical power output

Q_r - Rotor reactive power output

Q_s - Stator reactive power output

$R_{'kd}$ - resistance of the amortisation circuit

R'_r - the rotor equivalent resistor

R_a - rotor equivalent resistor

R_{ech} – equivalent resistance

R_{prim} – resistance of the primary side of the transformer

R_s – stator resistance of the machine

Rsec – resistance of the secondary side of the transformer

S – slip

T_e - electromagnetic torque

T_{em} - Electromagnetic torque applied to the rotor by the generator

T_L - load torque

T_m - Mechanical torque applied to rotor

u_g- grid voltage

u_r – rotor voltage

u_s – stator voltage

V_d – d axis voltage

V_q – q axis voltage

ω_e the reference frame speed (arbitrary),

Φ_d – d axis flux

Φ_q – q axis flux

$\underline{\Psi_r}$ – rotor flux space vector

Ψ_s – stator flux space vector

ω_m - Angular velocity of the rotor

ω_r - Rotational speed of rotor

ω_s -Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed.

1.2. Abbreviations

DFIG - Doubly Fed Induction Generator

FRT - Fault Ride Through

LVRT - Low Voltage Ride Through

TSO - Transmission System Operator

Appendix 2: Terminology

In this appendix, simple definitions of basic concepts may be found. The information is complete with references for further follow-up.

Converter blocked – In case of over-currents in the rotor of the DFIG, the converter is disconnected from the rotor. This is done as a safety measure to protect the converter.

Crowbar – DFIG system fault protection that consists of short-circuiting the rotor with a set of resistors. The protection is integrated in the rotor circuit through switches [46], [47], [48], [49], [50].

The space vectors rotate at synchronous speed (relative to the reference frame) at normal operation. The variation of the stator flux is directly proportional to the stator voltage. This is acceptable if the stator resistance is ignored. In case the stator voltage drops, the stator flux stop rotating producing a DC component in the stator flux. The DC component rotates with the rotor speed. Large oscillating currents caused by the voltage dip flow through the rotor circuit. As the rotor is connected to the converter, measures must be taken to protect the electronics as the transients might destroy the switches. In case of the fault, the rotor is disconnected from the converter and connected to a set of crowbar resistors. The fault current would flow through the resistors protecting the converter. [42]
When the crowbar protection is active, the following actions might be taken:

- Disconnecting both the stator and the rotor from the grid [48],
- Keep the only rotor disconnected [14]. The result is an induction machine with a high rotor resistance

Keep the stator rotor and converter connected in the system [46][47][49].this would allow for rapid resuming of normal operation after the fault had past.

When dimensioning the crowbar resistor, the value of the short-circuit current must be taken into account.

An approximation of the maximum short-circuit stator current [42]

$$i_{s,max} \approx \frac{1.8V_s}{\sqrt{X_s'^2 + R_{crowbar}^2}} \qquad (48)$$

As can be seen from the formula the crowbar resistance has a great influence on the current value. For the short *circuit current to decrease the value of the resistance should be large.* However a large resistance would give a high voltage drop in the rotor circuit. This should be avoided to not destroy the insulation [42].

The maximum value of the crowbar resistor can be obtained with the following formula [42]:

$$R_{crowbar} < \frac{\sqrt{2}V_{r,max}X_s^{'}}{\sqrt{3.2V_s^2 + 2V_{r,max}^2}} \quad (49)$$

$V_{r,max}^2$ is the maximum allowable rotor voltage

There are two main crowbar topologies:

1) Passive crowbar, with a diode rectifier or a pair of antiparallel thyristors used for short-circuiting the rotor terminals. With this topology special measured must be taken to deactivate the protection after the fault has passed.

2) The active crowbar –with IGBT switches to short the rotor.

This solution is faster (acting time<100 ms).

Cut in speed – the wind speed at which the wind turbine is allowed to generate into the grid

Fault ride-throuh represents the ability of a generator connected to the grid to withstand a voltage drop during a short circuit on the transmission line without tripping. The phenomenon may also be found in the literature as "low voltage ride-through". [51], [52], [53]

Tripping implies disconnecting the turbine due to unpermitted transients do to fault. Grid codes state that tripping should be avoided to not cause instabilities in the grid system. The consequence of tripping is the phenomena called islanding. Grid codes of various countries specify constraints related to this phenomenon [51], [53], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68].

Islanding disconnection of dispersed generators from a system due to dangerous fault effects. The generator continues to operate autonomously. This type of functioning implies difficulty at reconnecting to the network be severed off from the grid but continue to operate after the utility supply is disconnected. Also difficulty is encountered in supplying the power contracted by the user.

Pitch angle controller- controls the rotor when the previous method is no longer effective. This is the case of the high winds speeds. In these circumstances, the speed control method would lead to overloading of generator and rotor side converter. At having high wind speeds, the system may only extract part of the power by tilting the turbine blades (pitching) as to not to catch the maximum wind strength.

Appendix 3: Utility Requirements

In this appendix, requirements for power utilities are presented. Grid code specifications are given to form an idea on the limits and restraints of grid connected systems. Solutions for meeting demands are discussed herein. The chapter concludes with underlining the ride through solutions taken into account by the simulation model. This appendix is to serve as a starting point for future work on the fault ride through simulation model of the DFIG.

The wind turbine may be regarded as a plant due to the fact that power circulation is bidirectional. Standards for plants connected to the grid are comprised in a set of rules called 'GRID CODE'. The rules often differ from country to country as will be shown in this appendix. [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68]

Next, a few rule of interest are presented in the following.

For limiting the negative effects of faults:

- The plant should supply the grid with electricity throughout their operation. The voltage magnitude and frequency supplied must match those of the network.

- Reactive power must be compensated. This is achieved by control of the plant converters. Distribution and transmission system operators require wind farms and plants to behave like conventional power stations.

- Balanced and unbalanced fault management

Specific interconnection requirements are [69]:

- Low voltage ride through (LVRT) for wind machines
- Voltage control and reactive power capability
- Behaviour under system fault conditions
- Protective system performance
- System reserve requirements to handle tripping of large wind farm output
- System monitoring
- Wind forecasting

In the following the connection criteria of wind farms in accordance with the Danish TSOs [71] are briefly presented:

The main control issues for a wind turbine application are:

- Power and frequency control

  Control in a plant is first implemented at turbine level. The reason for this is that frequency control is much faster than if it would be implemented at a wind farm level. [70], [71] Control of reactive power and voltage control is done in accordance to a PQ diagram. An example of such a curve is presented in Figure 43. Reactive power may be used to control the power factor and in automatic voltage control.

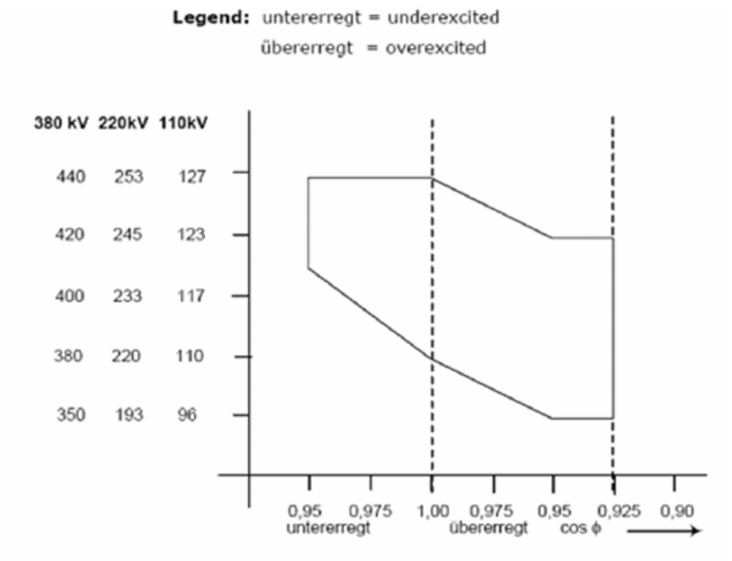


Figure 43: Power Factor Requirements (German Grid Code) [56]

Wind farms are often placed in areas having week and unbalanced grids as rural areas for example. Turbines in the system must remain operational during faults. A range of abnormal voltage and frequency values should be withstood by the system for a limited time.

A chart depicting active and reactive powers is shown in Figure 44.

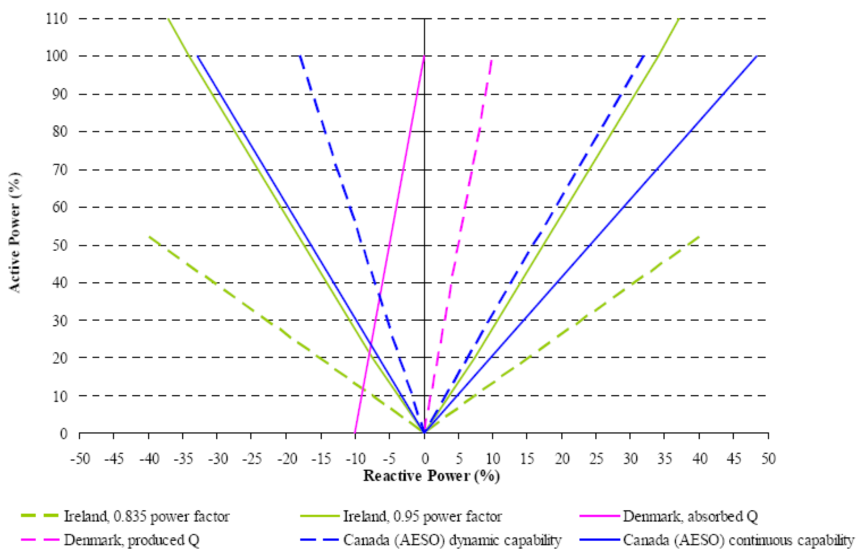


Figure 44: Comparison of Active and Reactive Power Requirements Imposed by Grid Codes [56]

When the doubly fed machine operate at increased slip values the reactive power is absorbed by the machine ,especially after fault had passed and partial voltage had occurred.

The following solutions increase the fault ride through response of variable speed drives(other than DFIGs)

- pitch control to regulate the mechanical torque. This may be done within certain limits because of mechanical considerations.
- Use of static compensators like SVCs or STATCOMs, FACTS (are complicated and costly devices, limited when it comes to close system faults, also can be used only for limited voltages

Drive systems having DFIGs have a number of advantages to statically compensated ones:

An advantage is the capability of enduring large variation of wind speed without becoming unstable (speed may increase safely e.g. 10-15% over the rated value).the surplus power due to shaft acceleration is buffered by the rotor until the pitch control is activated. In consequence they DIG systems are able to meet rigorous grid requirements.

In case of grid disturbances, transients are felt by the DFIG system. In the case of a short circuit, voltages and currents induced in the stator cause further disturbances. This is obviously viewed as a disadvantage.

To protect the power converters from faults, a device known as crowbar is used to stabilise the system. It consists of short-circuiting the rotor terminals as soon as faults are detected. With this protection the machine functions like an induction machine and the control over the generator is no longer possible (for more details, read from page 28 and Appendix 2).

Another practice is to disconnect the rotor from the system and connecting it to a dump resistor (see details on page 28).

Individual protection and control avoids taking out turbines that are not affected by a fault at a given time.

The automatic voltage control for example is to be done at wind plant level else the differently controlled connection points (corresponding to each turbine connected to the system) will produce instability and unnecessary reactive power flows between turbines. [71]

Individual control of a wind turbine does not change when integrating it a plant nor when it is part of a standalone system

This project focuses on the fault control simulation at turbine level. A simple model was aimed for to simulate the behaviour of fault condition. The model may be enhanced to take into account other aspects of normal and faulty cases.

During a three phased balanced short-circuit; the wind farm has to supply reactive current to the grid during the fault. A threshold for the voltage dip above which the turbine should start generating reactive current is mentioned in grid codes. Values may differ from country to country [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68].

Active power generation may be regulated by disconnecting turbines or by pitch control action. Frequency control implies tuning the quantity of output power with respect to frequency deviations. Regarding this aspect, grid codes differ from country to country [56] :

- Nordic Grid Code, with a ramp rate 10% of rated power per minute
- Germany, with a ramp rate 10% of grid connection capacity per minute.
- Ireland, with a ramp rate 1-30 MW per minute.
- Denmark, with a ramp rate 10-100% of rated power per minute.

In Figure 45 low voltage ride through requirements of various grid codes are presented.

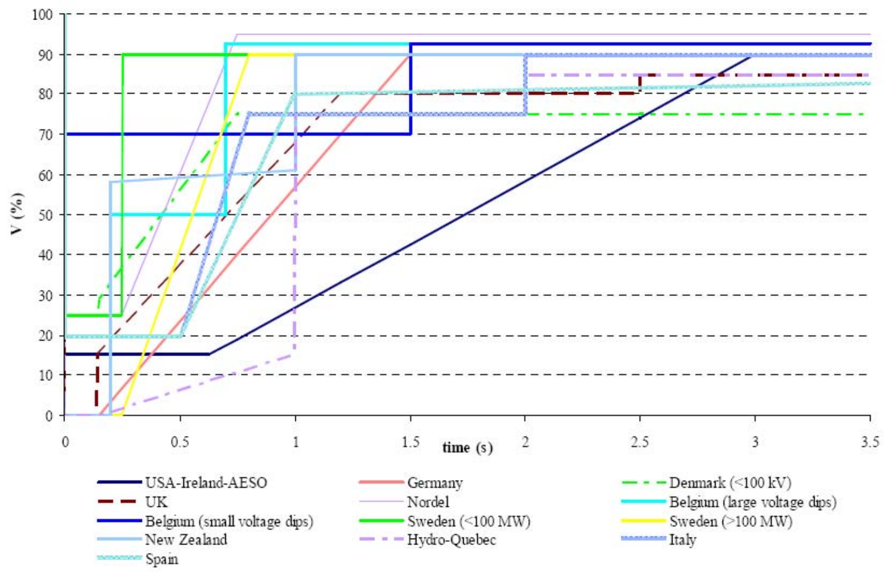


Figure 45: LVRT requirements of various grid codes [56]

The answer time of the compensation control to a fault is < 20 ms. The system must be capable to supply reactive of at least 100 % of the rated current. This refers to □10% dead band around nominal voltage. The amount of reactive power that needs o be generated depends on the network parameters short-circuit capacity and impedance value

Conclusions:

The issues focused on in this project are modelling of ride through capability of the DFIG system in the event of a three phase (symmetrical) short circuit. As solutions, the crowbar protection and dump resistor were modelled. Both of these are protections at turbine level and imply disconnecting the rotor from the generator system until after the high transients pass. In both cases, the stator remains connected to the grid.

Appendix 4:

Matlab Initialisation Code

The code used to initialise the simulation parameters is presented in this appendix.

% parameter source [29] note that some parameters derive from other sources

%Stator parameters of the DFIG p.u.

% Please note that not all the variables were used in a simulation. This is a general code that may be used with al the models.

Rs = 0.0021;

Ls = 0.11;

%Rotor parameters p.u.

Lr = 0.07;

Rr = 0.0021;

%Magnetisation Inductance of DFIG p.u.

Lm = 2.5;

Slip = 0.02;

%Line inductance

Rline=0.05;

Lline = 0.007;

%Protection parameters

Rcrowbar = 0.1;

Rdump = 0.2;

% transformer parameters p.u.

%primary winding parameters

Lprim=0.007;

Rprim=0.05;

% secondary winding parameters

Lsec = 0.007;

Rsec = 0.05;

%Equivalent parameters; Lech=Lline+Lprim+Lsec+Ls; Rech=Rprim+Rsec+Rs;

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