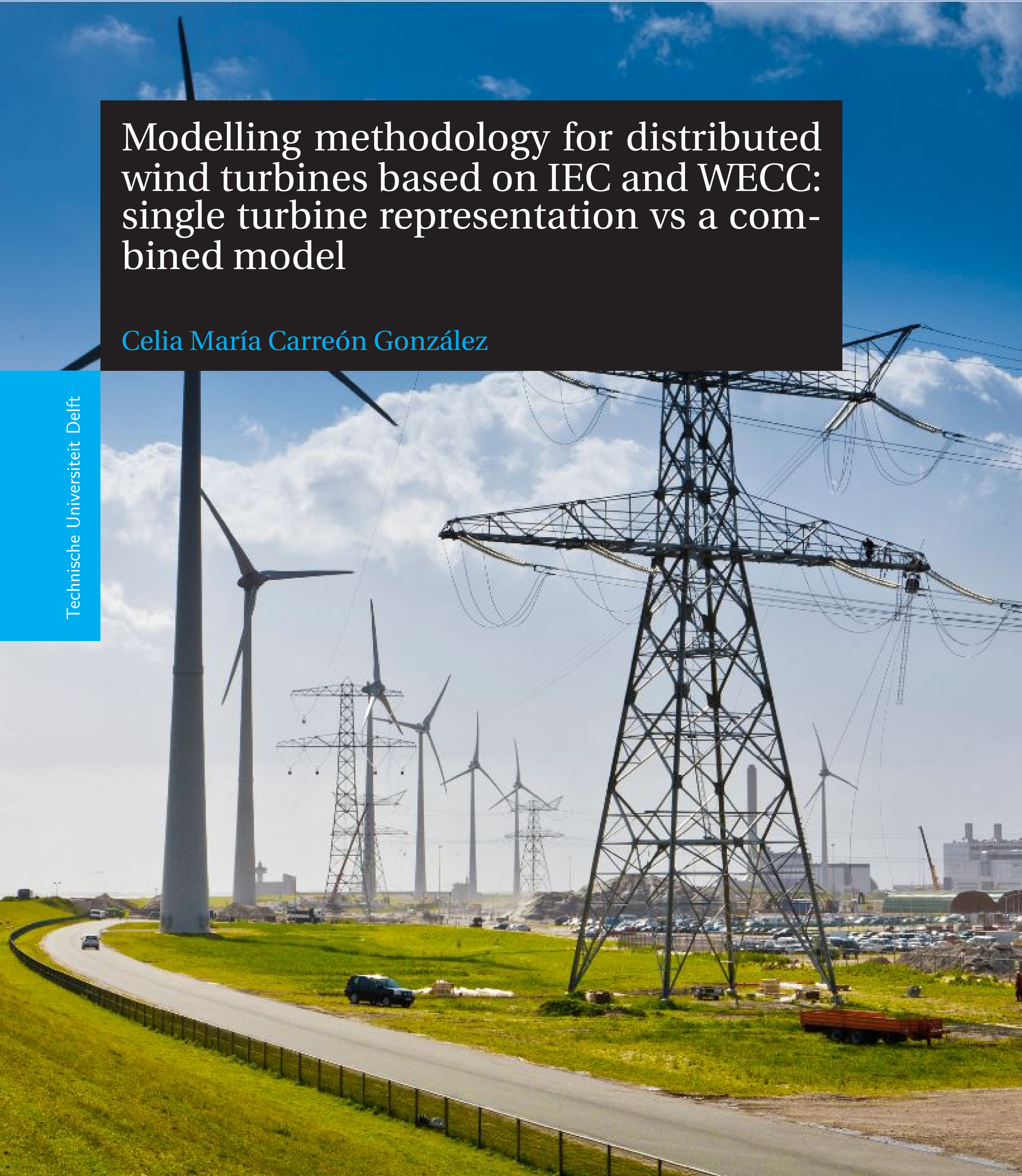
Modelling methodology for distributed wind turbines based on IEC and WECC: single turbine representation vs a combined model

Celia María Carreón González

Technische Universiteit Delft



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Modelling methodology for distributed wind turbines based on IEC and WECC: single turbine representation vs a combined model

by

Celia María Carreón González

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Supervisor: Dr. ir. Jose Rueda Torres
Thesis committee: Prof. dr. Peter Palensky, TU Delft
Dr. R. A. C. M. M. van Swaaij, TU Delft
Ir. Jorrit Bos, TenneT TSO B.V.

ABSTRACT

The use of renewable energies has been growing in a considerable way in the world. Until 2017, 18% of European Union's total installed power generation capacity was wind power capacity. The level of grid penetration of wind turbines has also increased significantly in the Netherlands. This high level of penetration of wind energy affects the behaviour of the system during an event (such as a short circuit), which is not the same that with only conventional generation in the system. The level of detail in the dynamic network model of a transmission system becomes of great importance when a big amount of wind energy is connected to the electrical system. In the current dynamic model of the Netherlands transmission system, negative load is used to represent wind turbines, however, this could be no longer sufficient if more wind turbines are connected to the grid.

The purpose of this Master Thesis Project is the study and analysis of voltage response of wind turbines models based on the IEC 61400-27-1 standard and the WECC Wind Plant Dynamic Modeling Guidelines, both of them currently implemented in several softwares.

This project proposes a modelling methodology for distributed wind turbines, using a single turbine representation and a combined model instead of a negative load directly connected to the grid.

PowerFactory and PSSE softwares are used for the modelling of wind turbines, allowing to compare the models based on the IEC standard and the models based on the WECC guidelines respectively. For the simulations performed in these two softwares, parameters suitable for comparing both of them are proposed. Besides, an analysis on the differences between both models is provided. The parameters proposed are used later on for the modelling of distributed wind turbines in the grid.

The methodology for the modelling of distributed wind turbines was proposed and analysed using a region in the Netherlands as case of study and the PSSE software (widely used by transmission system operators) with the generic parameters proposed in the previous analysis.

The proposed methodology and parameters show a more realistic behaviour of the wind turbines compared to the use of a negative load. It also provides a groupping proposal depending on the types of distributed wind turbines connected to the grid. In some cases, when the wind energy connected to the system has low impact, the use of a detailed model instead of a negative load is not very representative. Therefore, this project proposes a calculation for the impact that wind energy has in each substation, making easier to decide what is the most suitable level of modelling detail.

Acknowledgements

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LIST OF ABBREVIATIONS

AG	Asynchronous Generators
C	Capacitor
CB	Circuit Breaker
CH	Chopper
CRB	Crowbar
DFAG	Double Fed Asynchronous Generator
ENTSO-E	European Network of Transmission System Operators
FRT	Fault Ride Through
GB	Gearbox
IEC	International Electrotechnical Commission
LFSM-O	Limited Frequency Sensitive Mode — Overfrequency
PCC	Point of Common Coupling
SCC	Short Circuit Capacity
TSC	Thyristor Switched Capacitor Bank
VRRAG	Variable Rotor Resistance Asynchronous Generator
WECC	Western Electricity Coordinating Council
WTR	Wind Turbine Rotor
WP	Wind Power Plant
WT	Wind Turbine
WTT	Terminals of the Wind Turbine

1
Introduction

The use of renewable energies has been growing in a considerable way in the world. For example in Europe, in 2017, renewable energies generated 30% of the region electricity [8].

In the last two decades, the level of grid penetration of Wind Turbines (WTs) has increased significantly all over the world. In Europe, 85% of newly installed power capacity was renewable. Wind power and solar PV accounted for three-fourths of the annual increase in renewable power capacity, and offshore wind power represented around 20% of the total European wind power market in 2017 [8].

Until 2017, the European Union (EU) had 168.7 GW of installed wind power capacity (18% of EU's total installed power generation capacity): 90,7% of this capacity was onshore [9].

In the same year, an average of 11.6% of the EU electricity demand was covered with 336 TWh, which was the generated power in 2017 [9].

The behaviour of renewable energies during an event in the grid, such as a short circuit or loss of load, is different from a conventional source of energy, therefore, it is of big importance to model these energies accordingly. When the amount of renewable energies in the grid is not huge, the level of detail is not relevant, however, since the penetration level of renewable energies is going to continue growing, the detail on the modelling of these kind of energies is becoming of great importance.

Energy sources like wind and solar also differs from conventional energy in the power capacity. While the latter can have a great capacity, wind turbines (WTs) and solar modules are restricted to less than 10 MVA. Therefore, a wind or solar power plant consists of many modules or wind turbines.

1.1. State-of-the art & Scientific Gap

In the current dynamic network model of the Netherlands transmission system, renewable energies such as solar power plants and wind power plants (WPs) are represented just as negative load, which means that there is a lack of detail on their modelling. Because of this representation, there is not a voltage response of the solar and wind parks in the current dynamic model.

Several softwares for modelling electrical systems includes detailed modules of solar and wind energy sources based on different standards. These softwares include models for single modules and for power plants.

The scope of the present thesis is only wind energy. For the modelling of wind turbines, two standards are in current use:

- International Electrotechnical Commission (IEC) 61400-27-1 standard, Electrical simulation models – wind turbines

- Western Electricity Coordinating Council (WECC) standard, Wind Plant Dynamic Modeling Guidelines

In the grid, not only WPs are connected, but also several WTs can be found distributed in the network. Since modelling each wind turbine in a park is not a practical idea, aggregation techniques, like [10], have been proposed in order to synthesize the model. The methods used for having an aggregated model take into account the transformers used in each WT, the type of the WTs and the location of each WT regarding the substation of the plant. However, these techniques are intended only for WPs and not for the WTs distributed in the grid.

In the case of WPs, the parameters for the WTs and the rest of electrical components can be easily obtained from the manufacturer, however, the parameters for the distributed WTs are not that easy to obtain. Distributed WTs consist on different types of WTs, different manufacturers and different locations. Besides, their electrical components such as transformers and cables are also different among WTs.

1.2. SCOPE OF THE PROJECT & RESEARCH QUESTIONS

This project is going to focus only in wind energy and in voltage response. Based on the problems discussed in this chapter and in the state-of-the-art, there are two research questions for this thesis:

1. What are the main modelling differences and theoretical limitations between IEC and WECC models for single wind turbine representation regarding dynamic voltage response?

2. What are the main differences in the dynamic voltage response when distributed wind turbines of different types are represented in a single turbine representation and in a combined model?

For approaching the first research question, literature review, internal knowledge and simulations in PowerFactory and PSSE are going to be used.

For approaching the second question, a study case will be used. This case will be one of the regions of the Netherlands.

1.3. MASTER THESIS OUTLINE

In this section a description of the content of this thesis is provided.

CHAPTER 1: INTRODUCTION

This first chapter presents the topic of the thesis, the problem definition and the scientific gap. It also provides the state of the art and the scope of the work. The research questions are presented together with an outline of the thesis.

CHAPTER 2: WIND TURBINES CLASSIFICATION

In this chapter, a classification of the types of WTs is presented. Besides, the types of WTs that exists currently in the Netherlands are shown.

CHAPTER 3: IEC AND WECC COMPARISON

In this chapter, the IEC and WECC WTs models are described. A theoretical comparison between these two models is realized. After that, a comparison using two softwares is performed.

CHAPTER 4: REPRESENTATION OF DISTRIBUTED WIND TURBINES OF DIFFERENT TYPES

In this chapter, a study of the differences in the dynamic voltage response of distributed WTs of different types is performed.

Chapter 5: Conclusions and Recommendations

In this last chapter, the conclusions and answer of each research question are provided. Besides, recommendations for future work are presented.

2

WIND TURBINES CLASSIFICATION

2.1. TYPES OF WIND TURBINES

The first WTs used were just asynchronous generators connected directly to the grid with a capacity of less than 1 MW [2]. Through the years, not just the capacity of WTs has changed, but also the power electronics used for them, in order to increase the WTs efficiency and improve their dynamic behaviour. Since wind power have a significant impact on the grid nowadays, power electronics are also required for making WTs more suitable for their integration into the power grid [2]. This means that the WTs must meet the grid code requirements for the generators connected to the grid, for example the Fault Ride Through (FRT) capability and the Limited Frequency Sensitive Mode — Overfrequency (LFSM-O).

There are two basic categories for WTs: fixed-speed and variable-speed. WTs belonging to the fixed-speed category are the ones using induction generators, while a variable-speed WT can use a doubly fed induction generator (DFIG) or a synchronous generator. Variable-speed WTs can capture the wind energy in a wider range of wind speeds [11].

WT can be also classified according to the standard IEC 61400-27-1 (Edition 1 and 2) in four types.

2.1.1. TYPE1

The type 1 WT uses asynchronous generators (AG) directly connected to the grid. In between the wind turbine rotor (WTR) and the generator there is a gearbox (GB). Most Type 1 WTs have an electrical component called soft-starter [3], which is active during the connection of the WT to the grid. A soft-starter is used to reduce the in-rush current by building up the magnetic flux slowly in the generator, avoiding voltage disturbances on the grid.

The main components of this WT are shown in Figure 2.1. Type 1 WTs with fault-ride-through capabilities typically use thyristor switched capacitor bank (TSC) which is dynamically controlled during and after faults. The terminals of the WT (WTT), after the circuit breaker (CB) can be on either side of the transformer (TR) [1].

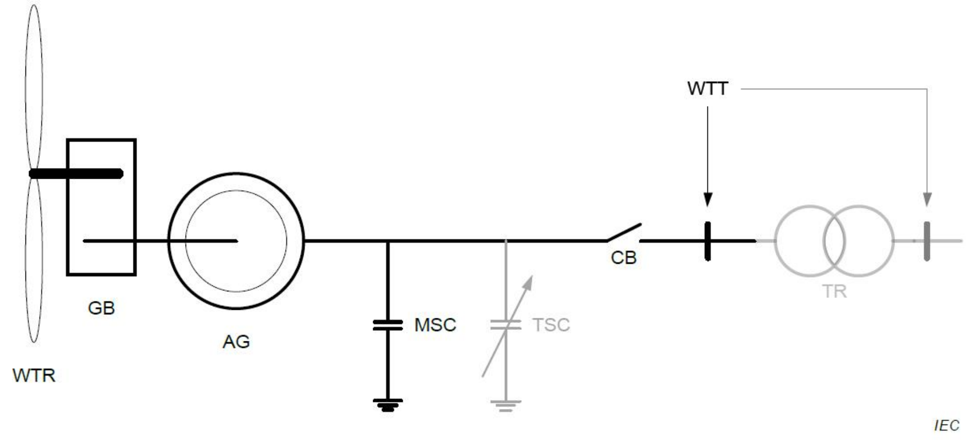

Figure 2.1: Wind Turbine type 1 [1].

There are two types of this WT:

1. Type 1A: WTs with fixed pitch angle. This type has no control on the angle of the blades, so there is no active power control in this WT.
2. Type 1B: WTs with Under Voltage Ride Through pitch control. This type has control on the angle of the blades, so different active power can be obtained. This control in WT type 1 is used in active Under Voltage Ride Through.

2.1.2. TYPE2

In Type 2, the asynchronous generator is directly connected to the grid, as in type 1. However, this generator is equipped with a variable rotor resistance (VRRAG) and it is normally equipped with pitch control [3].

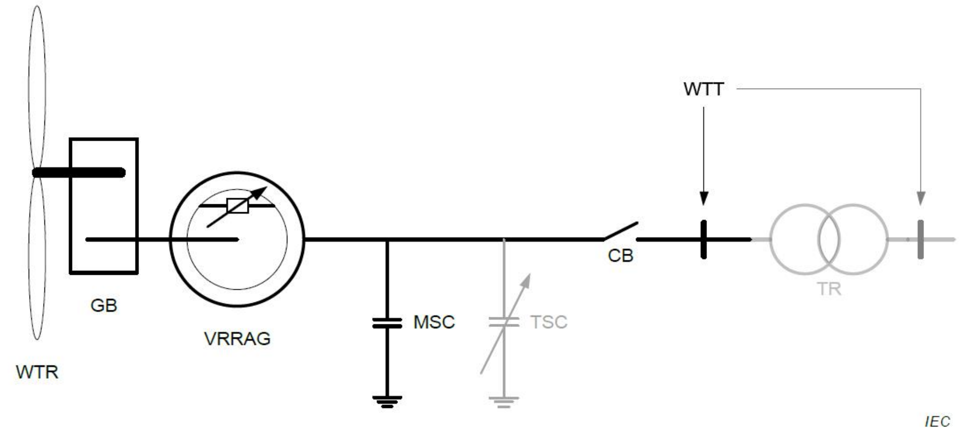

Figure 2.2: Wind Turbine type 2 [1].

2.1.3. TYPE3

A double fed asynchronous generator (DFAG) is used in type 3 WTs. In this type, the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter. In order to keep the WT connected to the grid when there is some disturbance in the system, some of these

WTs include either a chopper (CH) or a crowbar (CRB). The chopper limits the voltage rise within safe levels, while the crowbar makes the DFAG behave in the same way as a conventional squirrel cage induction generator, during the disconnection of the rotor side converter from the rotor winding [3, 12]. Two converters are used in this type of WT. The first one is the generator side converter (GSC), and the second one is the line side converter (LSC). If the WT includes a chopper, in between these converters, there is a DC link (DCL) that includes the chopper and a capacitor (C).

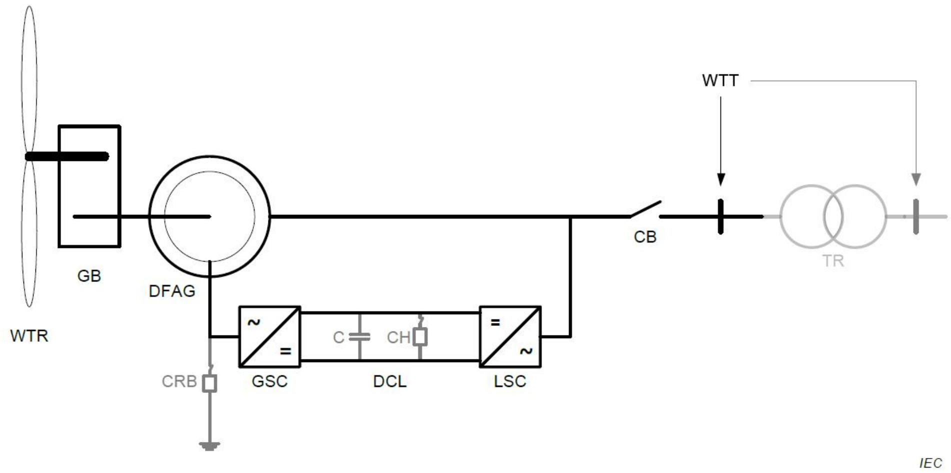

Figure 2.3: Wind Turbine type 3 [1].

2.1.4. TYPE4

These Wind Turbines are connected to the grid through a full scale power converter. They can use either synchronous generators (SG) or asynchronous generators (AG). If a synchronous generator with permanent magnets is used, this machine can easily have a large number of poles, which means that a lower speed in the rotor is needed. If this is the case, a gearbox is not needed for this WT. The full scale power converter guarantees 50 Hz at the grid, no matter the variable speed at the rotor.

Since this WT is completely decoupled from the grid, the generator does not “feel” the events occurring in the power system. For example, for a WT type 4 without controls, if there is load loss in the system, the generator would not decreased the active power produced.

WT type 4 has two possible models:

1. Type 4A: In this model, the aerodynamic and mechanical parts are not considered since choppers are included in the modelling. This implies, that post fault power oscillations are not injected.

2. Type 4B: This model does not consider choppers in it, so there is a post fault injection of power oscillations that are modeled by including mechanical parts (2-mass mechanical model) and assuming constant aerodynamic torque. Normally, this power oscillations does not affect the power system stability [3].

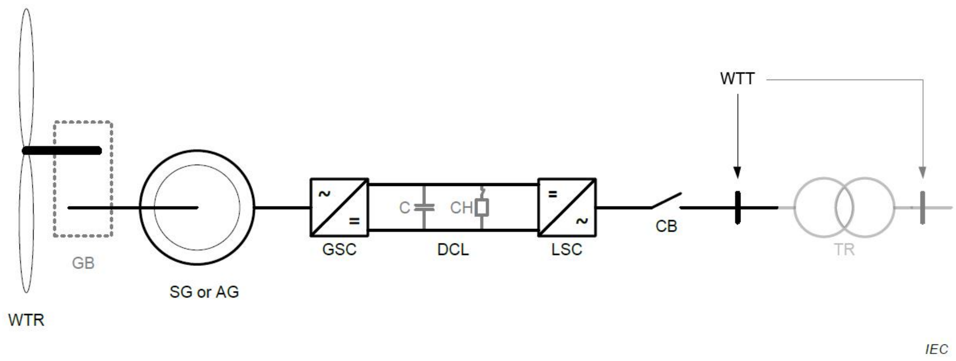

Figure 2.4: Wind Turbine type 4 [1].

2.2. WIND TURBINES IN THE NETHERLANDS

In the Netherlands, the wind energy was introduced as part of the Dutch energy policy in the 19970s, when it was clear that fossil fuel reserves were finite [13]. Through the years, there has been an increment of the WT and WPs in the grid.

In this section, all the WTs existing in the Netherlands in 2018 are classified. The classification was made according to the IEC (Type 1, 2, 3 or 4). The information of all the WT (until 2018) was provided by WindStats [10] to TenneT TSO B.V.

The information in the WindStats includes the location of each WT, the name of the WP where the WTs are located, the manufacturer, the model of WTs, their capacity and their physical characteristics such as the diameter of the rotor and the height of the WT. Finally, the date in which the WTs started to operate is also provided.

Since the WindStats information does not include the IEC classification of the WT, data available in internet (like data sheets or information of the manufacturer in their websites) was used to identify the type of each WT. Knowing some details such as the type of generator or the existence of power electronics, the determination of the type of WTs was possible. However, not for all WT was enough information available.

If not enough data was available, the type of the WT was determined based on the capacity and the diameter of the rotor obtained from the WindStats information. According to the size of WT, the diameter of the rotor (D) and even the year of manufacture, certain type of power electronics were used most likely (Figure 2.5). Once the power electronics used were identified, the type of WT can be determined. Based on the definition of each type of WT according to the IEC:

- soft starter is used in type 1
- rotor resistance control is used in type 2
- rotor power control is used in type 3
- full generator power control is used in type 4

Once this analysis was made for all the WT in the Netherlands, it can be concluded that there is a majority of type 4 WT. Using the WIndStats information, the installed capacity of wind energy in the Netherlands was calculated. In 2018, this sum was 4.275 GW.

In Table 2.1, the percentage of installed capacity per type can be seen.

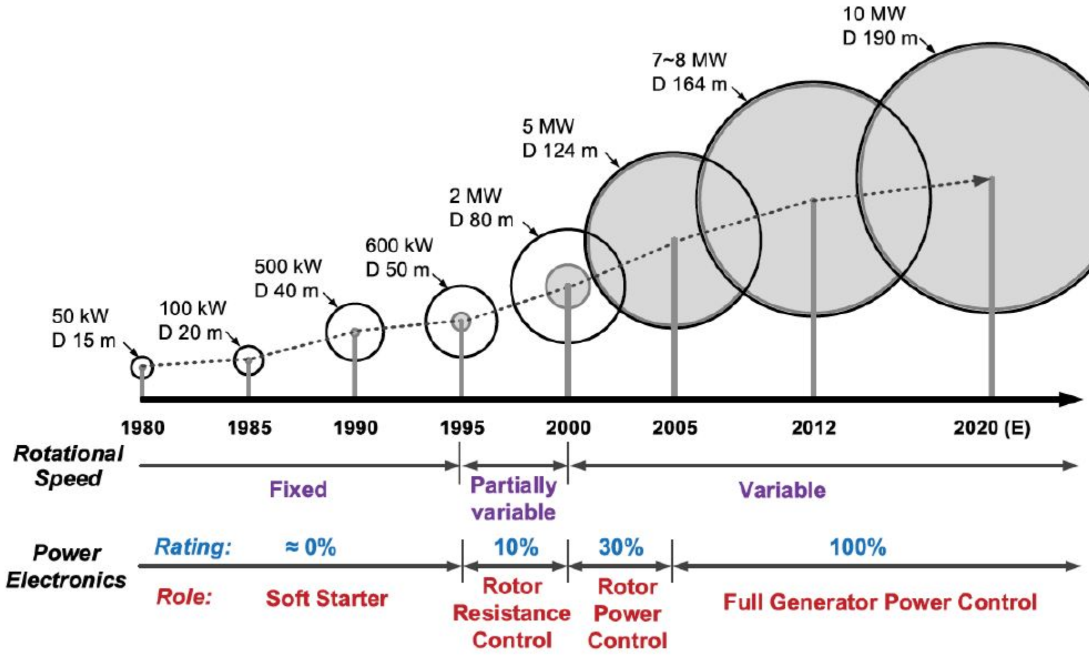

Figure 2.5: The evolution of Wind Turbines through the years can be seen. The grey area inside the turbine circle indicates the power rating coverage by power electronics [2].

Table 2.1: Percentage of the installed capacity per Wind Turbine type.

WT Type	Percentage %	MW installed
1	10.5	448
2	1.4	61
3	35.1	1500
4	53.0	2266

3

IEC and WECC Comparison

3.1. IEC 61400-27

The purpose of the IEC 61400-27 standards series is to provide an international standard for dynamic WT and WP models to be used in power system stability studies. In 2015, the first edition of this standard was published. Although the idea was to publish two parts (IEC 61400-27-1 and IEC 61400-27-2), just the first part was published.

In IEC 61400-27-1 (2015), dynamic models for the 4 types of WT were provided. In the second part of this standard, the idea was to provide the models of WP. However, WP models (just for type 3 and 4) were just specified in an informative Annex in the published part (IEC 61400-27-1). This first edition also includes a validation procedure for the WT models.

The models of the 2015 edition are developed to represent wind power generation in studies of large-disturbance short-term voltage stability phenomena, such as loss of generation or system faults. They are also applicable to study rotor angle stability (for example, system separation of one synchronous area into more), frequency stability (loss of loads) and small-disturbance voltage stability (incremental changes in system load) [1].

A new structure of the IEC 61400-27 was proposed and accepted. In this new edition of the standard, the first part (IEC 61400-27-1) will include the dynamic models for WT and WP (type 3 and 4), and in the second part (IEC 61400-27-2) validation procedure will be provided [3, 14].

The publication of these standards is expected at the end of 2019 or the beginning of 2020 [14].

The software DIgSILENT PowerFactory has already implemented the models of the IEC standard (2015) in its latest version. Besides, the European Network of Transmission System Operators (ENTSO-E) is coordinating implementation guidelines together with five software vendors (Eurostag, DIgSILENT, Neplan, Nettomac and PSSE), as part of the Common Grid Model Exchange Standard [15].

3.1.1. IEC Models

In Figure 3.1, a general block diagram of a WT according to the IEC standard can be seen.

Since for this work the second edition of IEC 61400-27 standard cannot be used (it has not been published, therefore is not implemented in any software), a comparison between the first and the second edition of the standard was made. The goal of this task is to find important differences that may change the dynamical behaviour of wind models.

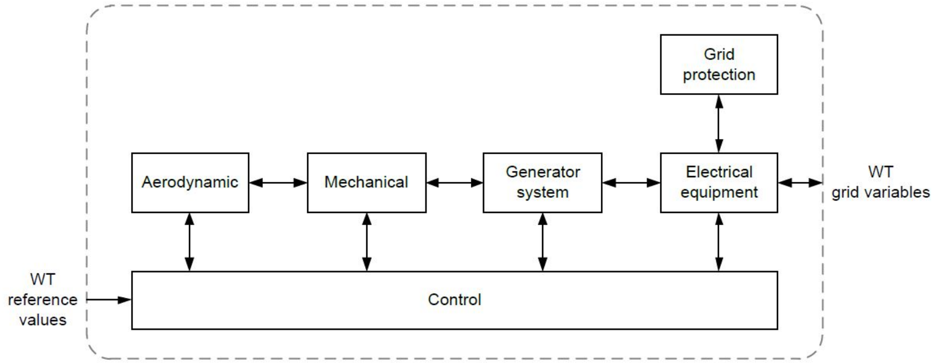

Figure 3.1: Generic structure of a Wind Turbine [1].

For the second edition, a draft from 2018 was used. In the following sections, the differences are presented.

GENERIC MODEL OF WIND TURBINES

In Table 3.1, the differences between both versions of the IEC standard can be seen.

Table 3.1: Differences in the Generic Model of Wind Turbine.

GENERIC MODEL OF WIND TURBINE		
	IEC 2015	**IEC 2018**
Control Model	One control module including all the controls	Controls in two modules: Pitch control and Generator control
Grid Protection *	Just one Grid Protection module. Grid Measurement is included in this module	There are three modules: Grid Protection, Grid Measurement (for protection) and Grid Measurement (for control)
U-f module	Inside Grid Protection module	More parameters (inside Grid Measurement for protection module)
Electrical system	The transformer of the WT is included in the generic model	The transformer is not included in the generic models of WT, but in generic model of WP
*This change is done to avoid duplicate specification of grid measurement models [14]		

The present work is going to consider constant speed and it is not considering electrical protections, the differences are therefore not detailed regarding mechanical and grid protection modules.

Wind Turbine Type 1

In Table 3.2, the differences of versions 2015 and 2018 regarding WT type 1 can be observed.

Table 3.2: Differences in the Wind Turbine type 1.

WIND TURBINE TYPE 1		
	IEC 2015	**IEC 2018**
Type 1A	Same model as 2015	Same model as 2018
Type 1B	Same model as 2015	Same model as 2018

Wind Turbine Type 2

In Table 3.3, the differences of versions 2015 and 2018 regarding WT type 2 can be observed.

Table 3.3: Differences in the Wind Turbine type 2.

WIND TURBINE TYPE 2		
	IEC 2015	**IEC 2018**
Rotor Resistance control	Filter gains for measurements are considered as part of this block	Measurement filter gains are not considered in this module, they are located in the Grid Measurement blocks

Wind Turbine Type 3

There is just one model of Type 3 (as explained in section 1.1) in both editions of the IEC. However, the Generator System could be type 3A or 3B. Generator System Type 3B is the simplification of type 3A but with the addition of a crowbar model. Generator System type 3A and 3B in the IEC 2015 edition are the same as in the IEC 2018 edition.

The Generator System can be either type 3A or type 3B, whereas the rest of the modules (like P control or Q control) are the same for both types.

In Table 3.4, the differences of versions 2015 and 2018 regarding WT type 3 can be observed.

Table 3.4: Differences in the Wind Turbine type 3.

WIND TURBINE TYPE 3		
	IEC 2015	**IEC 2018**
P control	Only generator speed is used. Contains measurement filter gains for power.	Rotor speed can be optionally used instead of generator speed as an efficient way to filter the speed. If the generator speed is used, the maximum torque will be calculated instead of reference speed [14]. Filter gains for power are considered in Grid Measurement modules.
Q control	It has the same 3 specific options of FRT as the IEC 2018, but no user defined option.	For the FRT Q control modes, there is an user defined option (where the reactive current injection during the voltage dip, and in an optional post-fault period can be defined)
Current limitation module	Includes a voltage measurement parameter.	Measurement parameters are located in Grid Measurement modules.

Wind Turbine Type 4

In Table 3.5, the differences of versions 2015 and 2018 regarding WT type 4 can be observed.

Table 3.5: Differences in the Wind Turbine type 4.

WIND TURBINE TYPE 4		
	IEC 2015	**IEC 2018**
P control (WT type 4A and WT type 4B)	Less detailed model, in this module a parameter for measurement is included.	More detailed model. Includes parameters for power reference (time constant in reference power order lag, maximum and minimum WT reference power ramp rate). Parameters for measurement are located in Grid Measurement modules.
Q control	It has the same 3 specific options of FRT as the IEC 2018, but no user defined option.	For the FRT Q control modes, there is an user defined option (where the reactive current injection during the voltage dip, and in an optional post-fault period can be defined)
Current limitation module	Includes a voltage measurement parameter.	Measurement parameters are located in Grid Measurement modules.

Wind Power Plants

As mentioned before in this section, WP in both editions of IEC 61400-27 are intended for WT type 3 and type 4.

In the first edition of the standard, a general structure of WP is not specified. However, the second edition defines the general structure of the WP as shown in Figure 3.2.

The AUX model in Figure 3.2 is used for auxiliary devices providing reactive power compensation. The WP control model includes power/frequency control and reactive power/frequency control. WT model consists of an aggregated model of the WT (represented as a single WT of one type), a WT transformer (TRWT), an aggregated collector line (ACL) and a WP transformer (TRWP), as shown in Figure 3.3. For calculating an appropriate equivalent for the collector system, there is a method explained in Annex A in the second edition of the standard [3].

In Table 3.6, the differences between both editions of the standard regarding WP are specified.

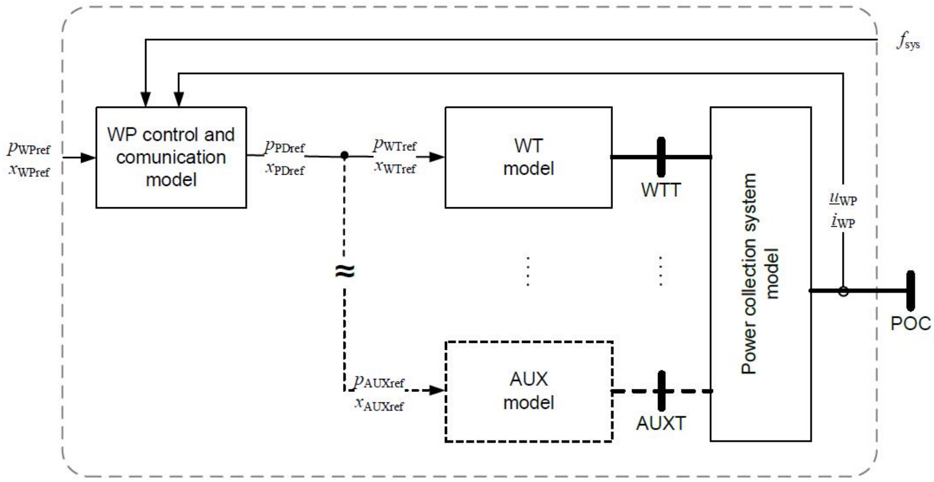

Figure 3.2: General Structure of a Wind Power Plant model according to IEC 61400-27-1 second edition [3].

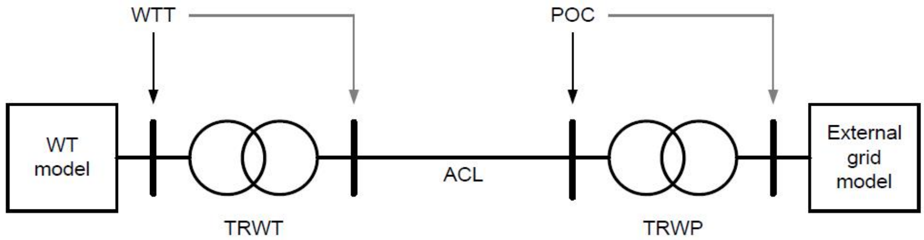

Figure 3.3: Basic single line diagram of a Wind Power Plant model without reactive compensation [3].

Table 3.6: Differences in the Wind Power Plants

WIND POWER PLANTS		
	IEC 2015	**IEC 2018**
WP Pf-control	Parameters for frequency and active power measurement are present in this module.	Addition of control errors. Parameters for measurement are located in the Grid Measurement module.
WP QU-control	Parameters for voltage and reactive power measurement are present in this module.	A voltage drop function (resistive and inductive component of WP voltage drop impedance) and additional limits (power dependent reactive power) were added. Addition of control errors. Parameters for measurement are located in the Grid Measurement module.
Grid Measurement	This module does not exist. Parameters for measurements are located inside the other modules.	Parameters for measurement are located in this module.

3.2. WECC

Besides the IEC models, WT and WP models developed by the WECC together with the Institute of Electrical and Electronics Engineers Working Group on Dynamic Performance of Renewable Energy Systems can be found. As the IEC models, WECC models have also a modular structure (so they can be augmented according to requirements) [15].

There are two generations of WECC models until now: 2011 and 2014. The intention when developing the IEC models was to make them compatible with the WECC models. Although this has not been completely fulfilled, the IEC models contained in the first edition are very similar to the second generation of the WECC models [15].

The WECC models have been implemented in Siemens PTI PSSE, GE PSLFTM, PowerWorld Simulator and PowerTech Labs and in the DIgSILENT PowerFactory software [13].

3.2.1. Models in Siemens PTI PSSE

In TenneT TSO B.V., the software tool used for dynamic simulations is Siemens PTI PSSE, so the WTs models available are only the WECC models.

In this section, the models that can be found in this software and its mayor differences with the first edition of IEC models are presented. Since the scope of the work is dynamic voltage response, a deeper analysis regarding reactive control is made.

In the documentation of the PSSE software there are two basic documents:

- Program Application Guide [4]. In this document, an explanation of how to use the models in the software and an example of a the parameters that can be used are presented. It is important to mention, that unfortunately, not all the models are included here.

- Model Library [5]. In this document, a scheme of the models as well as a list of used parameters are presented. However, for some of the most recent models, the scheme is not always presented.

Table A.1 shows the different models for WT and WP available in PSSE 34.4.

In the following section, a comparison using simulations of each type of WT and WP will be described.

The structure of the models was analysed to determine the differences between the WECC and the IEC models. Special attention was given to reactive control in case of WT3 and 4.

WT TYPE 1

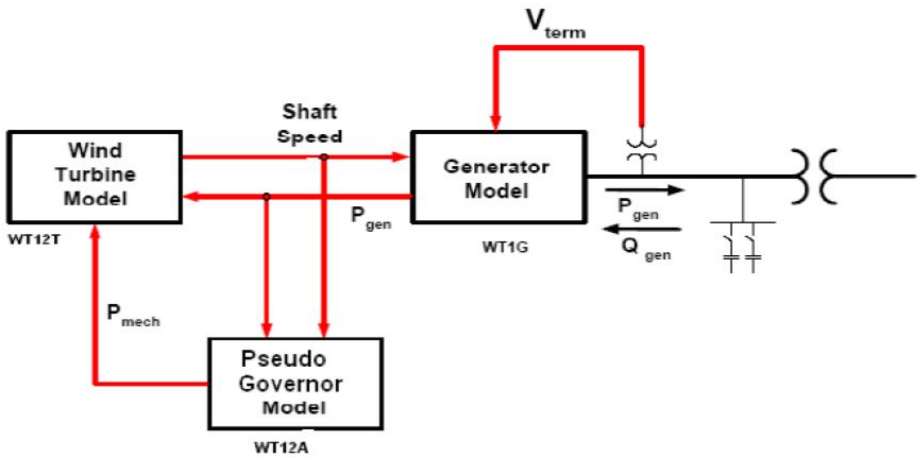

Figure 3.4: WT Type 1 in PSSE [4].

- Generator Model: meets the requirements of the IEC.
- Pseudo Governor Model (Aerodynamic model): More complex than the one established in IEC for this WT, which is just a constant.
- Wind Turbine Model (two mass model): This model is equivalent to the one specified in the IEC.

Since this work is going to consider constant wind speed, the difference in the aerodynamic models does not affect the dynamic behaviour of the WT.

Due to the absence of pitch control in this model, WT type 1 from PSSE is equivalent to the WT Type 1A of the IEC-61400-27-1.

WT TYPE 2

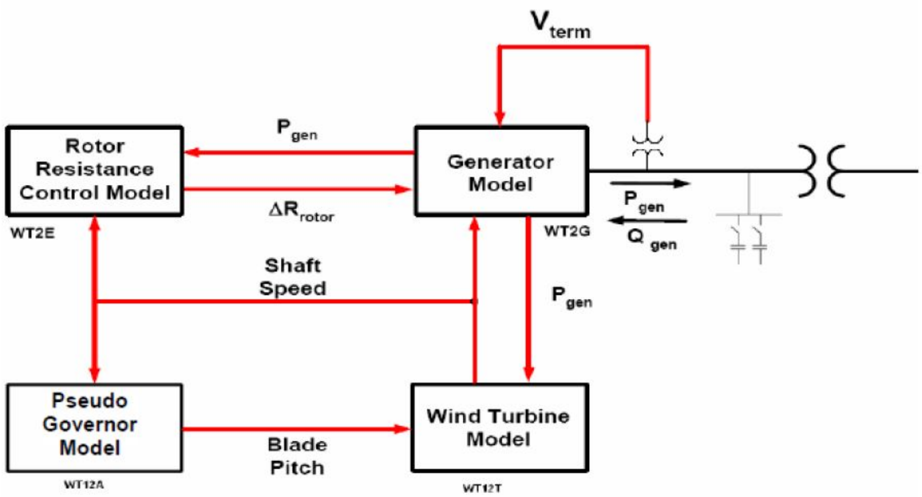

Figure 3.5: WT Type 2 in PSSE [4].

- Generator Model: meets the requirements of the IEC.
- Wind Turbine Model (two mass model): This model is equivalent to the one specified in the IEC.
- Pseudo Governor Model (aerodynamic model): More complex than the one established in the IEC for this WT, which is just a constant.
- Rotor Resistance Control Model: In the IEC are some parameters for measurement that are not in this model of PSSE. Since they do not affect the behaviour of the control, this is equivalent to the one in the IEC.

Since this work is going to consider constant speed, the difference in the aerodynamic models does not affect the dynamic behaviour of the WT. The WT type 2 from PSSE is equivalent to the IEC WT Type 2.

Type 3 (option 1)

In PSSE there are two options for modelling a WT type 3. The first option is the model presented in the WECC Wind Plant Dynamic Modeling Guidelines 2011 [16] and the second option is based in the WECC Wind Plant Dynamic Modeling Guidelines 2014 [17]. Both options are equivalent to WT type 3A of the IEC standard, however, the option 2 is a more detailed model and in general, it is more similar than the option 1 to the IEC standard.

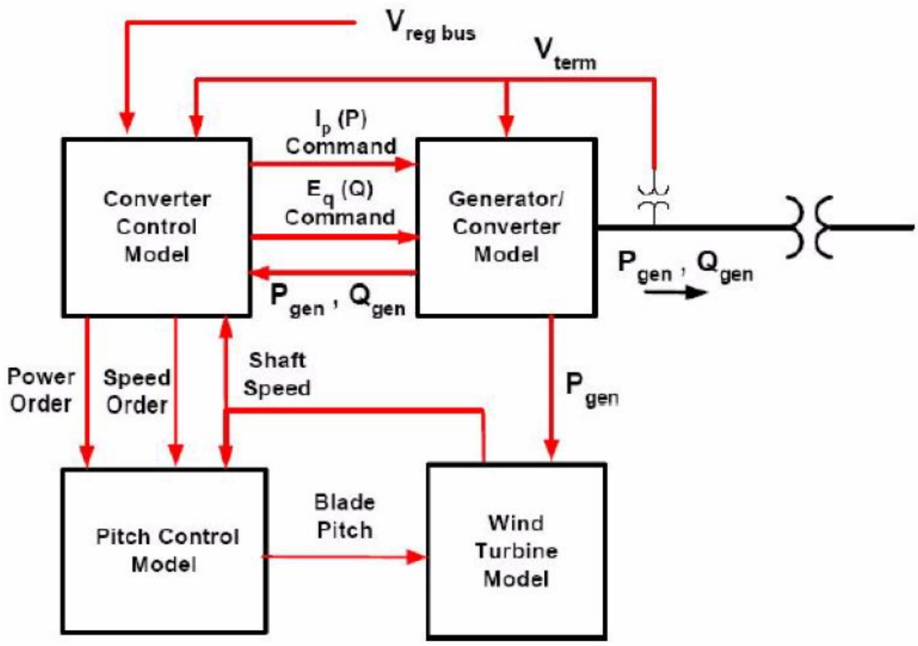

Figure 3.6: Wind Turbine Type 3 in PSSE [4].

- Generator/ Converter Model: This model has no option for a crowbar like the IEC. Because of that, it can be just comparable with the Generator model 3A of the IEC. Both generators models are slightly different: there is an absence of stator current limit in the WECC model and the IEC model contains a real current source whereas the WECC model uses an ideal current source [18].

- Wind Turbine Model (two mass model): This model is equivalent to the one specified in the IEC.

- Converter Control Model: This model is the equivalent to the active and reactive power control as well as the limitation models of the IEC. In the case of the active control, the IEC includes an active drive train damping block that is not included in the WECC model.

- Pitch Control Model: This model and the IEC pitch control model are different. Since this work is going to consider constant speed of wind, this model does not affect the behaviour of the WT.

This option does not have an aerodynamic model as the IEC model and it also lacks of a current limiter.

TYPE 3 (OPTION 2)

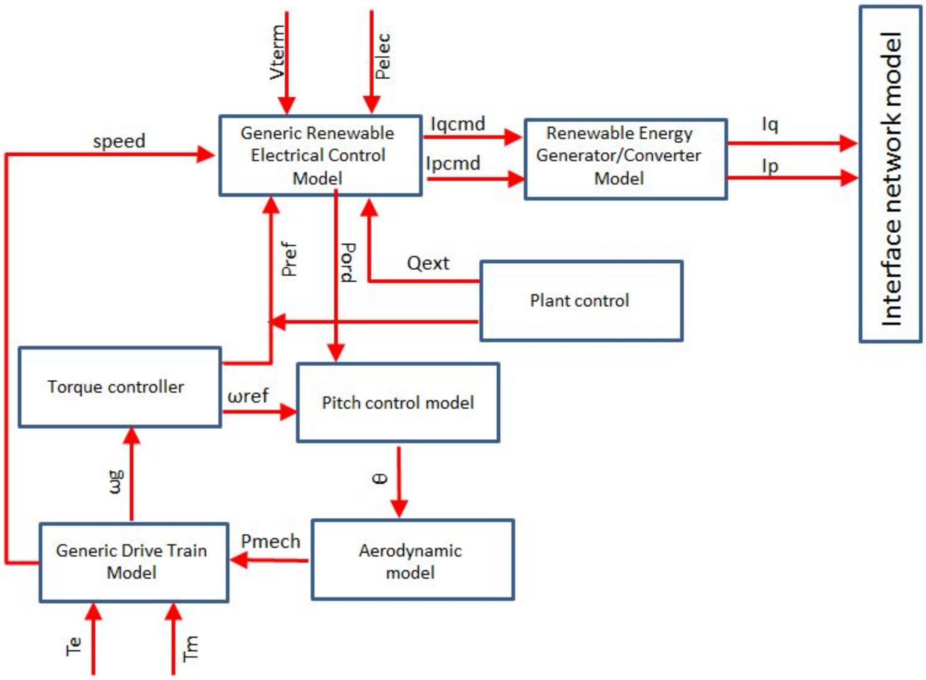

Figure 3.7: WT Type 3 (option 2) in PSSE.

WT3 option 2 is the model presented in the WECC Wind Plant Dynamic Modeling Guidelines 2014 (the most recent version) [17].

These models are not present in the Program Application Guide of PSSE 34.4 [4]. However, they are present on the Model Library [5].

- Renewable Energy Generator/Converter Model (REGCA1): This model has no option for a crowbar like the IEC. Because of that, it can be just comparable with the Generator model 3A of the IEC. Both generators models are slightly different: there is an absence of stator current limit in the WECC model and the IEC model contains a real current source whereas the WECC model uses an ideal current source [18].

- Generic Renewable Electrical Control Model (REECA1): This model includes the reactive and the active control. They are equivalent to the IEC controls. However, in the case of the active control, the IEC includes an active drive train damping block that is not included in the WECC model. The IEC includes in its control block a current limitation model and a QP and QU limitation model (the user can choose which one to use). In the WECC model REECA1, there is just one model for current limitation (the user can choose a priority for Q or P).
- Generic Drive Train Model (WTDTA1): This is equivalent to the mechanical model of the IEC (two mass model).
- Pitch control model (WTPTA1): This model and the IEC pitch control model are equivalent.
- Aerodynamic model (WTARA1): This model is the same as the one dimensional aerodynamic model of the IEC.
- Torque controller (WTTQA1): In the IEC, this block is inside the active power control and it is more complex that the one in the WECC.

Option 2 is based on the most recent version of the WECC Wind Plant Dynamic Modeling Guidelines [17], therefore, this model has more similarities with WT type 3A of the IEC 2015.

Type 4 (option 1)

In PSSE there are two options for modelling a WT type 4. The first option is the model presented in the WECC Wind Plant Dynamic Modeling Guidelines 2011 [16] and the second option is based in the WECC Wind Plant Dynamic Modeling Guidelines 2014 [17]. The option 2 is a more detailed model and in general, it is more similar than the option 1 to the IEC standard.

WT4 option 1 is the model presented in the WECC Wind Plant Dynamic Modeling Guidelines 2011 [16].

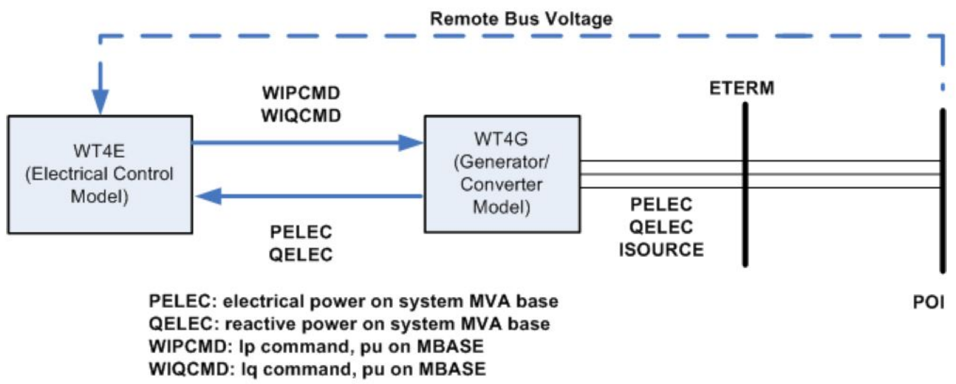

Figure 3.8: WT Type 4 in PSSE [4].

The model from Figure 3.8 does not include the mechanical part (two mass model), so it is only compared to the WT type 4A from IEC.

- Generator/Converter Model: The structure of both models is slightly different. The IEC model contains a Reference Frame Rotation where id and iq are transformed into a three phase current whereas the WECC model uses an ideal current source to inject the current into the WT terminals.
- Electrical Control Model: It includes the active and reactive power control as well as the limitation models of the IEC. However, it does not include the same options as the IEC for reactive current injection during normal operation, during fault and during post fault.

TYPE 4 (OPTION 2)

WT4 option 2 is the model presented in the WECC Wind Plant Dynamic Modeling Guidelines 2014 (the most recent version) [17].

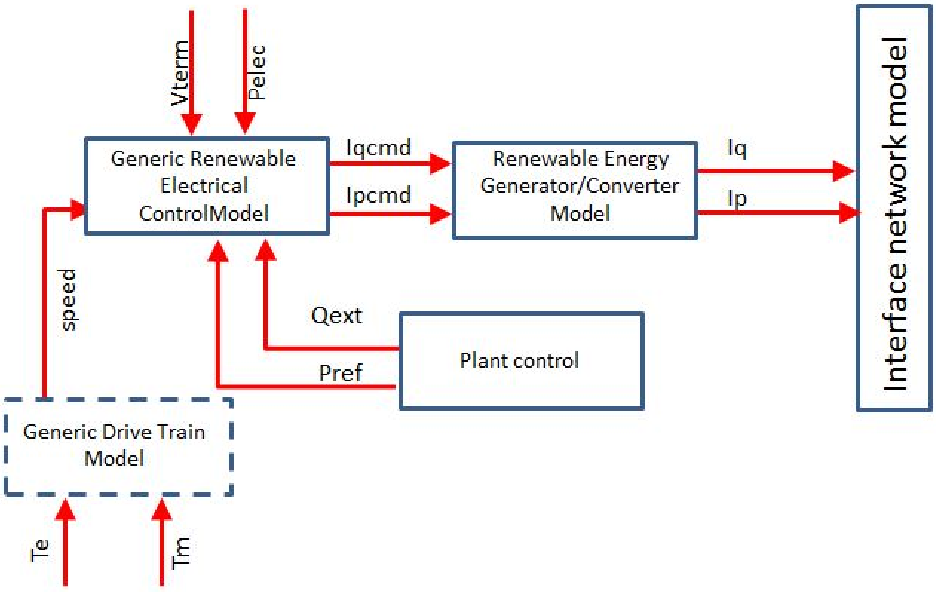

Figure 3.9: WT Type 4 (option 2) in PSSE.

These models are not present in the Program Application Guide of PSSE 34.4. However, they are present on the Model Library [5].

- Renewable Energy Generator/Converter Model (REGCA1): Both generators models are slightly different regarding the limitation of the current. However, in this option, in the WECC model the injection of the current is done in the Interface to Network Model instead of using an ideal current source. This is a more similar model to the IEC than the option 1.

- Generic Renewable Electrical Control Model (REECA1): This model includes the reactive and the active control. The reactive control is equivalent to the IEC control and it is more similar to it than the WT option 1. The active control is much more complex in the WECC model. The IEC includes in its control block a current limitation model and a QP and QU limitation model (the user can choose which one to use). In the WECC model REECA1, there is just one model for current limitation (the user can choose a priority for Q or P).

Optional:

- Generic Drive Train Model (WTDTA1): This is equivalent to the mechanical model of the IEC (two mass model).

Option 2 is based on the most recent version of the WECC Wind Plant Dynamic Modeling Guidelines [17], therefore, this model has more similarities with the IEC 2015. Since there is an option in PSSE for using a drive train model, it can be concluded that the WT type 4A and 4B from the IEC can be represented with the WECC models without significant differences.

Wind Power Plant Type 3 and Type 4

There are models for WP control available in PSSE: REPCTA2 (for WT3 option 2) and REPCA1 (for WT4 option 2). These models are described in the Model Library [5] but not in the Program Application Guide [4].

Active power/frequency control and reactive power/frequency control are included in the same control model in the WECC version. The WECC model includes a voltage drop function (resistive and inductive component of the WP voltage drop impedance), which makes it similar to the IEC 61400-27-1 second edition (See Figure 3.10).

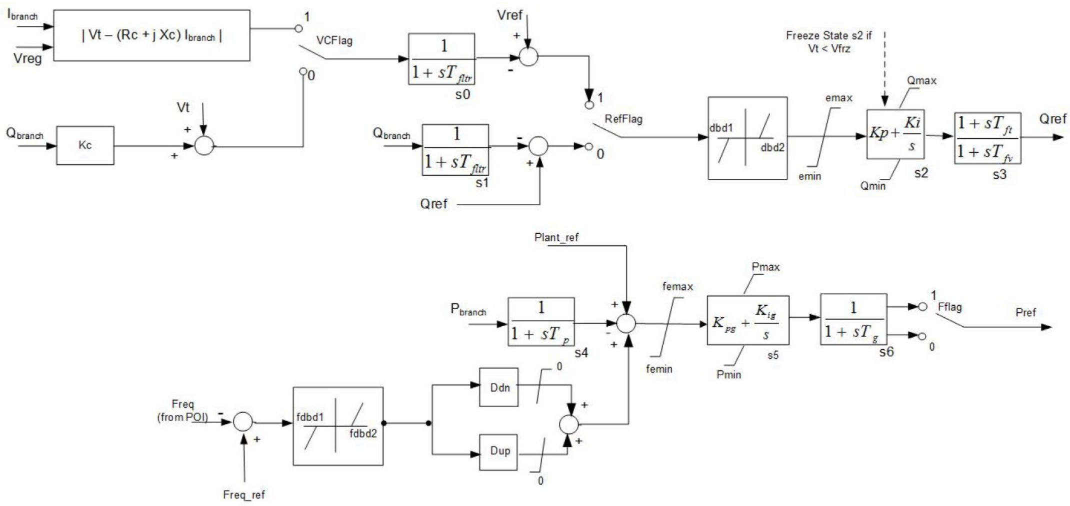

Figure 3.10: Plant Control Model in PSSE [5].

Equivalent WECC Models (to IEC)

As a result of the previous analysis, it can be concluded that the most IEC similar models in PSSE are those showed in Table 3.7.

Table 3.7: Models in PSSE 34 that are the most similar to the IEC models.

	Generator	Electrical control	Mechanical model	Pitch control	Aerodynamic model	Torque control	Plant control
			Wind Turbines				
WT 1	WT1G1		WT12T1		WT12A1		
WT 2	WT2G1	WT2E1	WT12T1		WT12A1		
WT 3 (option 2)	REGCA1	REECA1	WTDTA1	WTPTA1	WTARA1	WTTQA1	
WT 4 (option 2)	REGCA1	REECA1	Optional: WTDTA1				
			Wind Power Plants				
WP 3	REGCA1	REECA1	WTDTA1	WTPTA1	WTARA1	WTTQA1	REPCTA1
WP 4	REGCA1	REECA1	Optional: WTDTA1				REPCA1

The full description of the models presented in Table 3.7 can be seen as follows:

Generator

- WT1G1. Wind Turbine Type 1 Generator (version 1).
- WT2G1. Wind Turbine Type 2 Generator (version 1).
- REGCA1. Renewable Energy Generator/Converter Model (version 1).

Electrical control

- WT2E1. Wind Turbine Type 2 Electrical Control (version 1).
- REECA1. Renewable Energy Electrical Control Model (version 1).

Mechanical model

- WT12T1. Wind Turbine Type 1 and 2 Two-Mass Model (version 1).
- WTDTA1. Wind Turbine Drive Train model for Wind Turbine type 3 and 4 (version 1).

Pitch control

- WTPTA1. Pitch Control Model for Wind Turbine Type 3 (version 1).

Aerodynamic model

- WT12A1. Wind Turbine Type 1 and 2 Aerodynamic Model (version 1).
- WTARA1. Wind Turbine Aerodynamic model for Wind Turbine type 3 (version 1).

Torque control

- WTTQA1. Wind Turbine Torque Controller for Wind Turbine Type 3 and 4 (version 1).

Plant control

- REPCTA2. Renewable Plant Control Model for Wind Turbine Type 3 (version 1).
- REPCA1. Renewable Plant Control Model for Wind Turbine Type 4 (version 1).

3.3. MAIN MODELLING DIFFERENCES BETWEEN IEC AND WECC MODELS

In this section, a comparison of the behaviour of both models is realised using PowerFactory and PSSE. The objective is to compare the dynamic voltage response of the WTs when a three phase fault is created at the point of common coupling (PCC). In order to have a reference of the behaviour WT needs to meet, the Netcode elektriciteit (Grid Code of the Netherlands [19]) and the Wind Farm Connection Requirements [20] were used.

3.3.1. ANALYSIS OF THE REACTIVE CONTROL

To understand the differences in both models (IEC and WECC reactive control), an analysis of the reactive power control in both models was performed. This analysis was made for WT3 and WT4. In Figures 3.11 and 2.12 the models of the reactive power control can be observed.

In both models (IEC and WECC), $Iqcmd$ is the output current that is going to be send to the generator system.

There are some variables that are equivalent in both models (IEC and WECC):

• **XWTref and Qref**. These input variables can either be a voltage or reactive power command from the controller of the WP. When a single WT is used, these variables are initialized as constant inputs.
• **Uref0 and Vbias**. These variables are a user defined voltage offset. They are used in voltage control in normal operation.
• **tan and tan**(ϕ_{init}). These variables are initialized in the power flow calculation.
• **Tpost and Thld**. These are time variables that determine the time the post-fault operation state is going to last.

In the IEC model there is an important variable that is not used in the WECC model, the voltage droop shown in Equation 3.1:

$$u_{droop} = \sqrt{\left(u_{WT} - r_{droop}\frac{p_{WT}}{u_{WT}} - x_{droop}\frac{q_{WT}}{u_{WT}}\right)^2 + \left(x_{droop}\frac{p_{WT}}{u_{WT}} - r_{droop}\frac{q_{WT}}{u_{WT}}\right)^2} \qquad (3.1)$$

Where:

u_{WT} is the voltage at the terminals of the WT
p_{WT} is the active power at the terminals of the WT
q_{WT} is the reactive power at the terminals of the WT
r_{droop} is the resistive component of voltage drop impedance
x_{droop} is the inductive component of voltage drop impedance

In general, the WECC model works with pu values whereas the IEC model keeps the original units. This characteristics can be observed in the parameters of the reactive control.

This control can be analysed using 3 states:

• State 0: Normal operation
• State 1: Fault operation
• State 2: Post fault operation

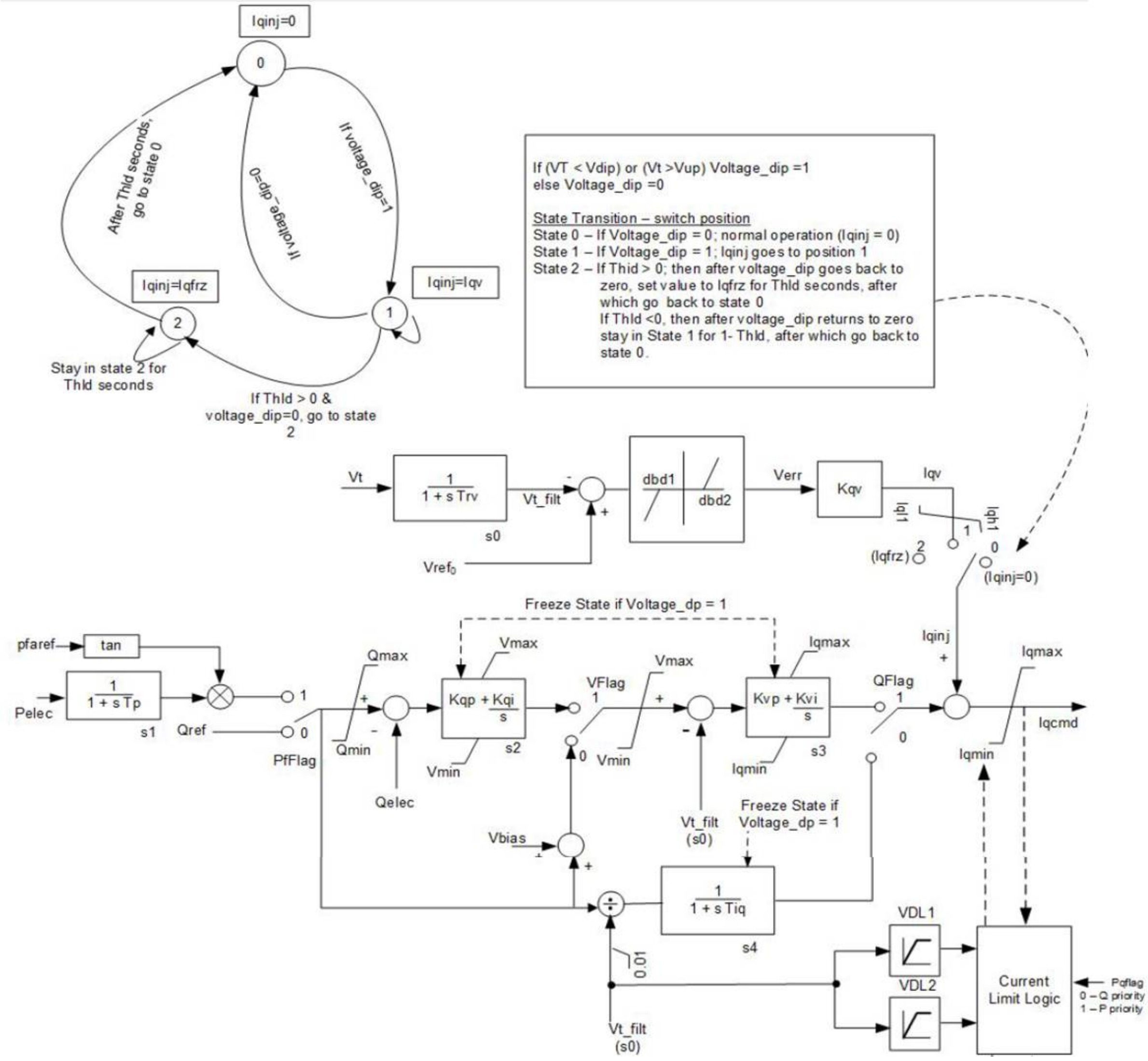

Figure 3.11: WECC reactive control for WT 3 and 4 [5].

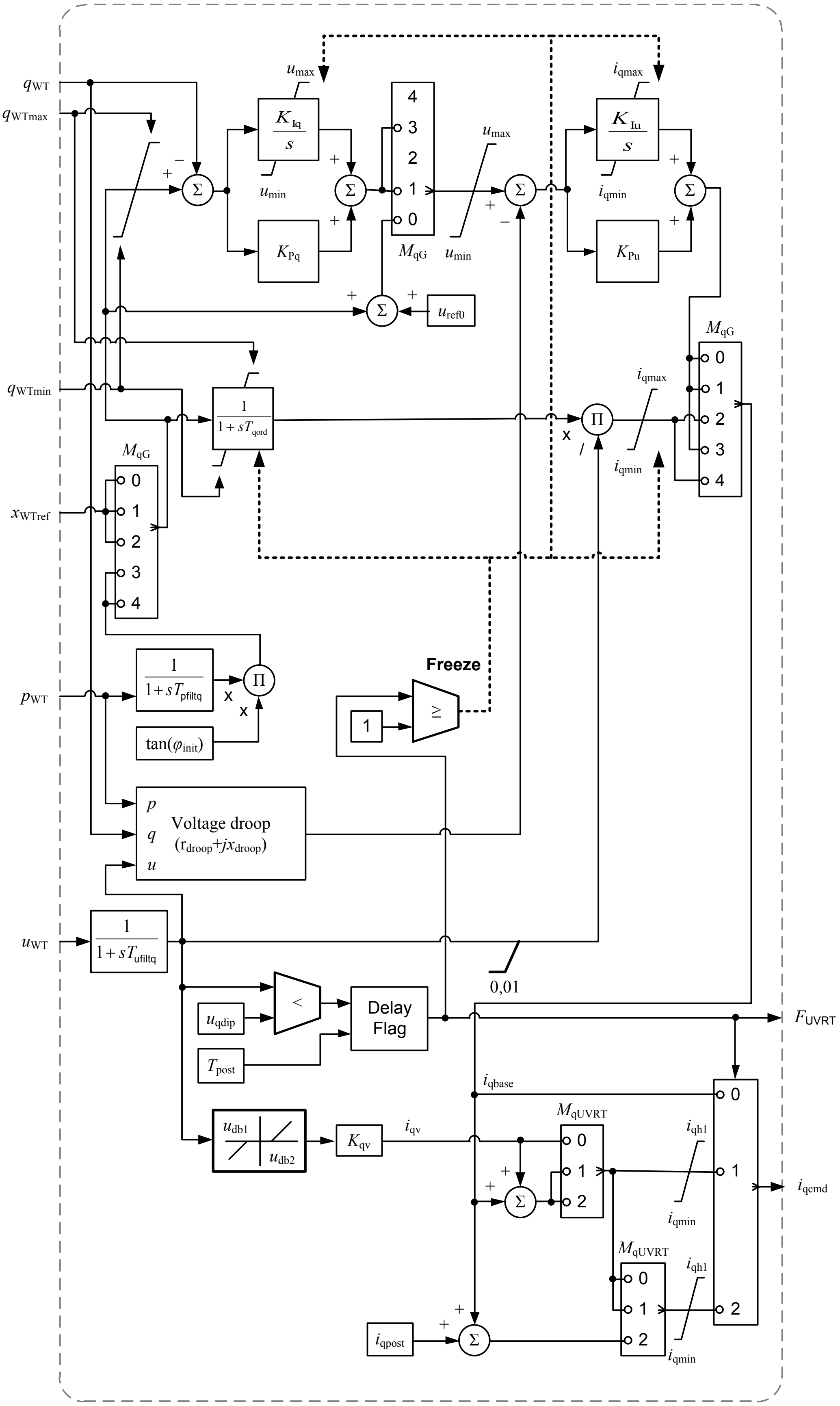

Figure 2.12: IEC reactive control for WT 3 and 4 [6].

STATE 0. NORMAL OPERATION

In the normal operation state, the control of both models (IEC and WECC) have 5 different modes:

1. Voltage control. The IEC control uses u_{droop} instead of the Vt_{filt} of the WECC control.
2. Reactive power control. The IEC control uses u_{droop} instead of the Vt_{filt} of the WECC control.
3. Open loop reactive power control. The signals in the IEC control are filtered before obtaining I_{qcmd}. In the WECC control, Q_{ref} is not filtered, only the current obtained with Q_{ref} and Vt_{filt}.
4. Power factor control. The IEC control uses u_{droop} instead of the Vt_{filt} of the WECC control.
5. Open loop power factor control. The signals in the IEC control are filtered before obtaining I_{qcmd}. In the WECC control q_{input} is not filtered, only the current obtained with q_{input} and Vt_{filt}.

The open loop configurations are used for single WTs, whereas the closed loop configurations are used for WPs. The detailed differences of WECC and IEC models in this state are described in Table B.1.

STATE 1. FAULT OPERATION

In this state, the IEC standard have 2 different modes of operation:

1. Voltage dependent reactive current injection.
2. Reactive current injection controlled as the pre-fault value plus an additional voltage dependent reactive current injection.

The WECC just have one of these modes:

1. Voltage dependent reactive current injection (only when $V_{ref0} = 0$). Both standards calculate the I_{qcmd} using the voltage at the terminals of the WT. However, the sign of this variable is positive in the case of the IEC standard and negative in the case of the WECC standard.

In both models there is a freeze action that avoids the injection of current as established in normal operation. The detailed differences of WECC and IEC models in this state are described in Table B.2.

STATE 2. POST FAULT OPERATION

In this state, the control of both models (IEC and WECC) have 3 different modes of operation:

1. Voltage dependent reactive current injection (only when $V_{ref0} = 0$). The IEC works directly with the voltage at the terminals of the WT, while the WECC uses the voltage error between the terminals and the reference.
2. Reactive current injection controlled as the pre-fault value plus an additional voltage dependent reactive current injection (only when $V_{ref0} = 0$). The IEC works directly with the voltage at the terminals of the WT, while the WECC uses the voltage error between the terminals and the reference.

3. Reactive current injection controlled as the pre-fault value plus an additional constant reactive current injection post fault. The WECC model does not work with a pre-fault current.

The detailed differences of WECC and IEC models in this state are described in Table B.3.

If *Thld* or *Tpost* are set as 0, the output current ($Iqcmd$) in post-fault operation will be the same as in normal operation.

It can be seen in the previous analysis that the most important difference between the IEC and WECC models is the use of a voltage droop (used in IEC). Since the model of a WT (without a Power Plant controller) is going to be tested, there are two modes in normal operation that can be used as equivalent between both models:

- Open loop reactive power control
- Open loop power factor control

For the fault operation there is just one possibility:

- Voltage dependent reactive current injection (using $V_{ref0} = 0$ in the WECC control)

And finally, for the post fault operation, using $Thld$ and $Tpost$ as 0, makes more similar both models. However, this means that there is no specific post fault behaviour.

3.3.2. FAULT RIDE THOUGH CAPABILITY REQUIREMENTS

The 4 types of WT of each standard (IEC and WECC) are going to be compared using two softwares. The parameters used in the models are not adapted to have an optimal behaviour, but to have the most similar behaviour between both standards. However, having a real behaviour is also an objective. Therefore, a real reference, such as the network code, is needed.

The *Netcode elektriciteit* is the network code of the Netherlands, where the requirements for connecting new generators or power plants are established. Since voltage stability is going to be analysed, the requirements for Fault Ride Through capability (FRT) are needed.

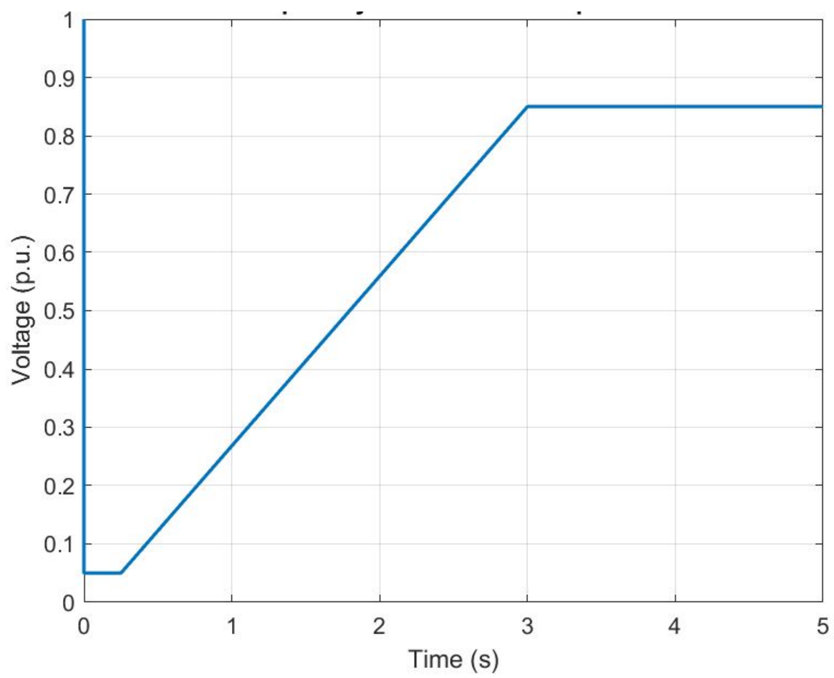

Figure 3.12: FRT capability for WT or WP up to 60 MW citeR17.

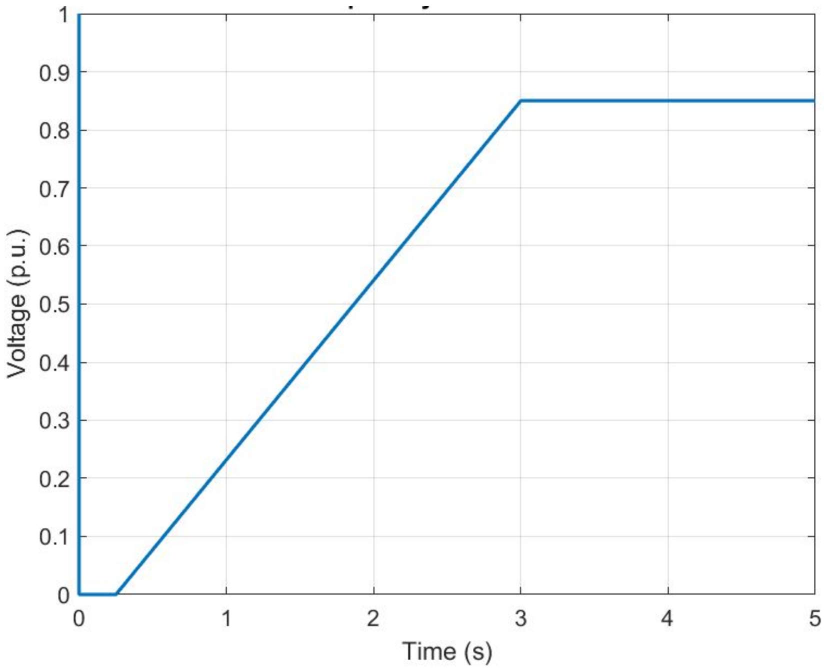

Figure 3.13: FRT capability for WP > 60 MW or voltage > 110 kV citeR17.

3.3.3. POWERFACTORY AND PSSE SIMULATIONS

For testing the four WTs, the system shown in Figure 3.14 was used, either in PSSE or PowerFactory. In order to use a typical value in the Netherlands for a three phase fault (R/X=0.1), an impedance for the fault of $R = 1\Omega$ and $X = 10\Omega$ was simulated at the Point of Common Coupling (PCC bus). The fault occurred at second 2 and it is cleared at second 2.25.

The fault causes a voltage dip of around 0.5 pu. In Table 3.8, the parameters for the external grid, the line and the transformers can be seen. For testing, a WP of 20 MW represented as a single WT is used.

Table 3.8: Parameters for the electrical system [7].

Line data (underground cable)	
Impedance	0.040+j0.110 Ω/km
Capacitance	300.0 nF/km
External network	
Inertia (H)	9 s
SCC	1500 MVA
Transformer data	
Voltage	0.69 kV/20 kV and 20 kV /150 kV
Capacity	20 MVA
Impedance	0.0088+0.059351 Ω

Since this work considers constant speed, the parameters for the aerodynamic models and the pitch control, are not present in any of the four WTs simulations. However, these parameters can be found in [18] and in the WECC Guidelines [17].

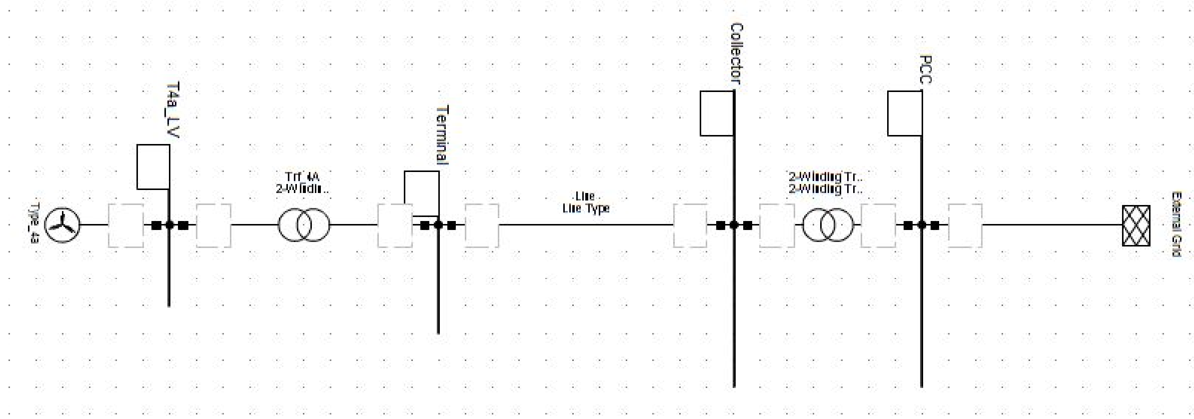

Figure 3.14: Electrical system used for testing WT.

SIMULATION FOR WT TYPE 1A

Used parameters

All the Tables with the proposed parameters can be found in Appendix C.

• **Generator**. The parameters used in PowerFactory (Table C.3) were the default parameters provided by the software. The parameters used in PSSE were obtained from the WECC Modeling Guidelines 2014 [16] and the examples in the Program Application Guide of PSSE [4] (Table C.1).

• **Mechanical model**. The parameters used in PowerFactory for this model (Table C.4) were the default parameters provided by the software. Using them as a reference, the equivalent parameters for the two mass model in PSSE were obtained (equations 3.2, 3.3, 3.4 and 3.5 [5]). The resulting parameters are showed in Table C.2.

$$H_t = H \times H_{tfrac} \tag{3.2}$$

$$H_g = H - H_t \tag{3.3}$$

$$K_{shaft} = \frac{2H_t \times H_g \times (2\pi \times Freq1)^2}{H \times \omega_0} \tag{3.4}$$

$$\omega_0 = 2 \times \pi \times f_{nominal} \tag{3.5}$$

Results

Some discrepancies can be seen in the simulations results in Figure 3.15. The IEC model does not reach the lower voltage during the fault as fast as the WECC model. Besides, the WECC model reaches the voltage stability a bit faster that the IEC model.

The IEC standard does not specify a model for the asynchronous generator, therefore, the differences observed in the voltage behaviour are due to the fact that this model is different in both softwares, for example, transient and subtransient variables are only appearing in the WECC model. This difference can be also observed in Figure 3.16, where the absorption of reactive power by the machine is showed. When the reactive power is a negative value, an injection of reactive power is occurring (due to capacitors or the induction generator), whereas there is an absorption of reactive power by the generator when the reactive power is a positive value. At the moment of the fault, there is bigger absorption of reactive power in the WECC model. When the fault is cleared, there is also bigger injection of reactive power in the WECC model, and it is observed, that the reactive power takes less time in reaching the stability (causing the same effect in the voltage stability).

The *Netcode* requirements are established for the interconnection point, so the voltage at the *PCC* bus should be within the lower limits showed in Figure 3.12.

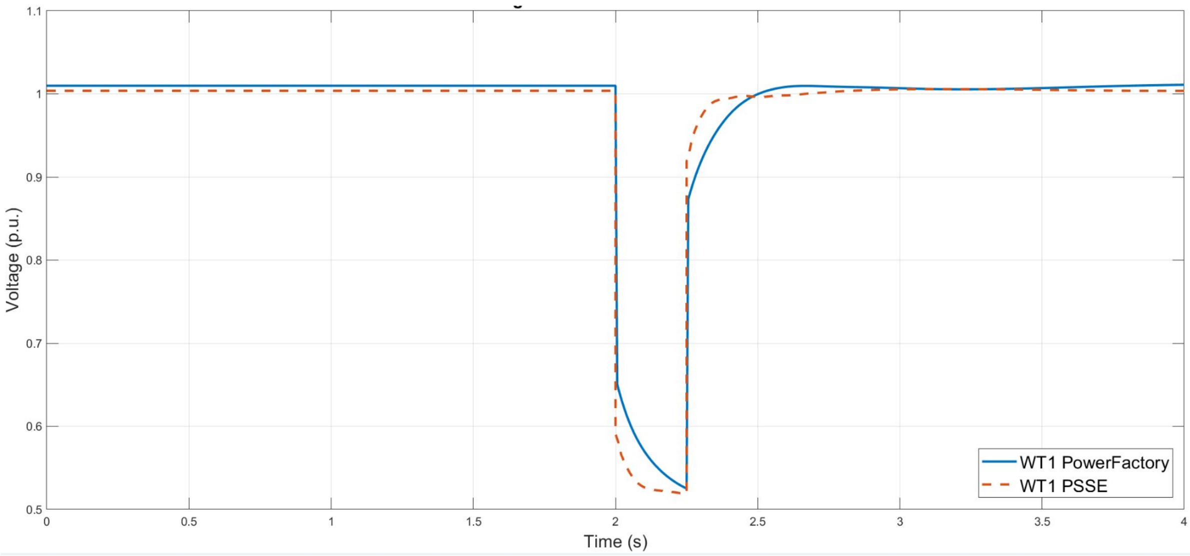

Figure 3.15: Voltage at the terminals of the Wind Turbine type 1A.

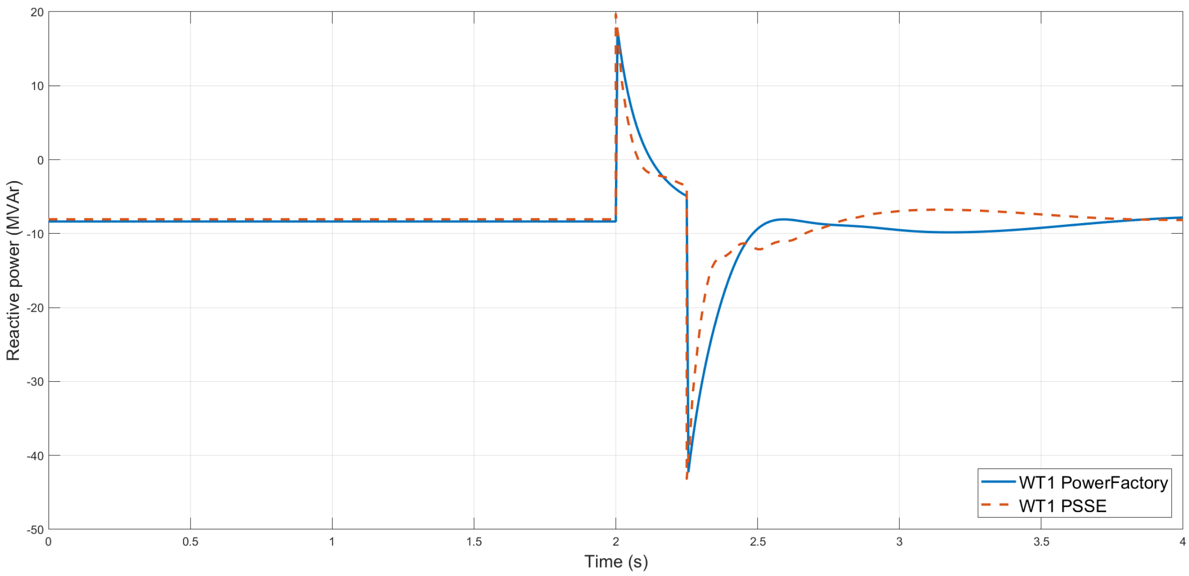

Figure 3.16: Reactive power at the terminals of the Wind Turbine type 1A.

SIMULATION FOR WT TYPE 2

Used parameters

All the Tables with the proposed parameters can be found in Appendix D.

• **Generator**. The parameters used in PowerFactory (Table D.3) were the default parameters provided by the software. The parameters used in PSSE were obtained from the WECC Modeling Guidelines 2014 [16] and the examples in the Program Application Guide of PSSE [4] (Table D.1).

• **Electrical Control**. The parameters used in PowerFactory (Table D.4) were the default parameters provided by the software. The parameters used in PSSE were obtained from the WECC Modeling Guidelines 2014 [16] and the examples in the Program Application Guide of PSSE [4] (Table D.2).

• **Mechanical Model**. The parameters used for the two mass model are the same as the ones used for WT1A (Tables C.2 and C.4).

Results

In Figure 3.17 can be seen that the behaviour of WECC model is more similar to the IEC model than in the case of the WT type 1. However, since the IEC standard does not specify a model for the asynchronous generator of WT type 2, the small differences observed during and after the fault are due to the different models for this generator in both softwares. Variables like transient and subtransient are only appearing in the WECC generator model.

In Figure 3.18 the behaviour of the reactive power is showed. When the reactive power is a negative value, an injection of reactive power is occurring (due to capacitors or the induction generator), whereas there is an absorption of reactive power by the generator when the reactive power is a positive value. There is bigger absorption of reactive power in the IEC model when the fault is created, when it is cleared, the injection of reactive power is the same in both models (IEC and WECC). The IEC model presents an oscillatory behaviour before and after the fault, but this behaviour in the reactive power does not affect the voltage stability (as seen in Figure 3.17). In the WECC model, there are also some oscillations after the fault is cleared. They last about 0.2 seconds, however, these oscillations can be seen in the voltage behaviour as well.

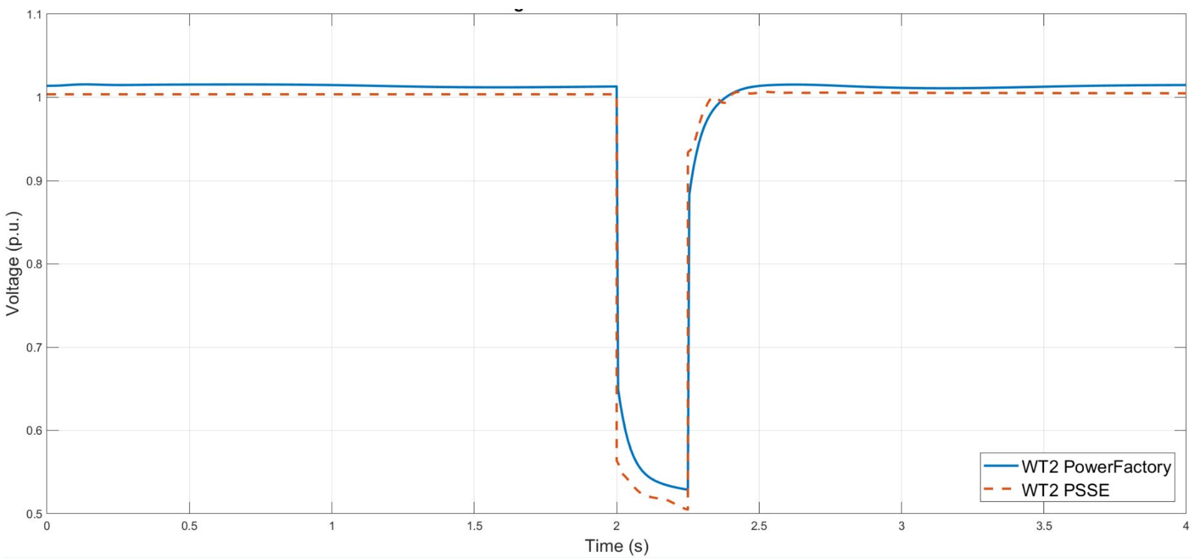

Figure 3.17: Voltage at the terminals of the Wind Turbine type 2.

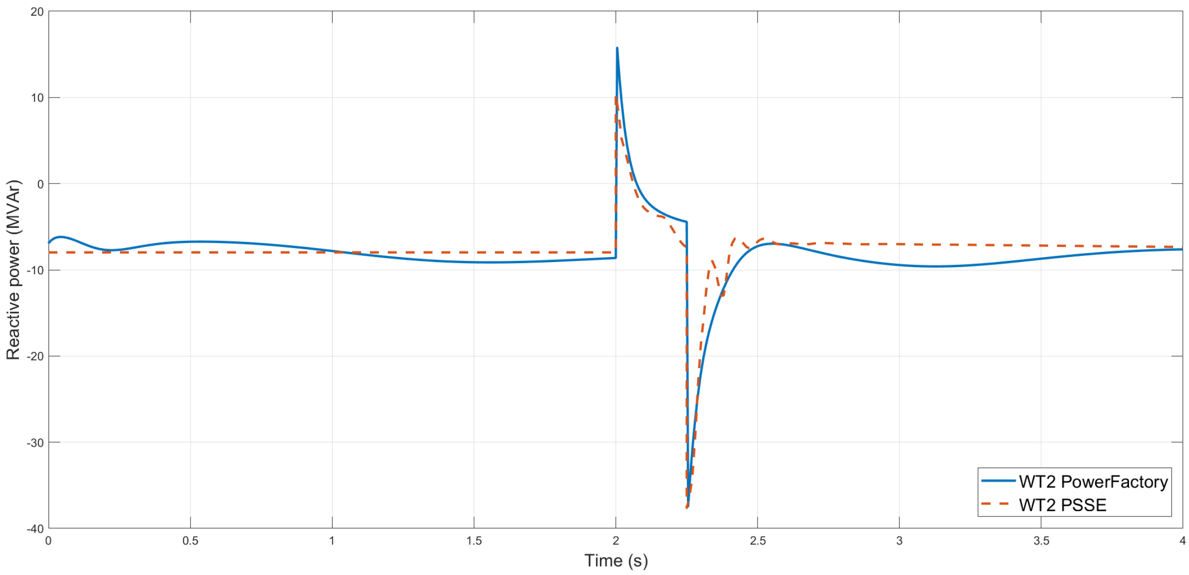

Figure 3.18: Reactive power at the terminals of the Wind Turbine type 2.

SIMULATION FOR WT TYPE 3A AND 4A

The WT type 3A (according to the IEC) was chosen since the WECC model does not include the use of a crowbar. The interest of this work is voltage stability, so the WT type 4A (according to IEC) was chosen. This model does not include the mechanical block that simulates power oscillations.

Used Parameters In general, the parameters for WT type 3A and type 4A were chosen and adapted

to make both models equivalent and not necessarily to have the best behaviour. All the Tables with the proposed parameters can be found in Appendix E.

• **Generator**. Table E.1 shows the parameters used in PSSE for the generator model of WT 3A and 4A. This parameters were chosen according to the WECC Modeling Guidelines [17]. This model is the most different from the IEC standard in these WTs. The parameters used in PowerFactory for the generator model are showed in Table E.2 for the WT3A and in Table E.3 for the case of WT4A. These parameters were the default parameters provided by the software.

• **Q control**. The parameters are showed in Table E.4 for PSSE and in Table E.5 for PowerFactory. These parameters were obtained from [18], the Wind Farm Connection Requirements [20] and the analysis of the reactive control in Section 3.3.1. According to the latter, the Open loop reactive power control was chosen. For the post fault operation state, $Tpost$ and $Thld$ were set to 0 (which means that the post-fault operation will be the normal operation).

• **Q limitation model**. In the IEC standard, there are two options for the *Q limitation model*:

1. *Constant Q limitation model*
2. *QP and QU limitation model*

However, in PSSE only the option 1 exists. In order to have more equivalence between the WECC model and the IEC model, option 1 was the *Q limitation model* chosen. The values for the *Q limitation model* are showed in Table E.12. The parameters were obtained from [18].

• **Current limitation model**. It is included in the electrical control (Table E.4) in the case of PSSE. The parameters of the PowerFactory model are in Table E.11. The parameters were obtained from [18].

• **Mechanical model**. For the WT3A, the parameters used for mechanical model are showed in Table E.6 for the PSSE simulation. This parameters were obtained from the ones used in PowerFactory (Table E.7) using Equations 3.2, 3.3, 3.4 and 3.5. The parameters from PowerFactory are the default parameters provided by the software.

• **P control**. In the case of PSSE, this control can be found in the electrical control (Table E.4) and in the torque control (Table E.9). In the case of PowerFactory, the parameters of this control are showed in TablesE.8 and E.10. All the parameters were obtained from [18].

Results for WT3A

When the Q control is set as it was mentioned in the definition of parameters, the result is not very similar to the WECC model. Besides, the behaviour of the voltage (Figure 3.19) when the fault is created and when the fault is cleared is not the expected one (since WT type 3 has more controls than WT type 2).

After testing the different options for setting the Q control in the IEC model, it was found that the normal operation mode that was used (Open loop reactive power control) is not the best for the IEC model. The modes for the normal operation state that are the most suitable for the IEC model are the ones that use the u_{droop} variable: voltage control, reactive power control and power factor control. For this simulation, the voltage control was chosen. The comparison between the use of open loop reactive power control and the voltage control can be seen in Figure 3.19.

In theory, the open loop reactive control mode for the normal operation was the most similar option to the Q control in the WECC model for normal operation. However, the simulations have proved that the IEC have a better behaviour using the voltage control mode. Besides, this behaviour is also more similar to the WECC model.

Due to the different settings in Q control of IEC and WECC models, to the absence of stator current limit in the WECC model generator and to the fact that the IEC model contains a real current source whereas the WECC model uses an ideal current source, discrepancies can be observed in the voltage behaviour of the IEC model (using voltage control mode) and the WECC model (Figure 3.19).

In Figure 3.20, the I_{qcmd} of the WECC model, the IEC model using open loop reactive control and the IEC model using voltage control can be seen. Again, the I_{qcmd} of the IEC model using the voltage control mode is more similar to the WECC model. It is observed that the injection of reactive power is bigger in the mentioned IEC model than in the WECC model. In this IEC model, there are some oscillations during and after the fault that can be seen in the voltage behaviour (Figure 3.19). The WECC model also has oscillations after the fault, however, these cannot be seen in the voltage behaviour.

In the case of the IEC model using the open loop reactive control, the injection of reactive current has an oscillatory behaviour and several overshoots when the fault is created and cleared that affect the voltage behaviour in Figure 3.19.

Figure 3.21 shows the reactive power behaviour, which corresponds to the I_{qcmd}. Here it is also observed that the IEC model using voltage control is more similar to the WECC model.

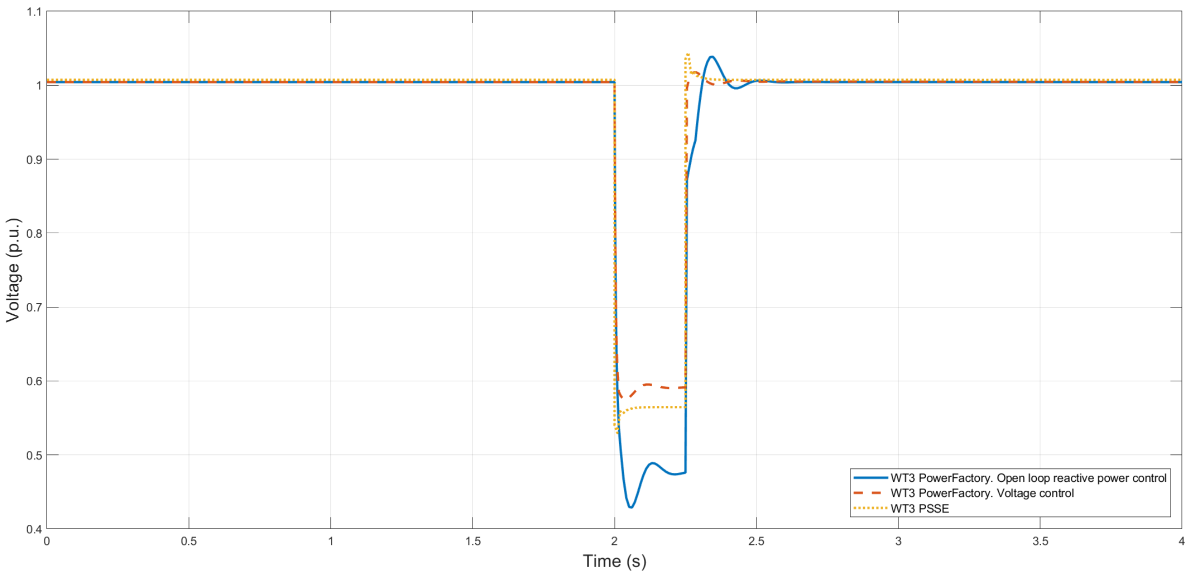

Figure 3.19: Voltage at the terminals of the Wind Turbine type 3A.

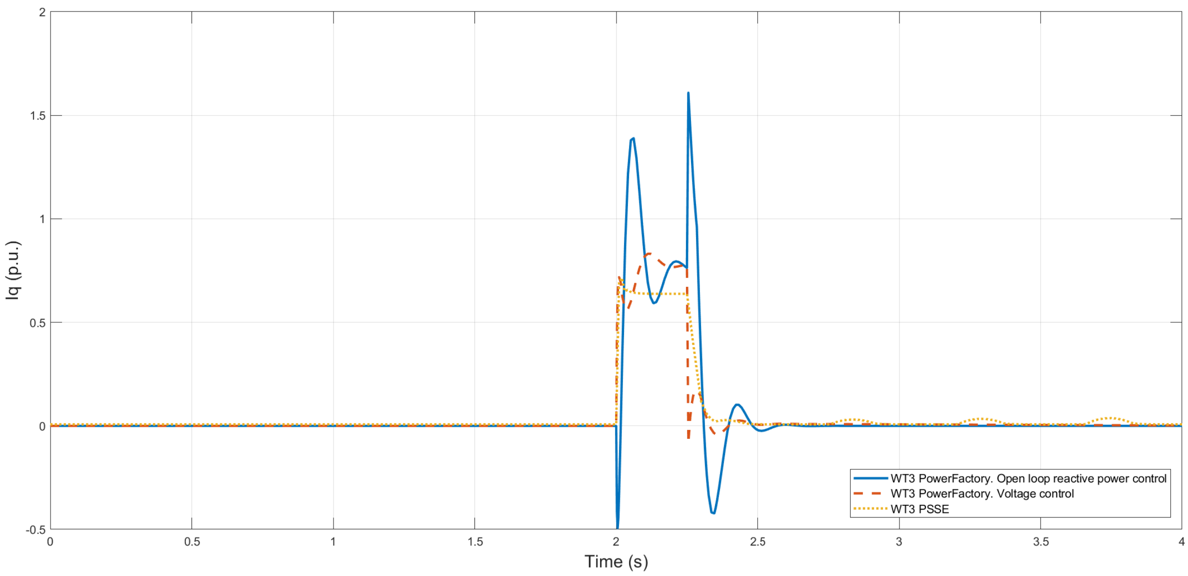

Figure 3.20: Wind Turbine type 3A Iq current.

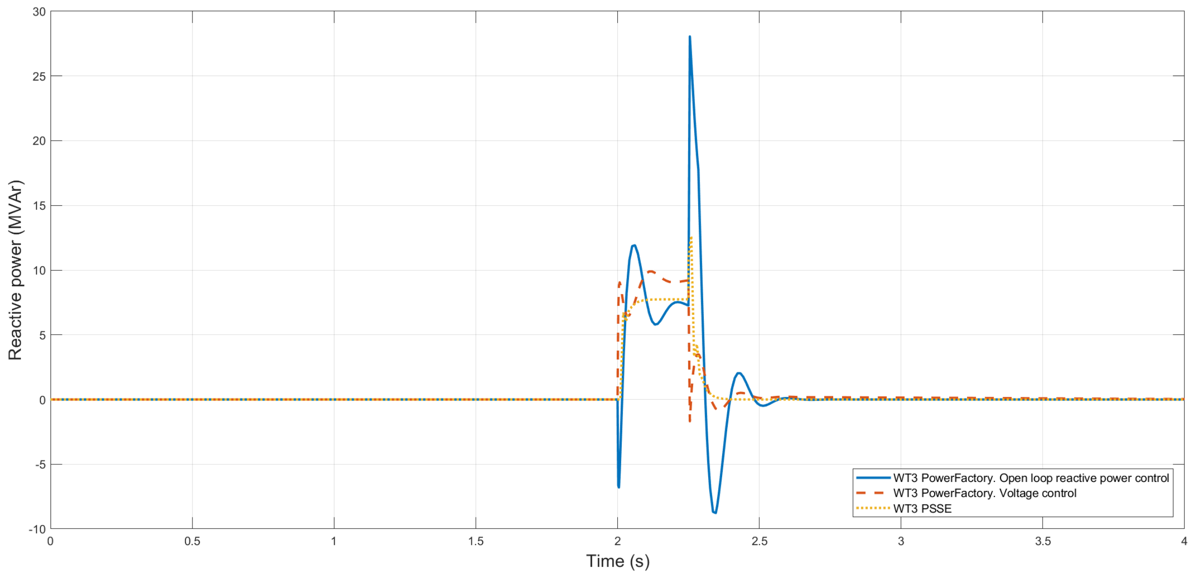

Figure 3.21: Reactive power at the terminals of the Wind Turbine type 3A.

Results for WT4A

Due to the absence of stator current limit in the WECC model generator, some discrepancies can be observed in the voltage at the terminals of the WT (Figure 3.22.) Besides, the IEC model contains a real current source whereas the WECC model uses an ideal current source. A difference of 0.04 pu in voltage is observed during the fault. After the fault, an overshoot can be observed in the WECC model, this disturbance is under study by the authors of [18].

The injection of current, I_{qcmd} can be seen in Figure 3.23). The IEC model has bigger injection of reactive power, and that can be seen in the voltage behaviour, since the IEC model has a smaller dip than the WECC model during the fault.

In Figure 3.24, the reactive power behaviour can be seen. As it is expected from I_{qcmd} in Figure 3.23, more reactive power is injected during the fault in the IEC model.

The differences on the reactive power injection are due to the differences in the Q control (Section 3.3.1).

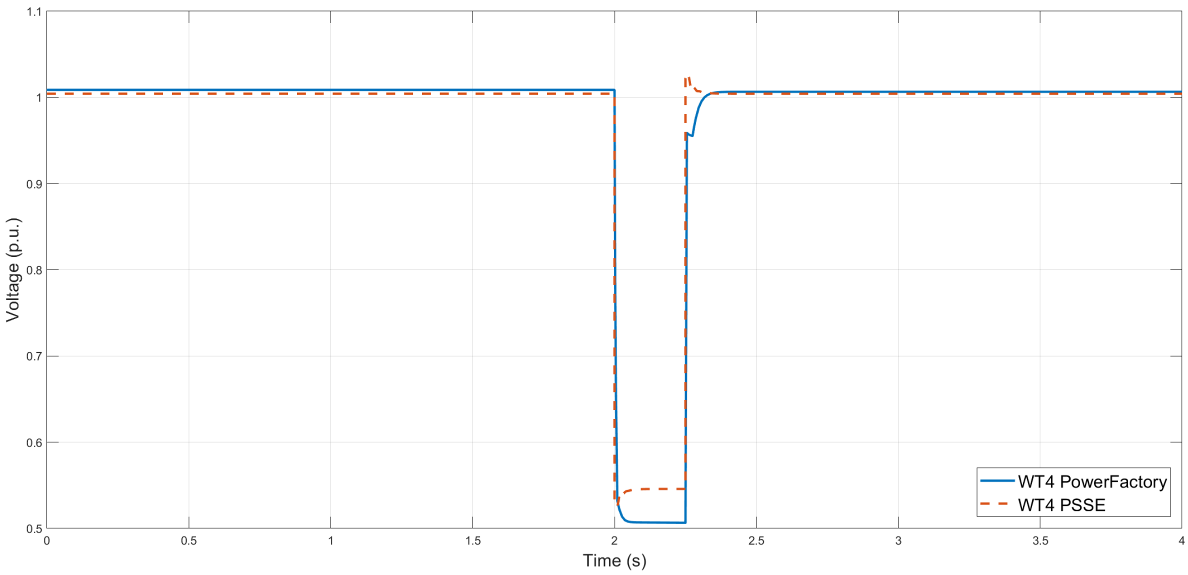

Figure 3.22: Voltage at the terminals of the Wind Turbine type 4.

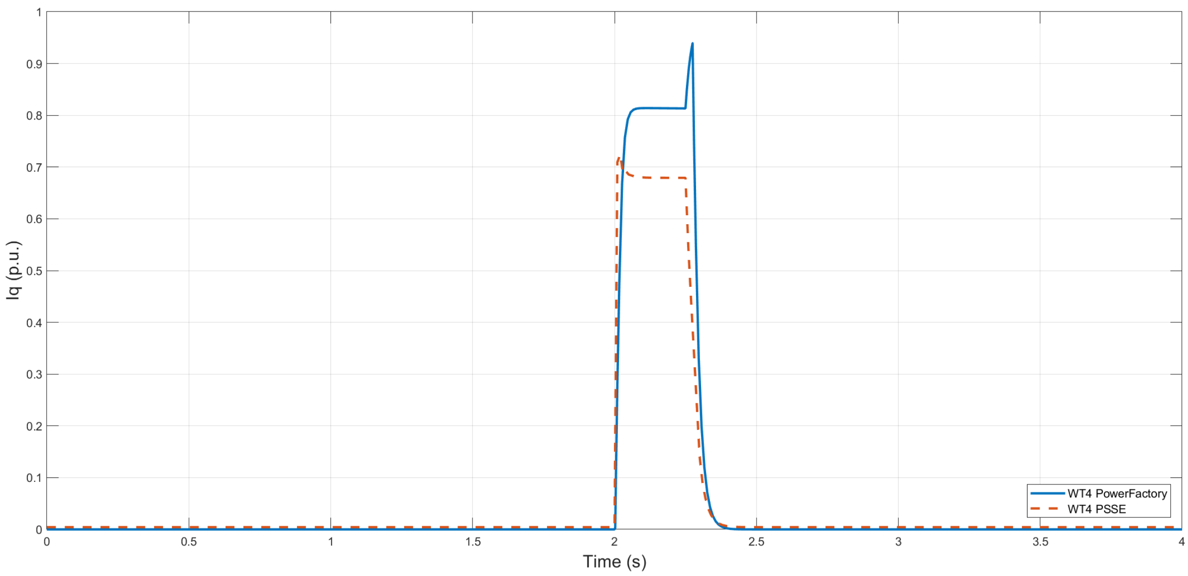

Figure 3.23: Wind Turbine type 4A Iqcmd current.

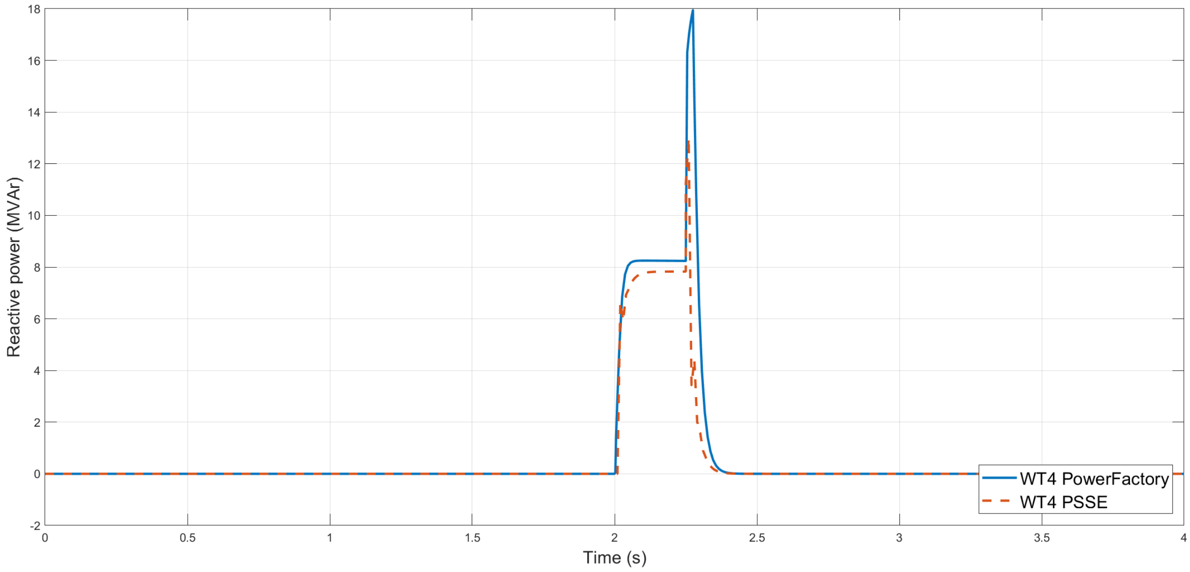

Figure 3.24: Reactive power at the terminals of the Wind Turbine type 4A.

4

Representation of Distributed Wind Turbines of Different Types

In this chapter, a study of the differences in the dynamic voltage response of distributed WTs of different types is going to be performed. These distributed WTs can be represented with a single WT for each type (one for type 1, one for type 2, etc.) or with a combined model, using a single WT for representing two types of WTs. For the latter representation, the results obtained in Chapter 3 are going to be used.

The software used in this Chapter will be PSSE (therefore, WECC models), since it is the software used by TenneT TSO B.V. for dynamic simulations. For representing the distributed WTs, the parameters proposed in Chapter 3 for PSSE are going to be used.

4.1. Case of Study

In order to have real information of distributed WTs in a zone for the analysis of using this two manners of representing distributed WTs, a region in the Netherlands was chosen.

The chosen region was Flevoland, a 150 kV region of the Netherlands where there is a great quantity of wind energy.

4.1.1. Description of Flevoland Region

The region of Flevoland is in the level of 150 kV. Here, there are six substations that receive wind energy:

- Dronten
- Kubbetocht
- Lelystad
- Pampus
- Zuiderveld
- Zeewolde

Based on the classification of Wind Turbines showed in section 2.2, an estimation of the types of WT that can be found in this region are presented in Table 4.1.

Table 4.1: Estimation of Wind Turbines types in Flevoland.

WT type	Percentage %	MW installed
1	15,8	187
2	3,2	38
3	28.0	332
4	52.9	628

In the current dynamic model of this region, the WTs and WPs are represented as negative load directly injected in the 150 kV substations (Figure 4.1).

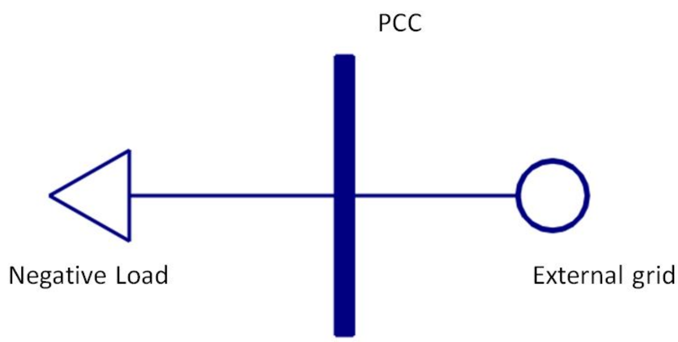

Figure 4.1: Current case in a substation (PCC bus) of Flevoland region and any substation of the Netherlands. The system is represented as an external grid with the corresponding substation short circuit level.

4.2. DETAILED MODELS PROPOSED

The first model proposed is using the four types of WT instead of the negative load. This proposal can be seen in Figure 4.2. This model implies a more complex system where the use of transformers and an underground cable is required. The first transformer (from bus WIND to bus LV) is used to step up the voltage of the WT: 0.69 kV to 20 kV. Then, an underground cable is used for the transport of the energy of the four Wind Turbines. Finally, the voltage is stepped up again in order to be connected to the system at 150 kV.

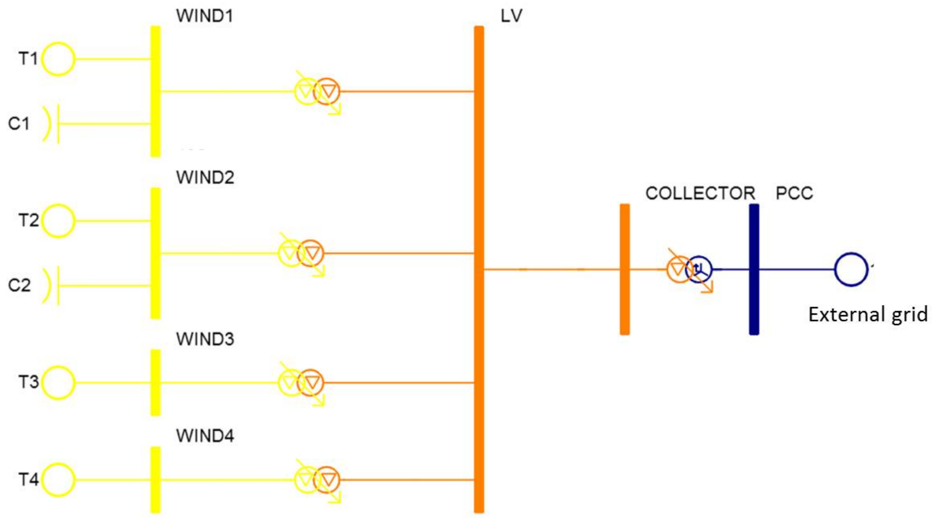

Figure 4.2: First model proposed: four types of Wind Turbines instead of a negative load. The system is represented as an external grid with the corresponding substation short circuit level.

The second model proposed is based on the similar behaviour between WT type 1 and 2 and between WT type 3 and 4 observed in Chapter 3, and based on the percentages of the WTs used in the Netherlands in Table 2.1. For a system with large number of generators, a single WT type 1 can represent WTs type 1 and 2. In the same way, a single WT type 4 can represent WTs type 3 and 4. This statement gives the possibility to simplify a model with four types of WTs into a model with two types of WTs without losing the dynamic behaviour of the different WTs. Using this grouping criterion, a second proposal is made (Figure 4.3).

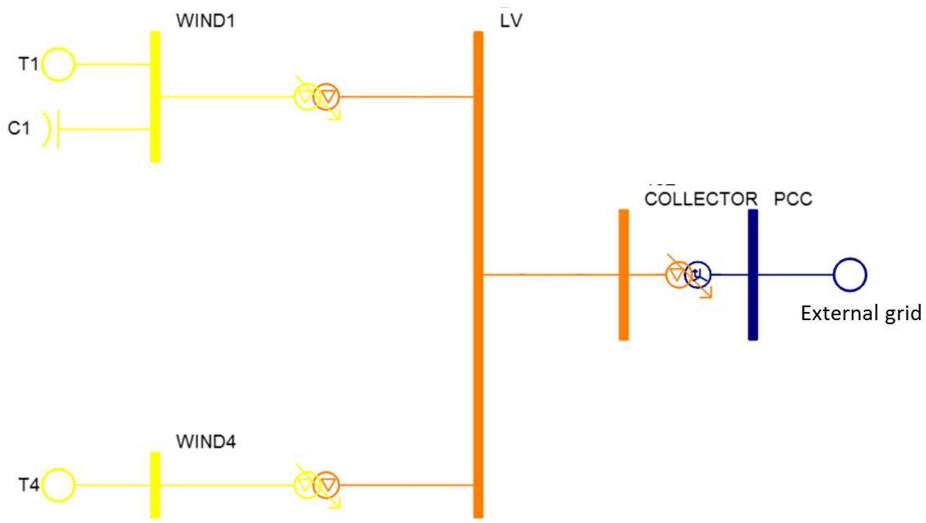

Figure 4.3: Second model proposed: two types of Wind Turbines instead of four types of Wind Turbines. The system is represented as an external grid with the corresponding substation short circuit level.

4.3. Test of the Proposed Models

To see the differences between the current model and the detailed models proposed, and to know if the second proposed model is valid, simulations of each substation were performed and compared. In summary, the cases compared are:

- **Case 1.** Negative Load. Figure 4.1.
- **Case 2.** First proposed model using four types of WTs. Figure 4.2.
- **Case 3.** Second proposed model using a grouping criterion. Figure 4.3.

From now on, the current model and the proposed models will be referred as case 1, case 2 or case 3.

For all the simulations a three phase fault (R=1Ω, X=10Ω) was simulated at second 2 in the PCC bus. The fault was cleared at 2.25 seconds.

4.3.1. Case 1. Negative Load

The chosen snapshot in the dynamic model represents a situation when the wind speed is high. Therefore, the active power injected in the system is also high and the negative loads used in the model are large. For testing this case in each substation, an external grid is needed. The parameter that PSSE uses in an external grid is the short circuit capacity (SCC). These two parameters required for simulating this case are shown in Table 4.2.

4.3.2. Case 2. Use of Four WTs

The generated active power at high wind speed is very close to the installed capacity of the WTs (78,5% of the installed capacity). However, they are not the same. For case 2, the installed capacity and the active power injected in the system were taken into account. By doing this, the reactive power that the WTs can provide during a fault is closer to the reality. These values, provided by TenneT, are shown in Table 4.2. Since the proposed models (case 2 and 3) and the current model were tested in each substation, an external grid is also required, for that, the SCC in each substation is also shown in Table 4.2.

Table 4.2: Parameters of each substation analysed in Flevoland.

Substation	Installed Capacity (MVA)	High Wind Speed Power (MW)	Short Circuit Capacity (MVA)
Dronten	175	137,41	5251
Kubbetocht	80	62,81	5367
Lelystad	71,11	55,84	10445
Pampus	16,55	13	3106
Zuiderveld	12,03	9,45	5687
Zeewolde	356,46	279,89	6147
Zeewolde (Wind Park)	122	95,80	6147

For the first proposed model, the installed capacity and the active power injected at high wind speed were distributed in the four types of WTs according to Table 4.1. The Zeewolde wind power was divided in two cases. The first one, called Zeewolde in the Table 4.2, considers distributed WTs of all the types. The second one, called Zeewolde (Wind Park) in the Table 4.2, considers just the existence of a WP with all the WTs of type 4.

The parameters for the transformers and for the line were the same as the ones used in Chapter 3 in Table 3.8. Only the capacity of the transformers was adjusted.

4.3.3. CASE 3. USE OF GROUPING CRITERION

For the second proposed model, the installed capacity and the active power injected of WT type 2 in the first proposed model were added to the WT type 1. In the same way, the installed capacity and the active power injected of WT type 3 were added to the WT type 4.

The WP of the Zeewolde substation has its own parameters defined by the manufacturer and they will be provided to TenneT TSO B.V. However, for this thesis the parameters were not available, so generic parameters for WT type 4 were also used for this WP. This WP was also grouped with the WT type 4 of the other case of the substation. This was realized only for adding more complexity to the case (taking advantage of not having the correct parameters available), but this assumption cannot be made if the specific parameters for this WP are given.

The idea of this second proposed model, is to have a simplified model with the same behaviour of the first proposed model.

TRANSFORMER EQUIVALENCY

Since for case 3, a group of two WTs is merged into one WT, also an equivalent transformer is needed. This new transformer should not affect the power flow obtained in the case 2. There are two approaches that can be used for doing this.

Case 3a. Parallel transformers

The first approach for obtaining this equivalent transformer is using the parallel impedance of the original transformers. This approach has different impact in the systems: if just two transformers are grouped, the difference between the case 2 and case 3a is not big. It is around 0.1 MVAr (see Figure 4.4), so it could be said that this approach is precise. However, this difference increases as more transformers are grouped. In the Zeewolde substation three transformers were grouped and the difference in reactive power (between case 2 and case 3a) is around 2 MVAr (see Figure 4.5). This approach could be used if just a reduced number of transformers is used (two for example), but is not a very precise method if a large number of transformers has to be grouped.

Case 3b. Muljadi's method

For having higher accuracy no matter the number of transformers used, a method proposed by Muljadi et al. [6] was performed.

For this method, an important consideration is made: all turbines are producing power at rated output [6]. This method of equivalency considers the voltage drop across the transformer impedance, as shown in Figure 4.6.

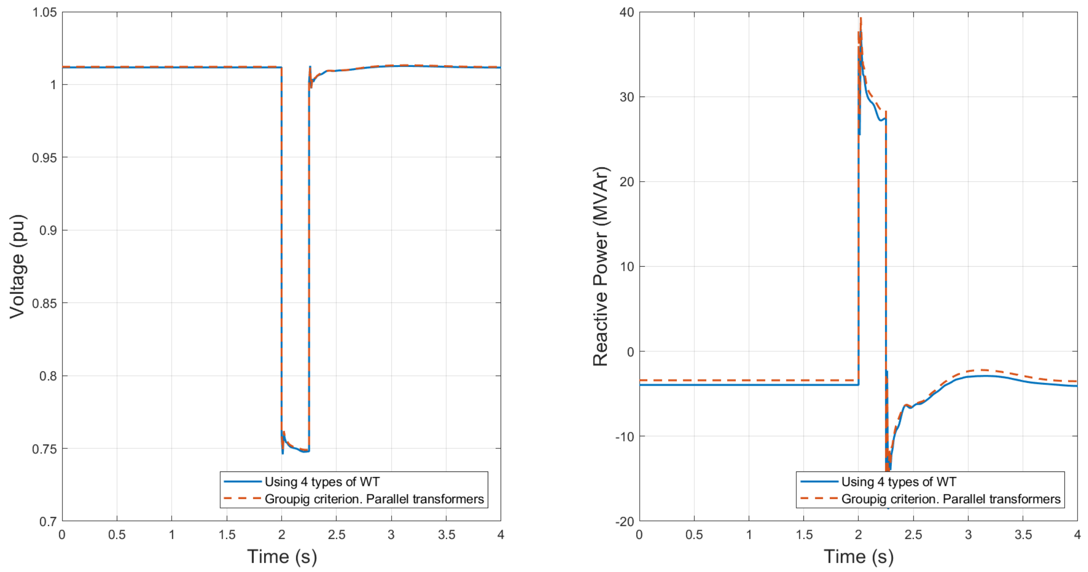

Figure 4.4: Voltage and reactive power at Dronten substation when a fault was created. The equivalent transformers were calculated as a parallel impedance of two transformers used in case 2.

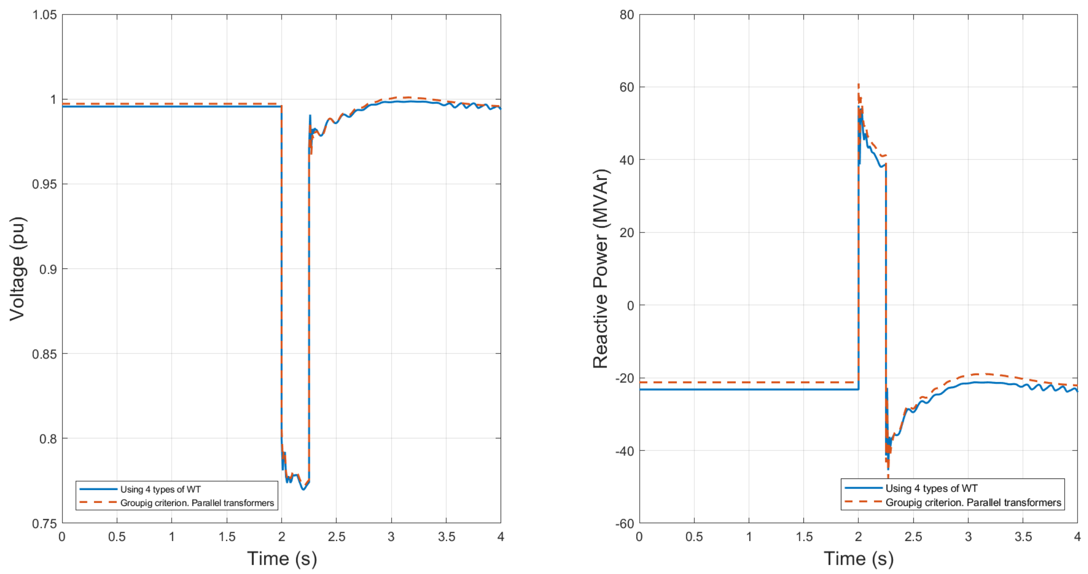

Figure 4.5: Voltage and reactive power at Zeewolde substation when a fault was created.The equivalent transformers were calculated as a parallel impedance of three transformers used in case 2.

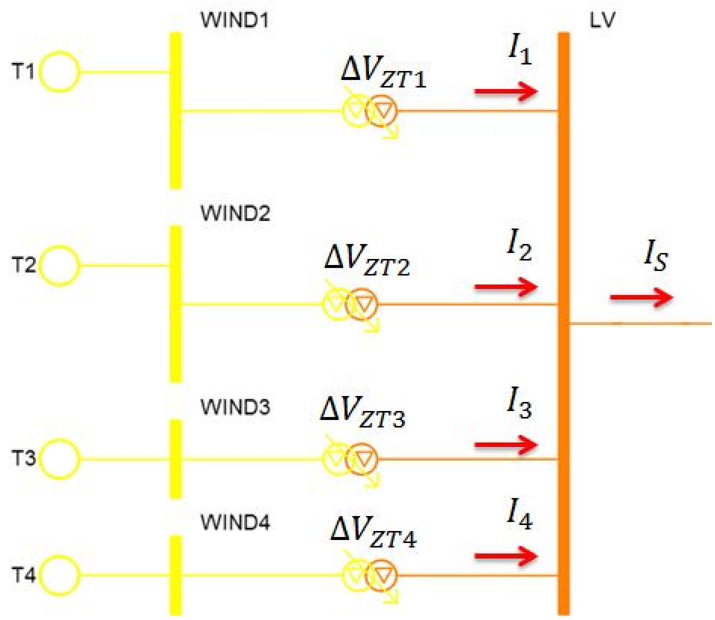

Figure 4.6: Voltage drops across the transformers. The four WT in this example are considered of the same type.

The equations for the voltage drop in the first transformer can be written as shown in Equations 4.1:

$$\Delta V_{ZT1} = I_1 Z_1 \tag{4.1}$$

$$\Delta V_{ZT1} = \left(\frac{S_1}{V} Z_1\right) \tag{4.2}$$

Since the production of the WTs is considered at rated output, S_1 can be substituted by P_1 as shown in Equation 4.3:

$$\Delta V_{ZT1} = \left(\frac{P_1}{V} Z_1\right) \tag{4.3}$$

The losses in each transformer can be expressed as Equations 4.4:

$$S_{Z1} = \Delta V_{ZT1} {I_1}^* \tag{4.4}$$

$$S_{Z1} = P_1 \frac{Z_{T1}}{V} \left(\frac{P_1}{V}\right)^* \tag{4.5}$$

$$S_{Z1} = {P_1}^2 \frac{Z_{T1}}{V^2} \tag{4.6}$$

The voltage drop and the losses for the other three transformers can be expressed in the same way.

If the equivalent system shown in Figure 4.6 is obtained, the equivalent system would be the one shown in Figure 4.7.

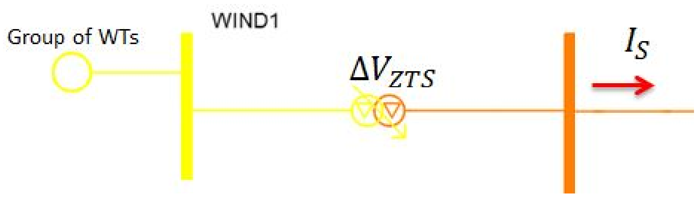

Figure 4.7: Voltage drop across the equivalent transformer.

In this equivalent system, the voltage drop in the transformer can be written as Equation 4.7:

$$\Delta V_{ZTS} = \frac{(P_1 + P_2 + P_3 + P_4)}{V} Z_{TS} \tag{4.7}$$

$$\Delta V_{ZTS} = \frac{P_{Tot}}{V} Z_{TS} \tag{4.8}$$

And the total loss in the equivalent transformer can be expressed as Equation 4.9:

$$S_{ZS} = \Delta V_{ZTS} {I_S}^* \tag{4.9}$$

$$S_{ZS} = {P_{Tot}}^2 \frac{Z_{TS}}{V^2} \tag{4.10}$$

By substitution, Equation 4.11 is derived:

$${P_{Tot}}^2 \frac{Z_{TS}}{V^2} = {P_1}^2 \frac{Z_{T1}}{V^2} + {P_2}^2 \frac{Z_{T2}}{V^2} + {P_3}^2 \frac{Z_{T1}}{V^2} + {P_4}^2 \frac{Z_{T1}}{V^2} \tag{4.11}$$

Finally, a general expression for obtaining an equivalent impedance can be written as Equation 4.12:

$$Z_{TS} = \frac{\sum_{m=1}^{n} {P_m}^2 Z_{Tm}}{\left(\sum_{m=1}^{n} P_m \right)^2} \tag{4.12}$$

Where m is each of the transformers in the system.

In order to compare, this method was applied in the same substations where the parallel impedance calculation was previously used: Dronten and Zeewolde. In Figures 4.8 and 4.9 no difference in the electrical system behaviour is observed, no matter the number of transformers grouped. Besides, for the case 3 in the Flevoland region, the power generated by the WTs is 78.5 % of the rated output. In Figures 4.8 and 4.9 can be seen that this difference is not important when this method is used. The validation when the power generated and the rated output is bigger, is going to be in Section 4.3.3.

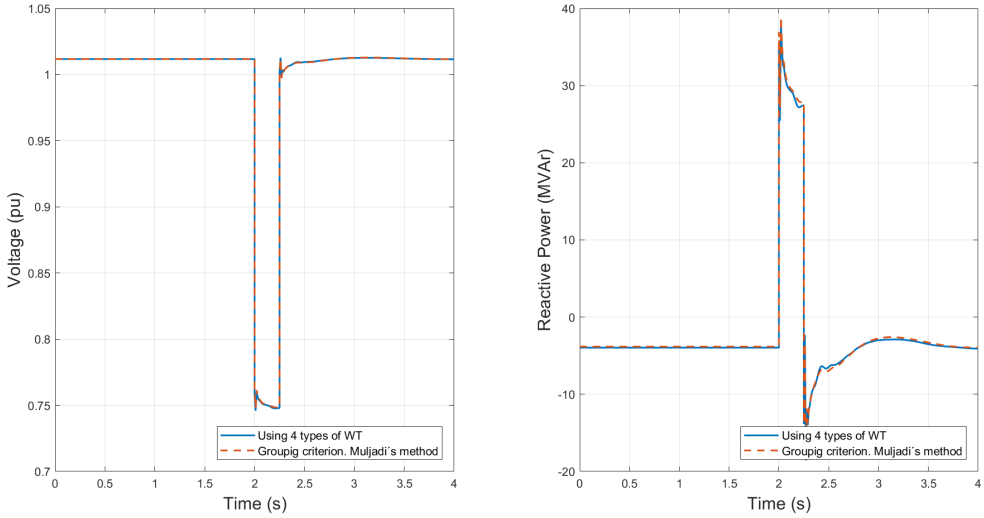

Figure 4.8: Voltage and reactive power at Dronten substation when a fault is created. The equivalent transformers were calculated with the method proposed by Muljadi et al. [6].

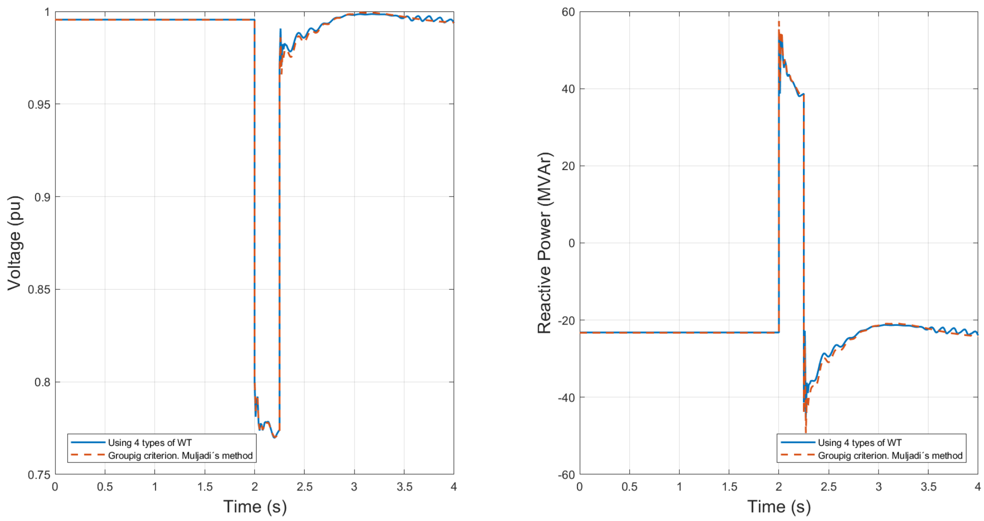

Figure 4.9: Voltage and reactive power at Zeewolde substation when a fault is created. The equivalent transformers were calculated with the method proposed by Muljadi et al. [6].

VALIDATION OF CASE 3B AT LOWER WIND SPEED

When case 2 and case 3 are built using the produced power at low wind speed, the equivalent transformers using the method by Muljadi et al. [6], are still valid (case 3b). This is due to the assumption that all WTs are producing power at rated output when the equivalent transformer is calculated. Therefore, the voltage drop across the transformers is not dependent on the active power that is being generated, the voltage drop is calculated only with the rated output. This way, the model built can be used for different cases: low wind speed, high wind speed, etc. without modifying the electrical system. In Figure 4.10, the Zeewolde substation is showed. Here, the generated power is 50% of the installed capacity, and it can be seen, that the case 2 and case 3b match perfectly. The same substation when the generated power is 20% of the installed capacity is showed in Figure 4.11. It can be seen, that case 2 and case 3b match perfectly.

Moreover, it is observed that the lower the generated power, the higher the reactive power that can be injected during a fault. This is because the difference between the generated power and the rated power output is big, therefore, there is more capacity available for injecting reactive power during a fault. The reactive power injected can be compared using Figures 4.12 and 4.10 or 4.11.

Since the result of this method is the most accurate, valid for a large number of transformers and also for low wind sped, case 3b was used for case 3.

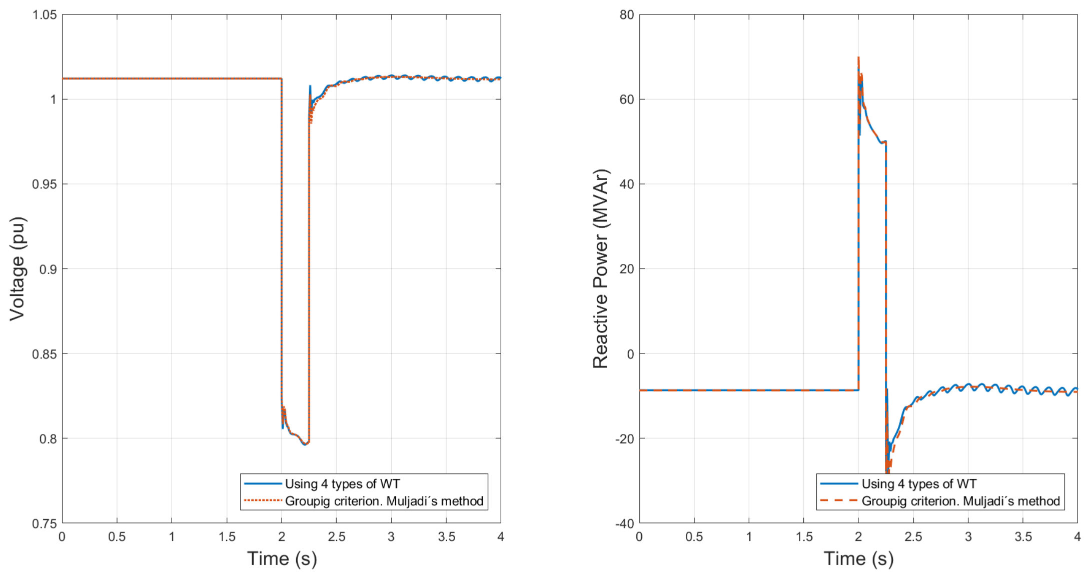

Figure 4.10: Voltage and reactive power at Zeewolde substation where the generated power is 50% of the installed capacity.

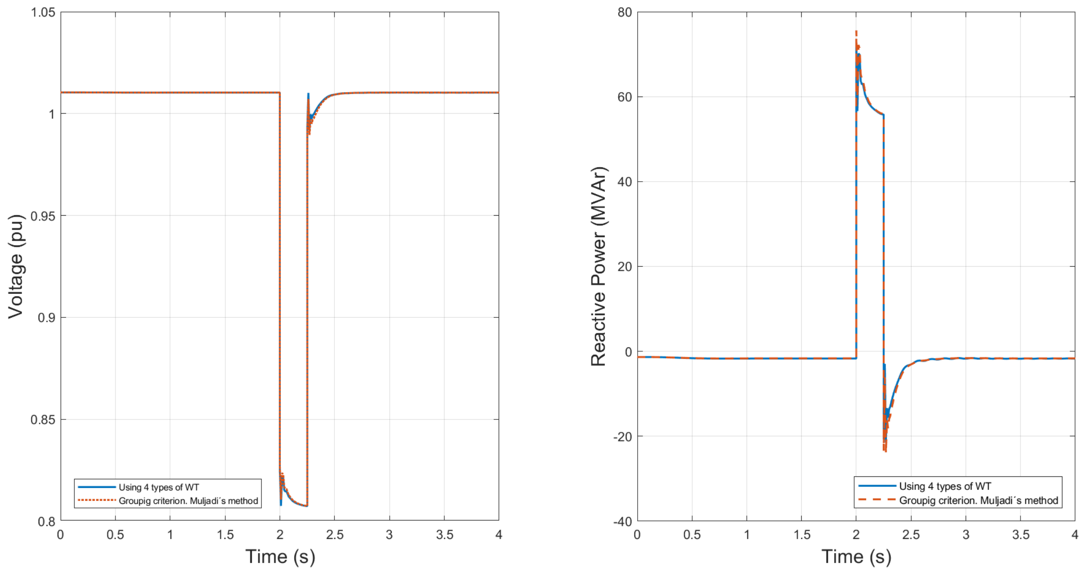

Figure 4.11: Voltage and reactive power at Zeewolde substation where the generated power is 20% of the installed capacity.

4.3.4. IMPACT OF THE WIND ENERGY IN THE SYSTEM

The grid stiffness is determined by the SCC, the higher the SCC, the stronger the grid. In the same way, the SCC determines how big is going to be the impact of having WTs connected to a system: a very strong grid (high SCC) will decrease the impact of WT or WP connected to that system. To measure in some manner the impact that the WTs connected to Flevoland can have, the following ratio (Equation 4.13) is proposed [6]:

$$ImpactRatio = \frac{WT_{capacity}}{SCC} \times 100\% \tag{4.13}$$

This equation gives an estimate of how much impact WTs are going to have. For having specific detail about the impact of the injection of reactive power during a fault on the system, the output power of the WTs should be taken into account (as seen in 4.3.3, the injected reactive power depends on the current output power). It is also important to remember, that only WT type 3 and type 4 can have a contribution of reactive power during a fault.

In Table 4.3, the general impact that WTs have in each substation is presented.

Table 4.3: Impact of Wind Turbines in each substation of Flevoland. The red values show the substation with less impact due to the wind turbines, and the blue values show the substation with the biggest impact due to the wind turbines.

Substation	WT 1	WT 2	WT 3	WT 4	Total impact
Dronten	0,52 %	0,10 %	0,93 %	1,76 %	3,33 %
Kubbetocht	0,23%	0,04 %	0,41 %	0,78%	1,49 %
Lelystad	0,10 %	0,02 %	0,19 %	0,36 %	0,68 %
Pampus	0,08 %	0,01 %	0,14 %	0,28 %	0,53 %
Zuiderveld	**0,03 %**	**0,006 %**	**0,05 %**	**0,11 %**	**0,21 %**
Zeewolde	**0,91 %**	**0,18 %**	**1,62 %**	**5,05 %**	**7,78 %**

COMPARISON OF THE THREE CASES

A simulation for each case and for each substation was performed. Then, a comparison between case 1, case 2 and case 3 was made. The two most relevant cases are shown in this Section.

Zeewolde

Due to the impact of WTs in this substation (see Table 4.3), here is where the biggest difference on using a negative load or WTs can be seen.

The case 3b can be used without problems, since in Figure 4.12 is observed that there is no difference on using case 2 or case 3b.

The result of the injection of reactive power during the fault when having the wind turbines models can be observed in Figure 4.12. The voltage level of case 2 and case 3b during the fault is higher than the level of the model with a negative load.

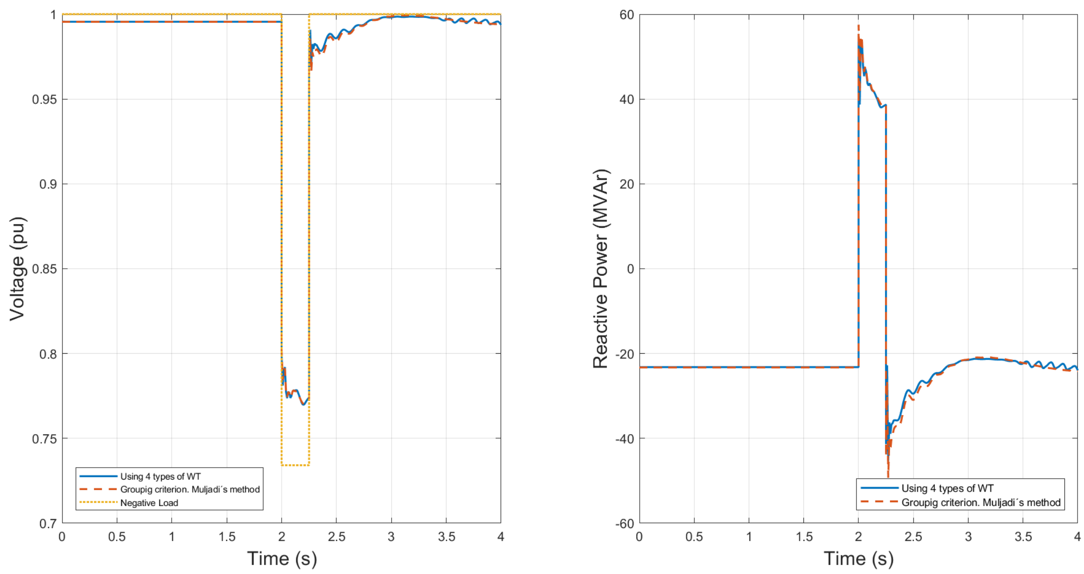

Figure 4.12: Voltage and reactive power of the three cases at Zeewolde substation.

Zuiderveld

Zuiderveld is the substation where the WTs have the lowest impact of all substations. Here, the smallest difference on using a negative load or WTs can be seen.

The case 3b can be used without problems, since in Figure 4.13 is observed that there is no difference on using case 2 or case 3b. However, for cases like this one, the use of WTs models instead of just a negative load does not have a great impact on the voltage level during a fault.

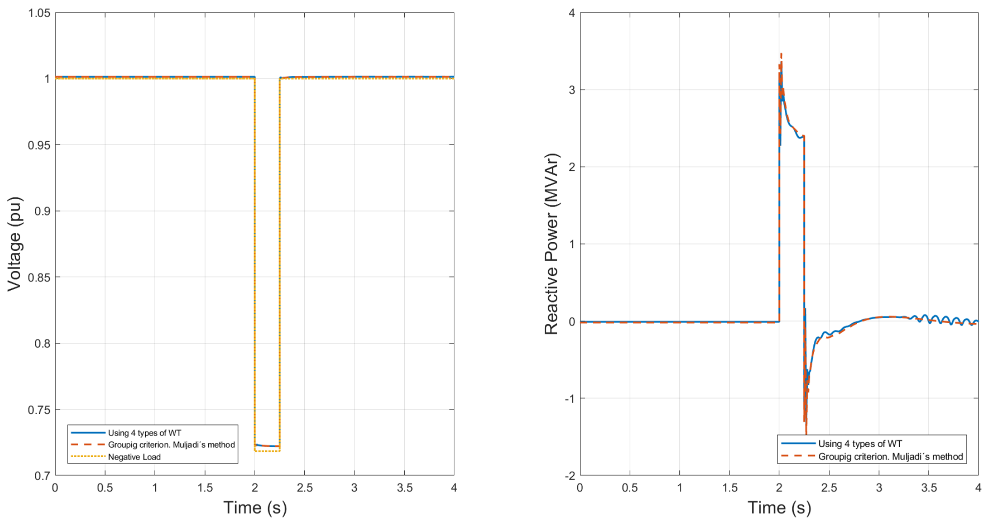

Figure 4.13: Voltage and reactive power of the three cases at Zuiderveld substation.

The first thing that is observed in these substations, is that the method applied for the equivalent transformer in the second proposed model works perfectly no matter the difference between the produced power at high wind speed and the installed capacity (which is quite small in this case).

The second aspect observed in general, is that there is minor difference between the case 2 and the case 3b.

The third aspect is that there are some oscillations in the reactive power after the fault when the four types of WTs are used (mostly in Zeewolde substation). These oscillations are caused by the behaviour of WT type 2, as it can be seen in Figure 3.18. They are reduced when the grouping criterion is applied (case 3b), since WT type 1 is used instead of WT type 2.

4.4. FLEVOLAND REGION MODEL

Since the use of a grouping criterion is valid, and since it a more convenient model than case 2, the next step is to implement the case 3b of each substation in the full model. The implementation was realized using the generated power at high wind speed. In order to see what is the behaviour of the system with this new model, a comparison between the use of WTs (case 3b) and the use of negative load (case 1) was made.

A three phase fault (R=1Ω, X=10Ω) was created in the substation Kubbetocht at 2 seconds and cleared after 0.25 seconds. The voltage level on substations Kubbetocht (Figure 4.14), Zeewolde (Figure 4.15) and Zuiderveld (Figure 4.16) was analysed.

The first thing observed, is that the voltage level before and after the fault (voltage in stationary situation) is different in both cases (case 1 and case 3b). However, the explanation for this situation is straightforward: the electrical system changes when the WTs are added because two transformers and an underground cable are also added to the system.

The second relevant thing in the behaviour is the voltage level during the fault. In the substations Kubbetocht and Zuiderveld, the voltage when using the WTs model is only around 0.005 pu higher than the negative load model when the fault occurs. And in the Zeewolde substation the voltage is around 0.02 pu higher during the fault when the negative load model is used.

If the voltage dip is compared in both cases (case 1 and case 3b), it is observed that in the case of the use of WTs, it is lower. For example, in the case of the Kubbetocht substation, the voltage dip is around 0.36 pu for the negative load model, and around 0.34 for the WTs model. In the case of Zeewolde substation is 0.20 pu for the negative load model and 0.17 pu with the WTs model. This values of voltage dip are according to the *percentage of impact* of the WTs in each substation presented in subsection 4.3.4. The values of voltage dip can be seen in Figures 4.14, 4.15 and 4.16.

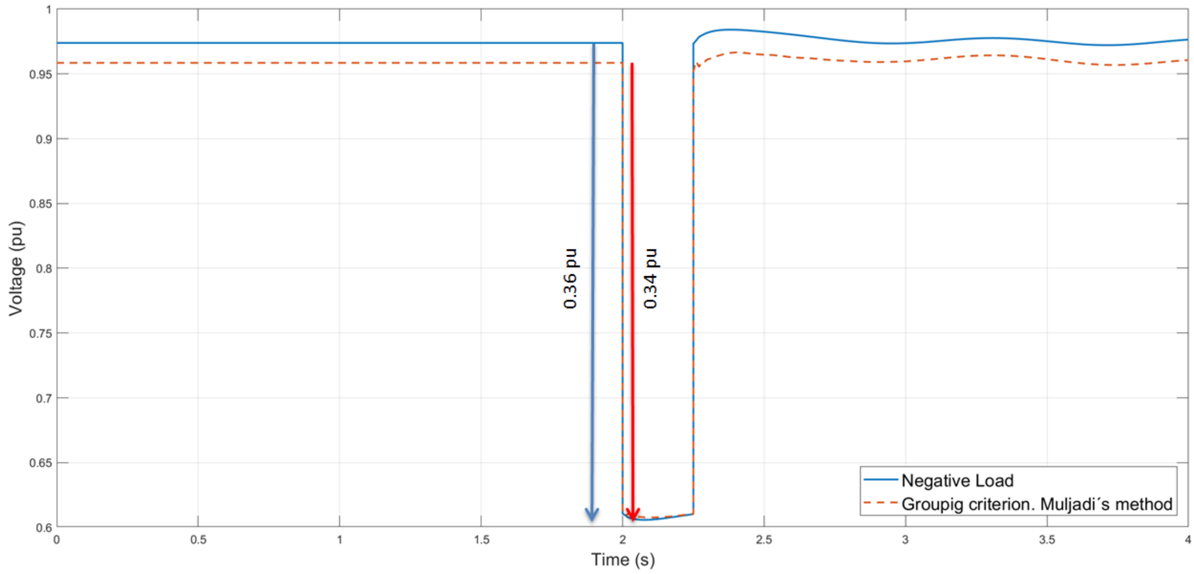

Figure 4.14: Voltage at Kubbetocht substation. Comparison of case 1 and case 3b.

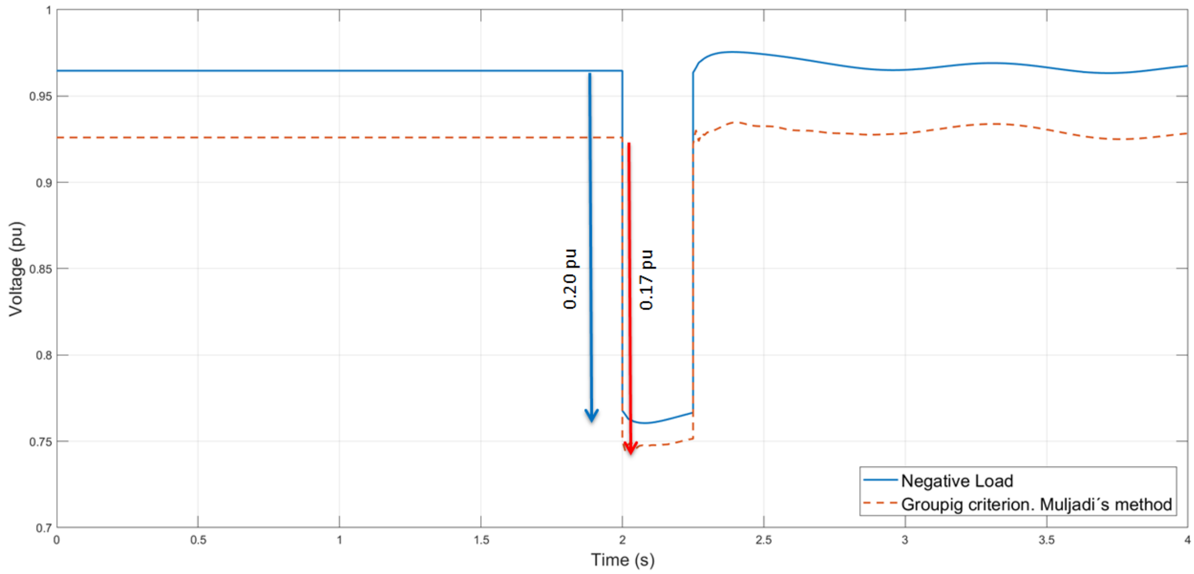

Figure 4.15: Voltage at Zeewolde substation. Comparison of case 1 and case 3b.

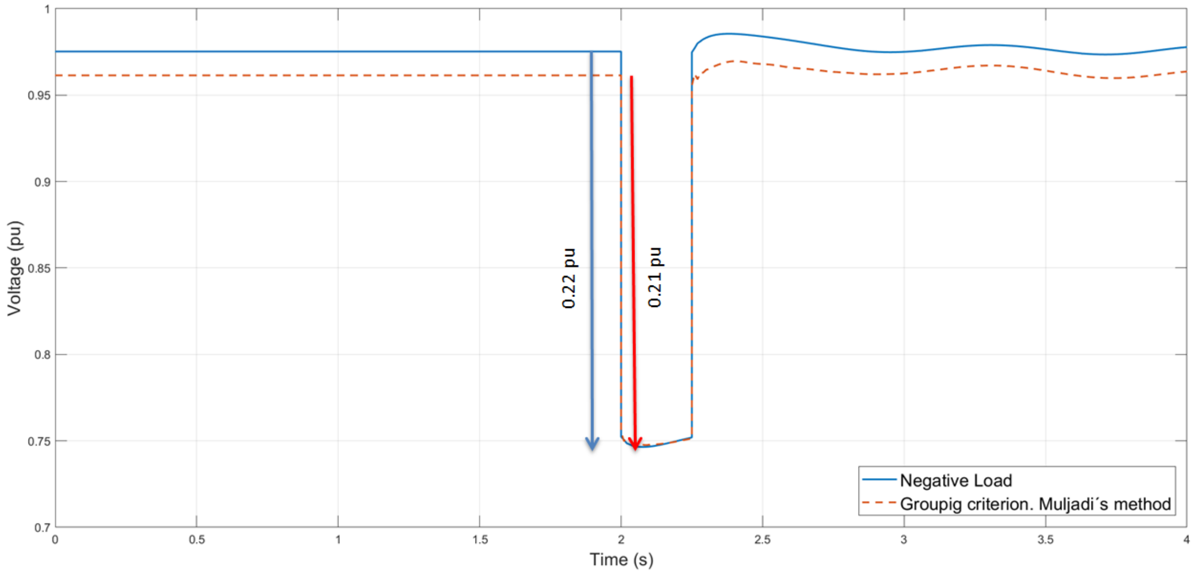

Figure 4.16: Voltage at Zuiderveld substation. Comparison of case 1 and case 3b.

5

Conclusions and Recommendations

In this chapter, the research questions proposed in Chapter 1 will be answered and conclusions for each one will be made. In the last section, some recommendations and future work will be discussed.

5.1. Conclusions

Research question 1: What are the main modelling differences and theoretical limitations IEC and WECC models for single wind turbine representation regarding dynamic voltage response?

The differences between the IEC and WECC models were analysed in a theoretical way, focusing mainly in the reactive control for WT type 3 and 4 in Chapter 3. This analysis was extended with the use of simulations using PowerFactory (for IEC models) and PSSE (for WECC models).

Conclusions for the First Research Question

- The recommendation of the library models usage in PSSE was made choosing the most similar models to the IEC standard.
- The parameters proposed for WTs type 1 and 2 in PSSE and in PowerFactory were suitable for comparing the WECC models with the IEC models.
- The parameters proposed for the WT type 3 in PSSE derived from the theoretical analysis were not the best choice for using them with the IEC models. According to the simulations, the IEC model does not work very well with the open loop reactive control mode (this control mode was chosen based on Section 3.3.1). The control modes that have a better performance in the IEC model are the ones using the variable u_{droop}, therefore, the voltage control was chosen for PowerFactory.
- The parameters proposed for WT type 4 in PSSE and in PowerFactory were suitable for comparing the WECC models with the IEC models.
- In PSSE, the reactive power of WT type 2 there are minor oscillations when the fault is cleared. They last less than 0.5 seconds.
- The voltage response of the WECC models is very similar to the IEC models, however, it is not the same. This discrepancies are due to the different asynchronous generator model used in PSSE and in PowerFactory for WTs type 1 and 2 (transient and subtransient variables are only

appearing in the WECC model). In the case of WTs type 3 and 4, the discrepancies are due to the differences in the generator model (IEC model uses a real current source and WECC model uses an ideal current source in the generator model) and in the reactive control used in PowerFactory and in PSSE (IEC model uses the u_{droop} variable that does not exist in the WECC model).

- Regardless of the software used, it is observed that WT type 1 and WT type 2 have a similar behaviour.
- Regardless of the software used, it is observed that WT type 3 and WT type 4 have a similar behaviour.

Research question 2: What are the main differences in the dynamic voltage response when distributed WTs of different types are represented in a single turbine representation and in a combined model?

For answering the second research question, the Flevoland region was used as study case. Three situations were analysed:

1. Case 1.Current model using negative load.
2. Case 2.First proposed model using four types of WTs.
3. Case 3.Second proposed model using a grouping criterion (use only of WT type 1 and 4).

The software used for this part of the thesis was only PSSE and the parameters used for WTs were the generic parameters proposed as a result of the first research question.

CONCLUSIONS FOR THE SECOND RESEARCH QUESTION

- When there is a large number of generators and the use of WTs type 1 is predominant, WTs type 1 and 2 can be grouped using only WT type 1.
- When there is a large number of generators and the use of WTs type 4 is predominant, WTs type 3 and 4 can be grouped using only WT type 4.
- Cases 2 and 3 require the use of transformers and an underground cable, whereas case 1 does not use any of this electrical components.
- For the equivalent transformers needed in case 3, Muljadi et al. method is more accurate than obtaining the parallel impedance of the transformers.
- Muljadi et al. method for obtaining the equivalent transformers needed in case 3, is valid for low and high wind speed. It also has the same accuracy regardless of the number of transformers.
- When Muljadi et al. method is used for case 3, case 2 and case 3 can be used indistinctly. However, the advantage of using case 3 is that less components are needed in the model. Besides, minor oscillations in the reactive power due to WT type 2 are eliminated.
- There is a difference in the voltage level during the fault when case 1 is used compared to case 2 or 3. However, this difference depends on the impact that the WTs have. In some cases, like Zuiderveld substation, this impact is so low, that there is almost no difference on using WTs or just a negative load.

- The impact that WTs have can be deterimed as a ratio between the WTs' capacity and the SCC.
- When the case 3 (using Muljadi et al. method for the equivalent transformers) was implemented in the full model of Flevoland, and was compared to case 1, a difference in the stationary voltage is observed. This difference is due to the use of the electrical components that case 1 does not use.
- The voltage dip decreases when WTs are used in the full model of Flevoland. However, their impact in the system is very low yet.

5.2. RECOMMENDATIONS AND FUTURE WORK

1. The parameters used for the WTs type 3 and 4 in this work were chosen for having a similar behaviour between the IEC and the WECC models, however, they are not the best ones in terms of dynamic behaviour. For example, the response of the reactive control in post-fault situation was omitted and replaced for the normal operation. With respect to the latter, more research in the use of different parameters could be realized.
2. The scope of this work was the dynamic voltage response, but there are some other aspects like the frequency response or the rotor angle stability that can be also studied. For studying these aspects, the proposed parameters have to be tested, in order to see if they are suitable for that studies.
3. Since some of the models used in PSSE are also suitable for PV generation, a similar work to this thesis can be done regarding solar energy.

A

MODELS

Table A.1: Wind Turbine and Wind Power Plant models available in PSSE 34.

	Generator	Electrical control	Mechanical model	Pitch control	Aerodynamic model	Torque control	Plant control
Wind Turbines							
WT 1	WT1G1		WT12T1		WT12A1		
WT 2	WT2G1	WT2E1	WT12T1		WT12A1		
WT 3 (1)	WT3G1	WT3E1	WT3T1	WT3P1			
WT 3 (2)	REGCA1	REECA1	WTDTA1	WTPTA1	WTARA1	WTTQA1	
WT 4 (1)	WT4G1	WT4E1					
WT 4 (2)	REGCA1	REECA1	Optional: WTDTA1				
Wind Power Plants							
WP 3	REGCA1	REECA1	WTDTA1	WTPTA1	WTARA1	WTTQA1	REPCTA1
WP 4	REGCA1	REECA1	Optional: WTDTA1				REPCA1

B

Analysis of reactive control of IEC and WECC standars

Table B.1: State 0. Normal Operation

State 0. Normal operation	
IEC	**WECC**
Voltage control	
Flags: MqG=0 The voltage $X_{WTref} + u_{ref0}$ is compared with u_{droop}. The resultant voltage error will be approached to zero by a PI controller. The output of this controller is the current I_{qcmd}.	Flags: PfFlag=0, VFlag=0, QFlag=1 The voltage $Q_{ref} + V_{bias}$ is compared with the voltage at the terminals Vt_filt. The resultant voltage error will be approached to zero with a PI controller. The output of this controller is the current I_{qcmd}.
Differences: - Use of u_{droop} in IEC model instead of Vt_filt.	
Reactive power control (for WP)	
Flag: MqG=1 I_{qcmd} is obtained by using two PI controllers. The first one will approach to zero the reactive power error obtained when X_{WTref} and q_{WT} (reactive power at the terminals of WT) are compared. The second one will deliver the I_{qcmd} by approaching the voltage error to zero. This error is obtained comparing the output of the first PI and u_{droop}.	Flags: PfFlag=0, VFlag=1 , QFlag=1 I_{qcmd} is obtained by using two PI controllers. The first one will approach to zero the reactive power error obtained when Q_{ref} and q_{WT} (reactive power at the terminals of WT) are compared. The second one will deliver the I_{qcmd} by approaching the voltage error to zero. This error is obtained comparing the output of the first PI and the voltage at the terminals Vt_filt (this variable is filtered).
Differences: - Use of u_{droop} in IEC model instead of Vt_filt.	

Table B.1 continued from previous page

State 0. Normal operation	
Open loop reactive power control (for WT)	
Flag: MqG=2 X_{WTref} (reactive power constant) and u_{WT} (voltage at the terminals of WT) are filtered. $I_{qcmd} = \frac{X_{WTref\_filt}}{u_{WT\_filt}}$	Flags: PfFlag=0, VFlag=0, QFlag=0 A current Iq is firstly obtained: $I_q = \frac{Q_{ref}}{Vt\_filt}$ Afterwards Iq is filtered: $I_{qcmd} = I_q\_filt$.
Differences: - The signals in the IEC are filtered before obtaining I_{qcmd}. In the WECC Q_{ref} is not filtered, only the current obtained with Q_{ref} and Vt_filt.	
Power factor control (for WP)	
Flag: MqG=3 I_{qcmd} is obtained by using two PI controllers. The first one will approach to zero the reactive power error obtained when q_{input} and q_{WT} (the reactive power at the terminals of the WT) are compared. q_{input} is obtained with the filtered active power at the terminals of the WT p_{WT}. $q_{input} = p_{WT\_filt} \times \tan(\phi_{init})$ The second one will deliver the I_{qcmd} by approaching the voltage error to zero. This error is obtained comparing the output of the first PI and u_{droop}.	Flags: PfFlag=1, VFlag=1, QFlag=1 I_{qcmd} is obtained by using two PI controllers. The first one will approach to zero the reactive power error obtained when q_{input} and $Qelec$ (the reactive power at the terminals of the WT) are compared. $Qelec$ is obtained with the filtered active power at the terminals of the WT ($Pelec$): $q_{input} = Pelec\_filt \times \tan(\phi_{init})$ The second one will deliver the I_{qcmd} by approaching the voltage error to zero. This error is obtained comparing the output of the first PI and the voltage at the WT terminals Vt_filt.

Table B.1 continued from previous page

State 0. Normal operation	
Differences: - Use of u_{droop} in IEC model instead of Vt_filt.	
Open loop power factor control (for WT)	
Flag: MqG=4 $q_{input} = p_{WT\_filt} \times \tan(\phi_{init})$ After that, q_{input} is filtered and I_{qcmd} is obtained: $I_{qcmd} = \frac{q_{input\_filt}}{u_{WT\_filt}}$	Flags: PfFlag=1, VFlag=0, QFlag=0 q_{input} is obtained firstly. Afterwards, I_q is obtained. $q_{input} = Pelec\_filt \times \tan(\phi_{init})$ $I_q = \frac{q_{input}}{Vt\_filt}$ Finally I_q is filtered $I_{qcmd} = I_q\_filt$
Differences: - The signals in the IEC are filtered before obtaining I_{qcmd}. In the WECC q_{input} is not filtered, only the current obtained with q_{input} and Vt_filt.	

Table B.2: State 1. Fault Operation

State 1. Fault operation	
IEC	**WECC**
Voltage dependent reactive current injection	
Flag: MqUVRT=0 The current I_{qcmd} is obtained as the voltage at the terminals of WT (filtered), multiplied by a gain (units are I/U). $I_{qcmd} = u_{WT\_filt} \times K_{qv}$	The I_{qcmd} is obtained as a gain multiplied by the voltage error between the voltage at the WT terminals (filtered) and the voltage reference: $I_{qcmd} = \left(V_{ref0} - Vt\_filt\right) \times K_{qv}$ This case is only comparable if $V_{ref0} = 0$
Differences: - Both standards calculate the I_{qcmd} using the voltage at the terminals of the WT. However, the sign of this variable is positive in the case of IEC standard and negative in the case of the WECC standard.	
Reactive current injection controlled as the pre-fault value plus an additional voltage dependent reactive current injection	
Flag: MqUVRT=1 and MqUVRT=2 The I_{qcmd} is obtained as the sum of the pre-fault current (that depends on the MqG chosen) and: $I_{qv} = u_{WT\_filt} \times K_{qv}$	This mode of operation does not exist in the WECC model.

Table B.3: State 2. Post Fault Operation

State 2. Post Fault operation	
IEC	**WECC**
Voltage dependent reactive current injection and Reactive current injection controlled as the pre-fault value plus an additional voltage dependent reactive current injection	
Flag: MqUVRT=0 and MqUVRT=1 During $Tpost$: the current I_{qcmd} is obtained as the voltage at the terminals of WT (filtered), multiplied by a gain (units are I/U). $I_{qcmd} = u_{WT\_filt} \times K_{qv}$ After $Tpost$, state 0 is reached again.	For Thld<0 During $Thld$: the I_{qcmd} is obtained as a gain multiplied by the voltage error between the voltage at the WT terminals (filtered) and the voltage reference: $I_{qcmd} = \left(V_{ref0} - Vt\_filt\right) \times K_{qv}$ After $Thld$, state 0 is reached again. This case is only comparable if $V_{ref0} = 0$
Differences: - The IEC works directly with the voltage at the terminals of the WT, while the WECC uses the voltage error between the terminals and the reference.	
Reactive current injection controlled as the pre-fault value plus an additional constant reactive current injection post fault	
MqUVRT=2 The I_{qcmd} is obtained as the sum of the pre-fault current (that depends on the MqG chosen) and a constant defined by the user ($iqpost$).	For Thld>0 $I_{qcmd} = I_{qfrz}$ Where I_{qfrz} is a current value (in pu) defined by the user.
Differences: - The WECC model does not work with a pre-fault current.	

C

Parameters for Wind Turbine type 1

Table C.1: Parameters for model WT1G1 (generator) in PSSE.

Name	Description	Unit	Value
T	Open circuit transient time constant	s	0.846
T”	Open circuit subtransient time constant	s	0 *
X	Synchronous reactance	pu	3.5
X’	Transient reactance	pu	0.1773
X”	Subtransient reactance	pu	0 *
Xl	Leakage reactance	pu	0.1
E1		-	1
S(E1)	Saturation factor at 1 pu flux	-	0.030
E2		-	1.2
S(E2)	Saturation factor at 1.2 pu flux	-	0.1790

* values for single cage

Table C.2: Parameters for model WT12T1 (mechanical model) in PSSE.

Name	Description	Unit	Value
H	Total inertia constant	s	5.3
DAMP	Machine damping factor	pu P/pu	0
H_{tfrac}	Turbine inertia fraction	(Hturb/H)1	0.9180
Freq1	First shaft torsional resonant frequency	Hz	5
Dshaft	Shaft damping factor	pu	1

Table C.3: Parameters for the generator model in PowerFactory.

Name	Description	Unit	Value
Rs	Stator resistance	pu	0
Xm	Mag. reactance	pu	3.5
Xs	Stator reactance	pu	0.1
RrA	Rotor resistance	pu	0.01
XrA	Rotor reactance	pu	0.1

Table C.4: Parameters for the two mass model model (mechanical model) in PowerFactory.

Name	Description	Unit	Value
HWTR (ht)	Inertia constant of wind turbine rotor	s	5
cdrt	Drive train damping	Tb/wb	0.5
kdrt	Drive train stiffness	Tbase	100

D

PARAMETERS FOR WIND TURBINE TYPE 2

Table D.1: Parameters for Model WT2G1 (generator) in PSSE.

Name	Description	Unit	Value
XA	Stator reactance	pu	0.1
XM	Magnetizing reactance	pu	3.5
X1	Rotor reactance	pu	0.1
R_ROT_MACH	Rotor resistance	pu	0.01
R_ROT_MAX	A sum of R_ROT_MACH and total external resistance	pu	0.1155
E1	First saturation coordinate	-	1
SE1	First saturation factor	-	0
E2	Second saturation coordinate	-	1.2
SE2	Second saturation factor	-	0
POWER_REF_1	First of 5 coordinate pairs of the power-slip curve	-	0
POWER_REF_2		-	0.25
POWER_REF_3		-	0.5
POWER_REF_4		-	0.75
POWER_REF_5		-	1
SLIP_1	First of 5 coordinate pairs of the power-slip curve	-	0
SLIP_2		-	0.125
SLIP_3		-	0.25
SLIP_4		-	0.375
SLIP_5		-	0.5

Table D.2: Parameters for model WT2E1 (electrical control) in PSSE.

Name	Description	Unit	Value
T_{sP}	Rotor speed filter time constant	s	0.0500
T_{pe}	Power filter time constant	s	0.0500
T_i	PI-controller integrator time constant	s	1
K_p	PI-controller proportional gain	pu	1
ROTRV_MAX	Output MAX limit	-	0.9900
ROTRV_MIN	Output MIN limit	-	0.05

Table D.3: Parameters for the Generator model in PowerFactory.

Name	Description	Unit	Value
Rs	Stator resistance	pu	0.1
Xm	Mag. reactance	pu	3.5
Xs	Stator reactance	pu	0.1
RrA	Rotor resistance	pu	0.01
XrA	Rotor reactance	pu	0.1

Table D.4: Parameters for the rotor control of WT2 in PowerFactory.

Name	Description	Unit	Value
$T_{pfiltrr}$	Filter time constant for power measurement	s	0.01
K_{pfilt}	Filter gain for power measurement	-	1
$T_{\omega filtrr}$	Filter time constant for generator speed measurement	s	0.01
$K_{\omega filt}$	Filter gain for generator speed measurement	-	1
$p_{rr}(\Delta\,\omega)$	Power versus speed change (negative slip) lookup table	P_n	*
K_{Prr}	Proportional gain in rotor resistance PI controller	Z_{base}/P_n	0.5
K_{Irr}	Integral gain in rotor resistance PI controller	$Z_{base}/P_n/s$	1
r_{max}	Maximum rotor resistance	Z_{base}	5
r_{min}	Minimum rotor resistance	Z_{base}	0.01

* See corresponding lookup table in Table D.1

E

PARAMETERS FOR WIND TURBINE TYPE 3 AND 4

Table E.1: Parameters for model REGCA1 (generator model) in PSSE (for WT3A and WT4A).

Name	Description	Unit	Value
Lvplsw	(Low Voltage Power Logic) switch (0: LVPL not present, 1:LVPL present)	-	1
T_g	Converter time constant	s	0.0200
Rrpwr	Low Voltage Power Logic (LVPL) ramp rate limit	pu/s	10
Brkpt	LVPL characteristic voltage 2	pu	0.900
Zerox	LVPL characteristic voltage 1	pu	0.400
Lvpl1	LVPL gain	pu	1.1
Volim	Voltage limit for high voltage reactive current management	pu	1.2
Lvpnt1	High voltage point for low voltage active current management	pu	0.800
Lvpnt0	Low voltage point for low voltage active current management	pu	0.400
Iolim	Current limit for high voltage reactive current management	pu	-1
Tfltr	Voltage filter time constant for low voltage active current management	s	0.0100
Khv	Overvoltage compensation gain used in the high voltage reactive current management	-	0.700
Iqrmax	Upper limit on rate of change for reactive current	pu	9999
Iqrmin	Lower limit on rate of change for reactive current	pu	9999
Accel	Accel, acceleration factor	-	0.5

Table E.2: Parameters for the generator model of WT3A in PowerFactory.

Name	Description	Unit	Value
K_{Pc}	Current PI controller proportional gain	-	40
T_{Ic}	Current PI controller integration time constant	s	0.0200
x_s	Electromagnetic transient reactance	Z_{base}	0.4
di_{pmax}	Maximum active current ramp rate	I_n/s	9999
di_{qmax}	Maximum reactive current ramp rate	I_n/s	9999

Table E.3: Parameters for the generator model of WT4A in PowerFactory.

Name	Description	Unit	Value
Tg	Time constant	s	0.02
di_{qmin}	Minimum reactive current ramp rate	I_n/s	-9999
di_{pmax}	Maximum active current ramp rate	I_n/s	9999
di_{qmax}	Maximum reactive current ramp rate	I_n/s	9999

Table E.4: Parameters for model REECA1 (electrical control) in PSSE (for WT3A and WT4A).

Name	Description	Unit	Value
PFFLAG	1 if power factor control, 0 if Q control	-	0
VFLAG	1 if Q control, 0 if voltage control	-	0
QFLAG	1 if voltage or Q control, 0 if constant pf or Q control	-	0
PFLAG	1 if active current command has speed dependency, 0 for no dependency	-	0
PQFLAG, P/Q	(for current limiter) 0 for Q priority, 1 for P priority	-	0
Vdip	low voltage threshold to activate reactive current injection logic	pu	0.9
Vup	Voltage above which reactive current injection logic is activated	pu	1.1
Trv	Voltage filter time constant	s	0.01
dbd1	Voltage error dead band lower threshold	pu	-0.1
dbd2	Voltage error dead band upper threshold	pu	0.1
Kqv	Reactive current injection gain during over and undervoltage conditions	pu	2
Iqh1	Upper limit on reactive current injection Iqinj	pu	1
Iql1	Lower limit on reactive current injection Iqinj	pu	-1
Vref0	User defined reference (if 0, model initializes it to initial terminal voltage)	pu	0
Iqfrz	Value at which Iqinj is held for Thld seconds following a voltage dip if Thld > 0	pu	0
Thld	Time for which Iqinj is held at Iqfrz after voltage dip returns to zero	s	0
Thld2	Time for which the active current limit (IPMAX) is held at the faulted value after voltage dip returns to zero	s	0
Tp	Filter time constant for electrical power	s	0.01

Table E.4 continued from previous page

Name	Description	Unit	Value
Qmax	Limit for reactive power regulator	pu	0.5
Qmin	Limit for reactive power regulator	pu	-0.5
VMAX	Max. limit for voltage control	pu	1.1
VMIN	Min. limit for voltage control	pu	0.9
Kqp	Reactive power regulator proportional gain	pu	1
Kqi	Reactive power regulator integral gain	pu	5
Kvp	Voltage regulator proportional gain	pu	1
Kvi	Voltage regulator integral gain	pu	5
Vbias	User-defined bias (normally 0)	pu	0
Tiq	Time constant on delay s4	s	0.01
dPmax	Power reference max. ramp rate	pu/s	999
dPmin	Power reference min. ramp rate	pu/s	-999
PMAX	Max. power limit	pu	1
PMIN	Min. power limit	pu	0
Imax	Maximum limit on total converter current	pu	1.3
Tpord	Power filter time constant	s	0.01
Vq1	Reactive Power V-I pair, voltage	pu	0
Iq1	Reactive Power V-I pair, current	pu	1
Vq2	Reactive Power V-I pair, voltage	pu	0.1
Iq2	Reactive Power V-I pair, current	pu	1
Vq3	Reactive Power V-I pair, voltage	pu	0.5
Iq3	Reactive Power V-I pair, current	pu	1
Vq4	Reactive Power V-I pair, voltage	pu	1
Iq4	Reactive Power V-I pair, current	pu	1
Vp1	Real Power V-I pair, voltage	pu	0.7
Ip1	Real Power V-I pair, current	pu	0.5
Vp2	Real Power V-I pair, voltage	pu	0.75
Ip2	Real Power V-I pair, current	pu	0.6
Vp3	Real Power V-I pair, voltage	pu	0.9
Ip3	Real Power V-I pair, current	pu	1.3
Vp4	Real Power V-I pair, voltage	pu	1
Ip4	Real Power V-I pair, current	pu	1.3

Table E.5: Parameters for the Q control of WT3A and WT4A in PowerFactory.

Name	Description	Unit	Value
M_{qG}	General Q control mode	-	2 or 0
M_{qUVRT}	UVRT Q control modes	-	0
T_{ufiltq}	Voltage measurement filter time constant	s	0.01
T_{pfiltq}	Power measurement filter time constant	s	0.01
K_{Pq}	Reactive power PI controller proportional gain	U_n/P_n	1
K_{Iq}	Reactive power PI controller integration gain	$U_n/P_n/s$	5
K_{Pu}	Voltage PI controller proportional gain	I_n/U_n	1
K_{Iu}	Voltage PI controller integration gain	$I_n/U_n/s$	5
u_{db1}	Voltage dead band lower limit	U_n	-0.1

Table E.5 continued from previous page

Name	Description	Unit	Value
u_{db2}	Voltage dead band upper limit	U_n	0.1
K_{qv}	Voltage scaling factor for UVRT current	I_n/U_n	3
u_{max}	Maximum voltage in voltage PI controller integral term	U_n	1,1
u_{min}	Minimum voltage in voltage PI controller integral term	U_n	0.9
u_{ref0}	User defined bias in voltage reference	U_n	0
u_{qdip}	Voltage threshold for UVRT detection in q control	U_n	0.9
T_{qord}	Time constant in reactive power order lag	s	0.01
T_{post}	Length of time period where post fault reactive power is injected	s	0
i_{qmax}	Maximum reactive current injection	I_n	1
i_{qmin}	Minimum reactive current injection	I_n	-1
i_{qh1}	Maximum reactive current injection during dip	I_n	1
i_{qpost}	Post fault reactive current injection	I_n	0
r_{droop}	Resistive component of voltage drop impedance	Z_{base}	0.06
x_{droop}	Inductive component of voltage drop impedance	Z_{base}	0.01

Table E.6: Parameters for Model WTDTA1 (mechanical model) for WT3A in PSSE.

Name	Description	Unit	Value
H	Total inertia constant	s	6
DAMP	Machine damping factor	pu P/pu	0.1
H_{tfrac}	Turbine inertia fraction	(Hturb/H)1	0.8330
Freq1	First shaft torsional resonant frequency	Hz	21.85
Dshaft	Shaft damping factor	pu	0.5

Table E.7: Parameters for the two mass model of WT3A in PowerFactory.

Name	Description	Unit	Value
Tg	Time constant	s	0.02
di_{qmin}	Minimum reactive current ramp rate	I_n/s	-9999
di_{pmax}	Maximum active current ramp rate	I_n/s	9999
di_{qmax}	Maximum reactive current ramp rate	I_n/s	9999

Table E.8: Parameters for P control of WT3A in PowerFactory

Name	Description	Unit	Value
ω_{offset}	Offset to reference value that limits controller action during rotor speed changes	Ω_{base}	0.05
$\omega(p)$	Power vs. speed lookup table	$\Omega_{base}(P_n)$	*
K_{Pp}	PI controller proportional gain	T_{base}/Ω_{base}	2
K_{Ip}	PI controller integration parameter	$T_{base}/\Omega_{base}/s$	10
$T_{pfiltp3}$	Filter time constant for power measurement	s	0.01
$T_{ufiltp3}$	Filter time constant for voltage measurement	s	0.01
$T_{\omega ref}$	Time constant in speed reference filter	s	60

Table E.8 continued from previous page

Name	Description	Unit	Value
$T_{\omega filtp3}$	Filter time constant for generator speed measurement	s	0.05
K_{DTD}	Gain for active drive train damping	P_n/Ω_{base}	0
p_{DTDmax}	Maximum active drive train damping power	P_n	0.15
ζ	Coefficient for active drive train damping	-	0.5
ω_{DTD}	Active drive train damping frequency	Ω_{base}	11.3
T_{pord}	Time constant in power order lag	s	0.01
dp_{max}	Maximum WT power ramp rate	P_n/s	999
dp_{refmax}	Maximum ramp rate of WT reference power	P_n/s	0.3
dp_{refmin}	Minimum ramp rate of WT reference power	P_n/s	-0.3
u_{pdip}	Voltage dip threshold for P control	U_n	0.8
$d\tau_{max}$	Ramp limitation of torque	T_{base}/s	10
τ_{emin}	Minimum electrical generator torque	T_{base}	0
τ_{uscale}	Voltage scaling factor of reset torque	T_{base}/U_n	1
M_{pUVRT}	Enable UVRT power control mode (0: reactive power control – 1: voltage control)	-	1
$d\tau_{maxUVRT}$	Limitation of torque rise rate during UVRT	T_{base}/s	0
u_{DVS}	Voltage limit for hold UVRT status after deep voltage sags	U_n	0.8
T_{DVS}	Time delay after deep voltage sags	s	0

*See Table E.9 for this array.

Table E.9: Parameters for model WTTQA (torque control) for WT3A in PSSE.

Name	Description	Unit	Value
Kpp	Proportional gain in torque regulator	pu	0.5
KIP	Integrator gain in torque regulator	pu	1
Tp	Electrical power filter time constant	s	0.05
Twref	Speed-reference time constant	s	60
Temax	Max limit in torque regulator	pu	1.1
Temin	Min limit in torque regulator	pu	0
p1	power	pu	0.2
spd1	shaft speed for power p1	pu	0.58
p2	power	pu	0.4
spd2	shaft speed for power p2	pu	0.720
p3	power	pu	0.6
spd3	shaft speed for power p3	pu	0.860
p4	power	pu	0.8
spd4	shaft speed for power p3	pu	1
TRATE	Total turbine rating	MW	20

Table E.10: Parameters for the P control of WT4A in PowerFactory.

Name	Description	Unit	Value
$T_{ufiltp4A}$	Voltage measurement filter time constant	s	0.01
$T_{pordp4A}$	Time constant in power order lag	s	0.01
dp_{maxp4A}	Maximum WT power ramp rate	P_n/s	999

Table E.11: Parameters for the current limitation model of WT3A and WT4A in PowerFactory.

Name	Description	Unit	Value
imax	Maximum continuous current at the WT terminals	I_n	1.3
imaxdip	Maximum current during voltage dip at the WT terminals	I_n	1.3
M_{DFSLim}	Limitation of type 3 stator current (0: total current limitation, 1: stator current limitation)	-	1
M_{qpri}	Prioritisation of q control during UVRT (0: active power priority – 1: reactive power priority)	-	1
ipmax(u_{WT})	Lookup table for voltage dependency of active current limits	$I_n(U_n)$	*
iqmax(u_{WT})	Lookup table for voltage dependency of reactive current limits	$I_n(U_n)$	*
$T_{ufiltcl}$	Voltage measurement filter time constant	s	0.01
u_{pqumax}	WT voltage in the operation point where zero reactive current can be delivered	U_n	1.1
K_{pqu}	Partial derivative of reactive current limit vs.voltage	I_n/U_n	2

* See the corresponding lookup tables in Table E.4

Table E.12: Parameters for the Q limitation model in PSSE and PowerFactory for WT3A and WT4A.

Name	Description	Unit	Value
qmax	Maximum reactive power	pu	0.5
qmin	Minimum reactive power	pu	-0.5

Bibliography

[1] IEC, *International standard iec 61400-27-1: Electrical simulation models – wind turbines,* (2015).

[2] F. Blaabjerg and K. Ma, *Wind energy systems,* Proceedings of the IEEE **105**, 2116 (2017).

[3] IEC, *International standard iec 61400-27-1: Electrical simulation models – wind turbines,* (2018), draft. Not published yet.

[4] P. 34.4, *Program application guide volume 2,* ().

[5] P. 34.4, *Model library,* ().

[6] E. Muljadi, S. Pasupulati, A. Ellis, and D. Kosterov, *Method of equivalencing for a large wind power plant with multiple turbine representation,* in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century* (2008) pp. 1–9.

[7] F. Shewarega, I. Erlich, and J. L. Rueda, *Impact of large offshore wind farms on power system transient stability,* in *2009 IEEE/PES Power Systems Conference and Exposition* (IEEE, 2009) pp. 1–8.

[8] *Renewable Energy Policy Network for the 21st Century (Ren 21), Renewables 2018. Global Status Report,* (2018), http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf.

[9] *Wind Europe. Wind in power 2017. Annual combined onshore and offshore wind energy statistics,* (2017).

[10] WindStats, https://windstats.nl/.

[11] G. Lalor, A. Mullane, and M. O'Malley, *Frequency control and wind turbine technologies,* IEEE Transactions on Power Systems **20**, 1905 (2005).

[12] M. B. Salles, K. Hameyer, J. R. Cardoso, A. Grilo, C. Rahmann, *et al.*, *Crowbar system in doubly fed induction wind generators,* Energies **3**, 738 (2010).

[13] B. C. Ummels, *Power system operation with large-scale wind power in liberalised environments,* (2009).

[14] P. E. Sørensen, Ö. Göksu, J. Fortmann, F. J. Buendia, and A. Morales, *Next edition of iec 61400-27: Electrical simulation models for wind power plants,* in *1st International Conference on Large-Scale Grid Integration of Renewable Energy in India* (2017) http://integrationworkshops.org/2019/wp-content/uploads/sites/14/2017/09/11C_2_GIZ17_xxx_paper_S%C3%B8rensen_170714.pdf.

[15] B. Andresen, F. Jens, P. Sørensen, N. Miller, Y. Kazachkov, B. John, and P. Pouyan, *Wind plant models in iec 61400-27-2 and wecc - latest developments in international standards on wind turbine and wind plant modeling.* in *14th International Workshop on Large-scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants* (2015).

[16] *Western Electricity Coordinating Council Modeling and Validation Work Group. WECC Wind Plant Dynamic Modeling Guidelines,* (2011).

[17] *Western Electricity Coordinating Council Modeling and Validation Work Group. WECC Wind Plant Dynamic Modeling Guidelines,* (2014), http://www.wecc.biz/committees/StandingCommittees/PCC/TSS/MVWG/Shared%20Documents/MVWG%20Approved%20Documents/WECC%2Wind%20Plant%20Dynamic%20Modeling%20Guidelines.pdf.

[18] Ö. Göksu, P. E. Sørensen, A. Morales, S. Weigel, J. Fortmann, and P. Pourbeik, *Compatibility of iec 61400-27-1 and wecc 2nd generation wind turbine models,* in *15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants* (2016).

[19] *Netcode elektriciteit,* https://wetten.overheid.nl/BWBR0037940/2019-02-01.

[20] T. T. B.V., *Wind farm connection requirements,* .