Real-time Active- and Reactive Power Control in a combined Wind- Solar PPM

BSc. Graduation Thesis

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TU Delft

Abstract

Increase in wind- and solar parks complicate grid stability due to their deterministic behaviour. ENTSO-E established requirements for generators for grid connection in Europe. A requirement is to have active- and reactive power control that implements a power setpoint given by the transmission system operator. This thesis describes the design and MATLAB implementation of these controllers in a combined wind- and solar power park module. Reactive power control is designed for two modes, namely reactive power control mode and voltage sub-mode 1. The active power control is designed as a rule based controller with a quadratic distribution of power over generator strings. The reactive power control mode is based on a variable structure PI with feedback and pro-rata distribution of reactive power. A design for voltage-submode 1 has been designed based on droop control, but is not corresponding the requirements of the considered case. The controllers are implemented in model of a real-life case from the company [redacted]

Preface

First of all, gratitude and acknowledgement goes to the company [redacted] for providing extensive outlines and documents for a real-case wind ark, namel [redacted] The power flow control modules are new for such projects and therefore provide an interesting subject for the BAP. As students, we are grateful to get a taste of the real-life experience and challenges. Special thanks go out to our supervisor dr. ir. José Rueda Torres for his time and guidance that realistically shaped, and helped us through the project. The complete project would not have been possible without the collaboration of our colleagues, Alexandru Neagu, Jinhan Bai, Farley Rimon and Marouane Mastouri. The positive online atmosphere was a delight in a time of COVID-19.

Dennis: As co-author, I dedicate this thesis to all family members abroad who have died due to COVID-19. Especially in memory to uncle José, who can be described as a genius without the privilege of much education. His enthusiasm about (micro)electronics will not be forgotten. May that humble us to the many educational possibilities that are provided.

Laurens: As co-author, I dedicate this thesis to my family members, my housemate Ullas and especially my wonderful girlfriend JT with whom I spend time with during the COVID-19 pandemic. Thank you for your love, support and wisdom. Success often means more when you can share it with the people you love.

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Contents

List of Abbreviations

Important and frequently used abbreviations are bold.

ATO	Aansluit- en transport overeenkomst (Connection Agreement)
BAP	Bachelor Afstudeer Project (Bachelor Graduation Project)
CFC	**Central Farm Controller**
ENTSO-E	European Network of Transmission System Operators for Electricity
IEC	International Electrotechnical Commission
LSFC	Local Solar Farm Controller
LWFC	Local Wind Farm Controller
MPC	Model Predictive Control
OLTC	**On-Load Tap Changer**
ONAF	Oil Natural Air Natural
ONAF	Oil Natural Air Forced
OSI	Open Systems Interconnection
PCC	**Point of Common Coupling**
PPA	Power Purchase Agreement
PPM	**Power Park Module**
RfG	**Requirements for Generators**
SLD	Single Line diagram
TCP	Transmission Control Protocol
TSO	**Transmission System Operator**
VSPI	**Variable Structure PI**
WTG	**Wind Turbine Generator**

Chapter 1

Introduction

1.1 Problem Definition

ENTSO-E established an European network code with requirements for grid code connection of generators [1]. As the amount of wind- and solar parks are increasing, the requirements for the parks become stricter to maintain grid stability. These requirements among others include the implementation of active- and reactive power control. Also, the case is becoming more popular that WTGs and photo-voltaic modules are combined into one PPM. These renewables have complementary natures which can be utilized advantageously, but also poses new challenges in control. In this thesis, a CFC will be designed that controls active- and reactive power flows in a substation of a combined wind- and solar power park. The design of the power control will be mainly based on ENTSO-E's requirements and on project outlines provided by [redacted] is also used as a case study in this project. The problem has societal relevance. According to chief transition officer Daan Schut of network operator Liander, 110 substation have to be extended and 100 new substations have to be build in the Netherlands before 2030. That is as much as the last 40 years [2]. Three main problems can be distinguished in this thesis and are prioritized as follows:

1. Design of active- and reactive power control schemes according to the requirements of [1, 3, 4].
2. Enlarging energy yields from renewables by optimisation of reactive power setpoints to generator strings. This thesis describes the implementation of an optimisation unit in the control schemes. The optimisation unit design is given in a fellow group thesis [5].
3. Consideration of how different natures of WTGs and PV modules can be utilized in the active- and reactive power flow control of a substation.

1.2 State of the Art

Current state of the art in wind farm control entails MPC which is used to predict for example wind speed and wake interaction [6–9]. These predictions are used to determine control actions and the distribution of power. Furthermore, PI controllers are also heavily utilized in designs of wind farm controllers ([10–14]). For example, [10] uses a PI controller in combination with varying distribution factors based on thrust measurements to coordinate structural loading and increase the lifetimes of the wind turbines. Distribution factors specify the relative amount each turbine has to contribute to the total power generation. Also, in [11] a PI controller is implemented and tested with static and dynamically changing distribution factors.

1.3 System overview

1.3.1 Power Park Module Overview

The considered PPM consists of a real-case wind park [15] and an additionally designed theoretical solar park. A simplified SLD of the complete system is given in Figure A.1 of Appendix A. The wind park is rated at [redacted] MW and the solar farm at 48 MW. [redacted] TG types [16–23] are interconnected in 13 strings. The WTG are gearless and variable speed. For each WTG, an annular generator generates AC power that is converted to 400 V AC 50Hz via AC-DC back to back converter. The voltage is stepped up with a transformer to connect the WTG to the 33kV cable network. The WTG strings are distributed over four 33 kV bus bars. Four identical PV module strings of 12 MW each are connected to a respective bus bar. Each string consists of 41667 PV modules of type SunPower X22-360 [24] and can output 14.3 MW and 4.76 MVAR. The design of the solar park is performed in [25]. Each string has a LWFC or LSFC that primarily implements active- and reactive power setpoints given by the CFC. Two 240 MVA ONAF transformers with OLTC [26] step up the voltage from 33 kV to 150 kV. Each transformer is connected to two bus bars. A 150 kV cable transports the power to PCC, namely TenneT's substation. A 12 MVAR 33kV shunt reactor [27] is connected between the secondary side of the transformers to compensate for the reactive power injection of the cable network.

1.3.2 Central Farm Controller Overview

The design of the control unit includes active- and reactive power control and is seen as a sub-module of the CFC. The designs of other CFC sub-modules are described in the respective theses by fellow group members of the BAP project. Namely, the optimisation unit [5] and the power flow modeling unit [25].

- The **power flow model**. It provides a realistic model of the system behaviour for power flow calculations. The power flow calculations are necessary for the optimisation unit.
- The **optimization unit**. Its primary goal is to determine reactive power set points for generator string controllers such that network losses are minimized. With that, it also calculates set points for the the OLTC and the reactor. However, determination of these optimal values is in the order of minutes.
- The **controller unit**. Real-time control and implementation of set point is performed by the controller unit. In steady state, it implements the string set points from the optimisation module. The controller unit controls the strings, OLTC and reactor and ensures grid compliance at all times.

Preferably, the farm would be continuously controlled by the optimisation unit, but the system is not fast enough. During the time that the optimisation unit generates string set points, the situations in the following points could occur. It emphasized the need for real-time control.

- The TSO changes the active or reactive power set point at PCC. The set points given by the optimization module are based on the previous TSO set point. Thus, the CFC has to control the strings while optimization is calculating new string set points based the current TSO request.
- High deviations of wind speeds result in a rapid changes in available active power. The capability curves of WTGs have non-rectangular regions and could possibly not deliver the suggested reactive power in certain ranges of wind speed. In this case the control until has to take over the optimization module and set points that are within the capabilities of the strings are delivered. Still it could occur that the generator capabilities can't fulfill the TSO reactive power set point with real-time control. In that case the control unit employs the shunt reactor and OLTC to fulfill the set point.

Figure 1.1 gives an overview of the CFC and the inter-module communication. The relevant input- and output variables for the control unit in Figure 1.1 are described in Table 1.1.

1.4 Synopsis

The thesis is structured as follows: First, the requirements related to the grid code and RfG are stated in Section 2.1. Subsequently, the testing and validation procedures for each of the relevant control methods are presented in Section 2.4. Afterwards, the designs of all required controllers are described and motivated in detail in Chapter 3. In Chapter 4, the implementation of the designs in MATLAB are explained and the results corresponding to the test cases are shown. The results are discussed and fulfillment of the requirements will be addressed in Chapter 5. Overall conclusions and recommendations for future work and suggestions physical realisation of the controller are also written in Chapter 5.

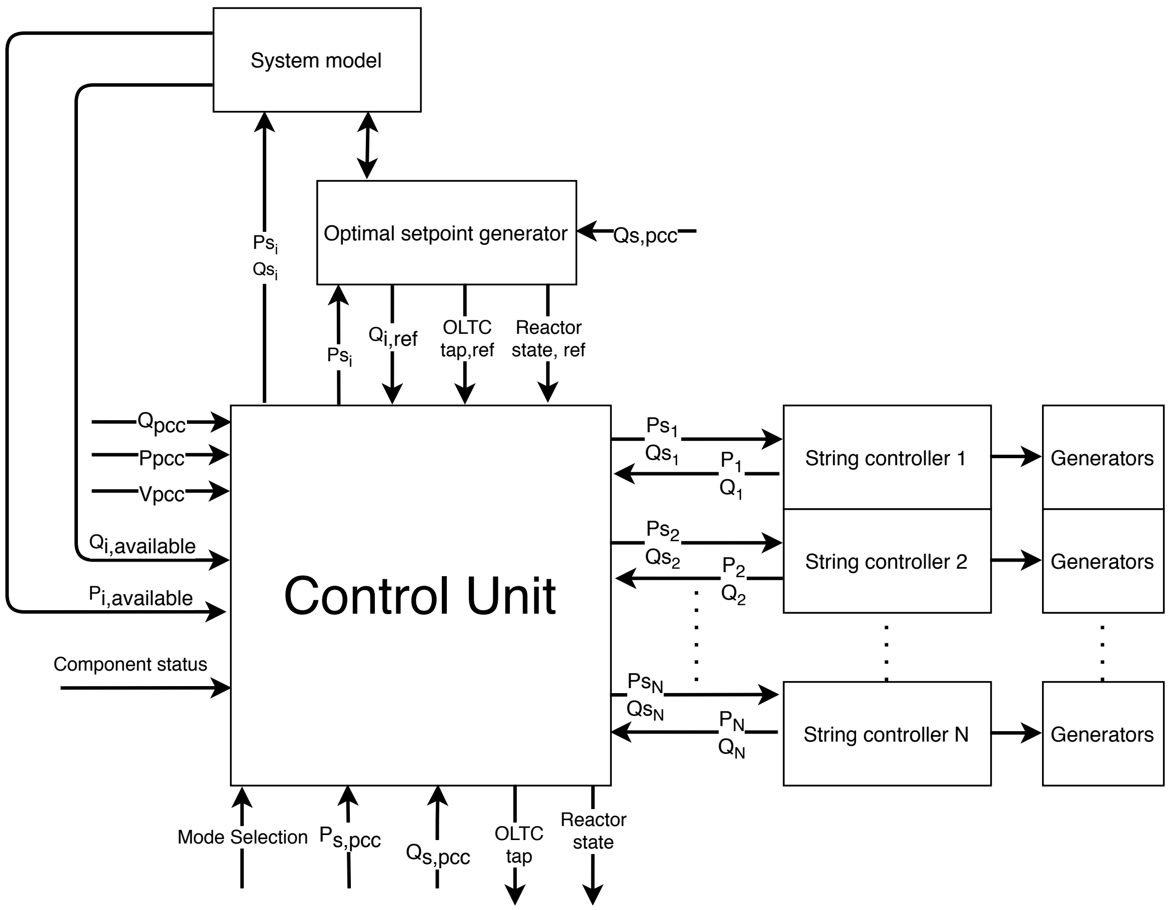

Figure 1.1: Overview of the central farm controller I/Os and communication with other modules.

Table 1.1: Symbols related to control unit and and inter-module communication.

Symbol	**Meaning**
$P_{s,PCC}$ and $Q_{s,PCC}$	The active- and reactive power setpoint that should be reached and maintained at PCC. The TSO setpoint is equal to the sum of PPA contractor setpoint requests unless the TSO requests otherwise.
P_{PCC}, Q_{PCC} and V_{PCC}	The actual measured values at PCC.
$P_{i,ref}$ and $Q_{i,ref}$	The sub-optimal set points for string i generated by the optimisation unit. The aim is to reach set-points in steady state while maintaining grid compliance.
$P_{i,available}$ and $Q_{i,available}$	The actual available active- and reactive power ranges at string i.
Ps_i and Qs_i	The active- and reactive power set points given to string i by the control unit.
P_i and Q_i	The actual active- and reactive power outputs of string i.
$Mode\_selection$	The signal with which the network operator selects the reactive power control mode.
$OLTC\_tap$	Command signal to change the tap position of the OLTC.
$Reactor\_state$	Command signal to connect or disconnect the shunt reactor.
$Component\_status$	A vector that indicates the states of the components in the network, i.e. connected or disconnected.
$Q_{i,ref}$, $OLTC\_tap\_ref$ and $Reactor\_state\_ref$	An optimal set of Qs_i can be calculated by the optimisation unit by passing a future prediction of Ps_i first. The optimisation unit also determines the most fitting OLTC tap position and reactor together with the calculated setpoints.

Chapter 2

Requirements

2.1 Program of Requirements

Requirements for the active- and reactive power flow controllers are set up according to the Dutch Grid Code [3] and ENTSO-E Requirements for Generators [1]. [redacted] also provided attachments with guidelines for the controller design [4, 28]. RfG bases requirements on the size of the generator unit. Generators are classified from type A-D according to their capacity. A full scheme of generator classification is given in Figure A.2 of Appendix A. The wind- and solar park is classified as type D, since it has a maximum capacity larger than 60 MW and a connection point above 110 kV. The system is also classified as a PPM, since it has an onshore synchronised grid connection. Requirements for type D PPMs conforming to the scope of the project are summarized in Table 2.1.

Table 2.1: PoR for the CFC's active- and reactive power control based on [1, 3, 4, 28].

Identifier	Requirement text	Source
Central farm control		
CFC-01	A central farm controller is required to ensure compliance to the grid codes and divide the load between generator strings. The central farm controller gives active- and reactive power setpoints to the controllers of the strings. The controllers on string-level are outside the scope of this project.	[28]
CFC-02	The measuring point for the central controller is at PCC. Response of the controller must be based on this measurement.	[28]
Active Power Control		
APC-01	With regard to active power controllability and control range, the Power-Generating Module control system shall be capable of adjusting an active power setpoint in line with instructions given to the Power-Generating Facility Owner by the relevant system operator or the relevant TSO. The relevant system operator or the relevant TSO shall establish the period within which the adjusted active power setpoint must be reached. The relevant TSO shall specify a tolerance (subject to the availability of the prime mover resource) applying to the new setpoint and the time within which it must be reached.	RfG Article 15.2.(a)
APC-02	The Power-Generating Module is capable of receiving a setpoint of the active power and to follow it according to the instructions of the relevant TSO. The following conditions apply: a. The control range is between the minimum regulating level and the actual maximum capacity, unless otherwise agreed between the TSO and the connected party b. The time period within which the adjusted setpoint for the active power must be achieved is laid down in the Connection Agreement (ATO) c. The tolerance for the new reference value is +/-2% of the maximum capacity.	Netcode elektriciteit Article 3.24
APC-03	Absolute production constraint - The function must be able to limit the wind farm's active power production in the PCC's to a maximum specifically indicated active power reference value (MW).	[28]

Reactive Power Control		
RPC-01	The following reactive control modes must be available: • Reactive power control - The function must control the reactive power output according to an indicated reactive power reference value (MVAr). • Voltage control – The purpose of this function is to regulate the reactive power output at PCC based on the voltage measurement, according to the requirements stated in the TSO grid codes. • Power Factor control - The function must control the reactive power output to have a constant power factor for varying active power production according to an indicated Cos(φ) value. However, Power Factor mode is omitted from the project.	RfG Article 21.3.(d).(i) and [28]
RPC-02	The default reactive power exchange at PCC is 0 MVAR. An capacitive or inductive offset in typical steps of 50 Mvar can requested by the network operator for a time interval. The time interval is typically one or several hours.	[4]
RPC-03	Reactive power output cannot excess the limit of the wind farm reactive power capability.	[28]
RPC-04	The controler can activate the 33kV shunt reactor and OLTC according to the control strategy.	[28]
RPC-05	The Network Operator determines the Reactive Power Control Mode (Voltage or Reactive Power).	[4]
RPC-06	Operation in the Forbidden Area (outside the park's power capability) is accepted in case it is caused by the parameters and control characteristics of the activated Reactive Power Control Mode.	[4]
RPC-07	The Set Point type is coupled to the selected Reactive Power Control Mode.	[4]
RPC-08	The Reactive Power Capability will apply pro rata to the amount of Generating Units In Service.	[4]
Reactive Power Control Mode: Voltage Sub-mode 1		
RPC-VM-01	Voltage control (U-control) is characterized by Voltage Droop, Set Point Voltage and Control Speed.	[4]
RPC-VM-02	Because the Reactive Power Control mode is Voltage the Reactive Power Exchange by the PPM at the PCC depends on the Voltage at the PCC.	[4]
RPC-VM-03	The PPM must have the ability to determine locally the Set Point Voltage based on the Agreed Steady State Reactive Power Exchange at the PCC indicated by the Reference Steady State Reactive Power Exchange. The PPM must have the ability to process the Reference Steady State Reactive Power Exchange indicated by the Network Operator.	[4]
RPC-VM-04	Every 15 minutes the Reactive Power Exchange at the PCC must be brought back by the PPM to the Agreed Steady State Reactive Power Exchange by adjustment of the Set Point Voltage (adjustment is only required in case the Reactive Power Exchange is outside a defined dead band).	[4]

RPC-VM-05	For the purposes of voltage control mode, the Power Park Module shall be capable of contributing to voltage control at the Connection Point by provision of reactive power exchange with the network with a setpoint voltage covering 0,95 to 1,05 pu in steps no greater than 0,01 pu, with a slope having a range of at least 2 to 7 % in steps no greater than 0,5%. The reactive power output shall be zero when the grid voltage value at the Connection Point equals the voltage setpoint. The default Voltage Droop is 10% at the PCC. This means that in case the Actual Voltage at the PCC drops with 10% the maximum Reactive Power Capability (100%) must be injected in the Network.	RfG Article 21.3.d.(ii) and [4]
RPC-VM-06	The PPM must determine the Set Point Voltage every time the Reactive Power Exchange has to be brought back to the Agreed Steady State Reactive Power Exchange.	[4]
RPC-VM-07	The setpoint may be operated with or without a deadband selectable in a range from zero to ± 5% of reference 1 pu network voltage in steps no greater than 0,5%.	RfG Article 21.3.d.(iii)
RPC-VM-08	Following a step change in voltage, the Power Park Module shall be capable of achieving 90% of the change in reactive power output within a time t1 to be specified by the relevant system operator in the range of 1 to 5 seconds, and must settle at the value specified by the slope within a time t2 to be specified by the relevant system operator in the range of 5 to 60 seconds, with a steady-state reactive tolerance no greater than 5% of the maximum reactive power. The relevant system operator shall specify the time specifications.	RfG Article 21.3.d.(iv)
RPC-VM-09	Regarding Voltage control sub-mode 1: • In case the reactive power exchange at the Connection Point has exceeded the predefined Dynamic Threshold (solid green lines in the figure 4.14), but has not exceeded the predefined Disturbance Threshold, the setpoint voltage must be adjusted by the PPM to re-establish the agreed steady state reactive power exchange at the Connection Point within 15 minutes (this is a slow control function over the voltage control). • In case the reactive power exchange at the Connection Point or the voltage deviation at the Connection Point exceeds the predefined Disturbance Threshold (solid red lines in the figure 4.14), the reactive power support of the PGM must be maintained for at least 15 minutes (this is a standard voltage control functionality).	Netcode elektriciteit Article 3.26.12
RPC-VM-10	When initiating Reactive Power Control Mode Voltage the Set Point Voltage must be made equal to the Actual Voltage at the PCC.	[4]
RPC-VM-11	The Set Points and Slope (Voltage Droop) must be adjustable, during normal operation.	[4]
RPC-VM-12	Adjustment of the Operating Point of the Slope must be possible within 15 minutes, to adjust the reactive power exchange a the PCC.	[4]
RPC-VM-13	During adjustment of the Set Point Voltage the Reactive Power Control Mode must remain Voltage.	[4]
RPC-VM-14	The Reactive Power Control Mode Voltage must result in a stable and damped behaviour of the voltage at PCC.	[4]
Reactive Power Control Mode: Reactive Power Control		
RPC-RC-01	Reactive Power control (Q-control) is characterized by its Set Point Reactive Power and Control Speed.	[4]
RPC-RC-02	The PPM must have the ability to process the Set Point Reactive Power indicated by the Network Operator.	[4]
RPC-RC-03	During normal operation (Reactive Power regulation at the PCC) the controller must periodically check for changes of the Set Point reactive Power indicated by the Network Operator.	[4]

2.2 Background and Explanation of Voltage Sub-mode 1

This section clarifies the requirements of voltage sub-mode 1 and is based on [4]. In voltage sub-mode 1, the PPM has too determine the voltage setpoint according to the TSO's reactive power request. When the reactive power at PCC exceeds the upper or lower dynamic thresholds, a new voltage setpoint has to be determined to reestablish the reactive power exchange to the TSO request. This behaviour is according to the voltage droop, which is the ratio of a change in voltage to a change in reactive power. After dynamic threshold violation, the restoration must be made within 15 minutes. The motivation behind the threshold and the restoration of reactive power exchange is to avoid interference with the secondary voltage control of the TSO. For example, correction is needed when the PPM's reactive power exchange is affected by the TSO's decision to change its voltage. Figure 2.1 demonstrates two violations of the dynamic thresholds (green lines) and the returning to the reference value. The second violation was caused by a changing TSO request. Namely, violation of the adjusted threshold corrected the reactive power exchange to the new request. In case the reactive power exchange exceeds the disturbance thresholds (red lines), the reactive power must be maintained at the maximum or minimum capability for at least 15 minutes. The background of this based on RfG Article 16.2.a.(v) [1] which states the time duration that a PPM should be able to remain connected for certain ranges of network voltages. This requirement prevents disconnection of generators as soon as the network voltage varies. Disconnections would then lead to cascading failures and a collapse of the network. The reactive power support aids the network in restoration of the reactive power balance. During the 15 minutes, the TSO employs its own assets to restore the balance.

Figure A.3 in Appendix A shows the voltage droop relation in the context of voltage sub-mode 1. The upper graph gives voltage changes in time intervals of 15 minutes. The lower graph gives the corresponding reactive power exchange. A net increase of reactive power over 15 minutes relates to a negative voltage deviation, and vice versa. As the maximum reactive power support is enabled, a large negative voltage deviation occurs. The reactive power is then maintained at the maximum and the voltage remains fairly constant.

Voltage sub-mode 2 is similar to voltage sub-mode 1, but does not have the disturbance operation functionality. Design and implementation of this mode is therefore disregarded from this report.

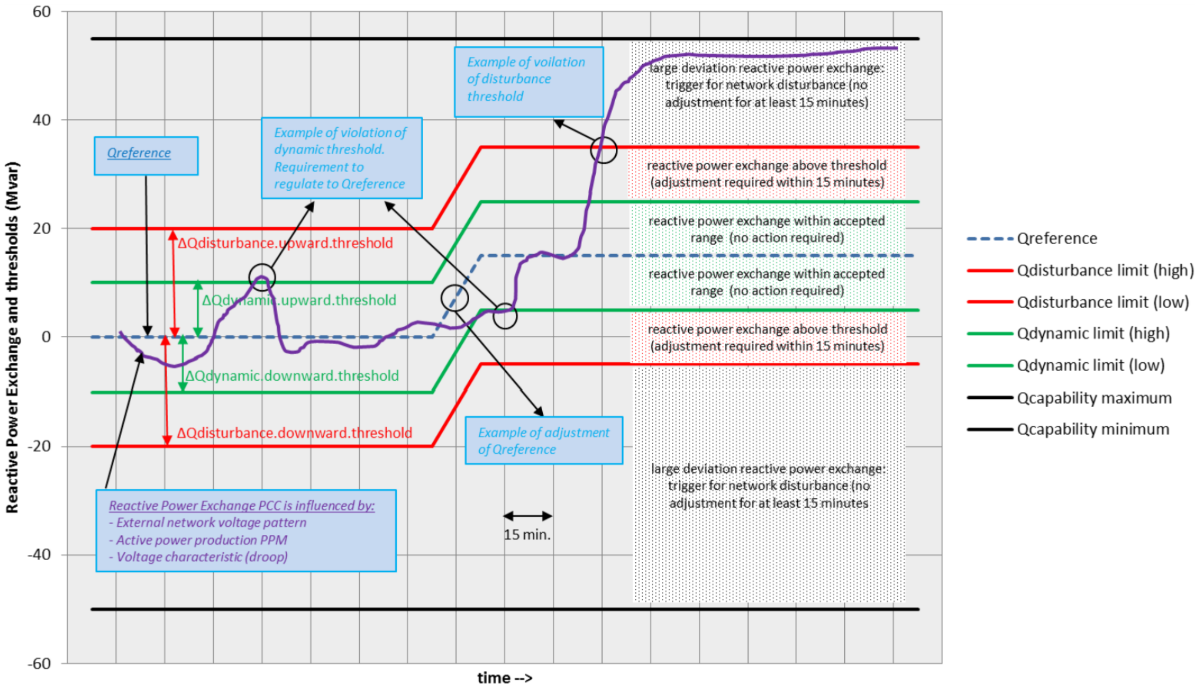

Figure 2.1: Example of reactive power exchange in relation to the thresholds in voltage sub-mode 1 [4].

2.3 Controller parameters

Parameters for the controllers are mutually agreed by the TSO and the PPM owner. Local network characteristics are taken into account. For this project, parameters are not yet agreed and therefore no specific tuning can be performed. An overview of the tuning parameters and other relevant parameters is given in Appendix B. Therefore, Chapter 3 and 5 describes tuning strategies.

2.4 Testing and Design Validation Procedure

2.4.1 Testing Procedure Active power control

The active power control requirements mainly regard the implementation of the TSO setpoint. Wind- and solar profiles do not specifically matter, because the TSO setpoint is within the actual capability. Therefore an average wind- and solar profile is sufficient for testing. An increasing and lowering setpoint needs to be implemented to test for under- and overshoot, i.e. the maintaining between +/- 2% of the maximum capacity. The test should demonstrate a time period in which the setpoint is achieved.

2.4.2 Testing Procedure Reactive Power Control Mode: Reactive Power

The main requirement of the reactive power control mode is to implement the TSO setpoint. The parameters in Appendix B emphasize that steady state should be reached and remain settled at. Any average wind profile will suffice for testing of setpoint changes. A increasing and decreasing setpoint must be performed to check for under- and overshoot. An other test with the same conditions should be performed to demonstrate the implementation of the optimisation setpoint in steady state. A last test is necessary to demonstrate the reactor and OLTC control with a TSO request that is beyond the capability of the system. A low, but nonzero wind profile is needed for this test. A solar profile is not necessary for the concept and can be disregarded as if this test was during night time.

2.4.3 Testing Procedure Reactive Power Control Mode: Voltage Sub-mode 1

The same tests and testing conditions from the reactive power control mode apply to voltage sub-mode 1, but with addition of dynamic- and disturbance thresholds. Functioning of dynamic thresholds should be tested by increasing and decreasing the TSO setpoint, such that the threshold trigger a voltage setpoint change. The change in voltage setpoint should restore the reactive power exchange within 15 minutes. An other test should be performed that triggers the disturbance threshold. Maximum reactive power support should be maintained.

Chapter 3

Design

3.1 Variable Generation of Wind- and Solar Park

WTGs and photo-voltaic modules are characterized by different intermittent natures.

First of all, their available active power is complementary in nature. There is more sun available during the summer but also less wind. During the other seasons there is more wind but also less sun. The designed controllers make use of this property since in the active power controller the distribution of power shall be based upon the available power corresponding to the strings. Thus, the strings with more available power take up more of the requested power by the TSO.

Also on a daily basis can there be found patterns in wind and solar profiles. Wind can be present at day and night. Solar irradiance is only available during the day. However, during certain periods of the year there is a reliable amount of irradiance every few hours of the day. The wind speed on the other hand is quite often very volatile when it is significantly high. This property could be also considered for the controller: During the time of the year when sun is reliably present during the afternoon, the controller ought to have a preference to increase the fraction of power generated by the PV modules instead of the wind strings were this to be required.

Finally, the speeds of the rotors of wind turbines suffer from inertia because of the rotating mass. This limits the speed at which the produced power of a turbine can be controlled. Active power produced by PV modules, on the other hand, is quite directly related to irradiance: Irradiance of photons excite electrons from the valence band to the conduction almost instantaneously. Therefore, control of PV modules can be more quick compared to control of wind strings. This property can also be utilized by leaning more on PV modules to take care of set point changes.

3.2 Active Power Control

In essence the active power control has to distribute the requested active power from the TSO over the strings. This is the case when not the maximum value is requested. When the maximum active power is requested, the strings simply produce the maximum available active power. In this chapter and for the remainder of the report, for the PPM containing N strings, the symbols listed in the table below will be used:

Table 3.1: Symbols related to active power control utilized in this report.

Symbol	Meaning
$\overrightarrow{P}$	N x 1 Vector containing the currently produced active power per string [MW]. Elements: $P_1...P_N$
$\overrightarrow{P_s}$	N x 1 Vector containing the set points for each string [MW]. Elements: $P_{s,1}...P_{s,N}$
$\overrightarrow{\Delta P}$	N x 1 Vector containing the differences between set point and currently produced active power per string [MW]. Elements: $\Delta P_1...\Delta P_N$
$\overrightarrow{P_a}$	N x 1 Vector which contains the maximum available power each string can produce [MW]. Elements: $P_{a,1}...P_{a,N}$
$P_{s,PCC}$	Active Power set point at PCC [MW].
ΔP_{PCC}	Difference between the set point at the PCC and the current active power at the PCC [MW].
P_{PCC}	Current active power at the PCC [MW].
$\overrightarrow{\beta}$	N x 1 Distribution coefficient vector. It determines how ΔP will de distributed over the strings. Elements (distribution factors): $\beta_1...\beta_N$

First of all, the control acts when there is a difference between the requested and the current value at the PCC:

$$\Delta P_{PCC} = P_{s,PCC} - P_{PCC} \tag{3.1}$$

This ΔP_{PCC} has to be distributed over the strings. The set point of each string is adjusted by adding a fraction $\beta_i \cdot \Delta P_{PCC}$ of ΔP_{PCC} to the currently produced active power. All the fractions add up to ΔP_{PCC}. Compactly written:

$$\overrightarrow{P_s} = \overrightarrow{P} + \overrightarrow{\Delta P} = \overrightarrow{P} + \overrightarrow{\beta} \cdot \Delta P_{PCC} \tag{3.2}$$

The set point for each string should never be greater than the maximum available power. Thus, the i^{th} element of $\overrightarrow{\beta}$ for string i is chosen to be equal to:

$$\beta_i \triangleq \frac{C \cdot P_{a,i}^2}{P_{a,i}^2 + \alpha_P} \cdot u(P_{a,i} - P_i) \triangleq C \cdot s_i \tag{3.3}$$

C will be the "normalization constant" and shall be dealt with expeditiously. s_i is the other part of the equation. This function is chosen because the distribution factor β_i increases when the available $P_{a,i}$ of string i increases. This is appropriate since the strings with most capability at the time ought to take up a higher amount of the requested active power compared to strings with less available power. The fraction is multiplied with the unit step function which equals 1 when $P_{a,i} > P_i$ and 0 when $P_{a,i} \leq P_i$. That is because a WTG should not produce more then its indicated maximum available power. Thus, when the turbine is performing at its maximum available power the control unit won't increase the set point.

Near the asymptote the function increases more slowly compared to a linear behaviour. This slow increase is more adequate since the set point reaches the limit less quickly. According to [29], wind turbines operating at maximum operating limits can increase wear outs of the converters and reducing the chances of reaching these limits improves the reliability. The quadratic behaviour was chosen because a higher order would change too fast. Thus, the function in Eq. 3.4 is chosen to reduce the possibility of reaching the maximum operating limits.

α_P is a constant that can be tuned. Smaller α_P gives a more quick control since the function in Eq. 3.3 increases more rapidly. α_P shall be increased or decreased depending on the weather conditions. When the weather is quite volatile, it will have to be smaller to counter the quick deviations in the available power per string. If the weather doesn't deviate as much, this won't be necessary and a larger α_P will be chosen to reduce stress on the components by preventing fast changing set points.

There are three distinct cases for the state of the PPM regarding the setpoint.

1. The requested set point from the TSO is feasible considering the wind turbines' capabilities.
2. The requested set point is too high and the turbines have to operate at maximum power.
3. A lowering of the set point from the TSO occurs while case 1 applies.

Considering case 1, to ensure all the necessary power is distributed, the following applies:

$$\sum_{i=1}^{i=N} \beta_i \cdot \Delta P_{PCC} = C \cdot \Delta P_{PCC} \cdot \sum_{i=1}^{i=N} s_i = \Delta P_{PCC} \Rightarrow C = \frac{1}{\sum_{i=1}^{i=N} s_i} \tag{3.4}$$

Combining this with Eq. 3.3:

$$\beta_i = \frac{s_i}{C} = \frac{s_i}{\sum_{i=1}^{i=N} s_i} \tag{3.5}$$

For case 2 each turbine produces its maximum available power. In this case, the value of C is irrelevant because it is not need to determine β. The set point per turbine is determined by Eq. 3.2. For the set point to be equal to the maximum value:

$$\overrightarrow{\beta} \cdot \Delta P_{PCC} = \overrightarrow{P_a} - \overrightarrow{P} \Rightarrow \overrightarrow{\beta} = \frac{\overrightarrow{P_a} - \overrightarrow{P}}{\Delta P_{PCC}} \tag{3.6}$$

Finally, for case 3, a turbine could be operating at maximum power. A lowering of the set point in this case could imply that operating at maximum power won't be necessary anymore for the turbine. The expression for s_i in Eq. 3.3 doesn't take this into account. Once it's operating at maximum power it will maintain that power. Thus, when a lowering of the set point occurs in case 1, the amount by which the set point changes will be divided over the amount of turbines operating at maximum power:

$$P_{sub} = \frac{P_{s,old} - P_{s,new}}{\#turbines\ at\ maximum\ power} \tag{3.7}$$

The active power set point for each turbine operating at its maximum will be reduced by the result of this division:

$$P_{s,i} = P_s - P_{sub}, \{i|P_i = P_{a,i}\} \tag{3.8}$$

Afterwards, the expressions related to case 1 shall be applied again.

3.3 Design Reactive Power Control

In this chapter and for the remainder of the report, for the PPM containing N strings, the symbols listed in the table below will be used:

Table 3.2: Symbols related to reactive power control utilized in this report.

Symbol	Meaning
$\overrightarrow{Q}$	N x 1 Vector containing the currently produced reactive power per string [MVar]. Elements: $Q_1 ... Q_N$
$\overrightarrow{Q_s}$	N x 1 Vector containing the set points for each string [MVar]. Elements: $Q_{s,1} ... Q_{s,N}$
$\overrightarrow{\Delta Q}$	Nx 1 Vector containing the differences between set point and currently produced reactive power per string [MVar]. Elements: $\Delta Q_1 ... \Delta Q_N$
$\overrightarrow{Q_a}$	N x 1 Vector which contains the maximum available power each string can produce [MVar]. Elements: $Q_{a,1} ... Q_{a,N}$
$\overrightarrow{DG}$	N x 1 Droop vector. It determines the droop for each string. Elements: $\frac{1}{R_1} \cdots \frac{1}{R_N}$
$Q_{s,PCC}$	Reactive power set point at PCC [MVar].
$V_{s,PCC}$	Voltage set point at PCC [MV].
ΔQ_{PCC}	Difference between the set point at the PCC and the current reactive power at the PCC [MVar].
ΔV_{PCC}	Difference between the set point at the PCC and the current voltage at the PCC [MV].
Q_{PCC}	Current reactive power at the PCC [MVar].
V_{PCC}	Current voltage at the PCC [MV]
R_u	-1 times the droop ($\frac{\Delta V}{\Delta Q}$) at PCC.

3.3.1 Design Reactive Power Control Mode: Reactive Power

In this mode reactive power setpoints have to be assigned to the strings in order to establish the requested reactive power $Q_{s,PCC}$ at PCC. However, due to wake effects, modelling errors and losses, distributing $Q_{s,PCC}$ via an open-loop approach won't be accurate as is shown in [11]. Therefore, a closed-loop with feedback method shall be considered.

Consideration of PID control

PI controllers are typically implemented in power flow controllers of PPMs. [30] explains principles behind PID controllers for second order plants. Proportional feedback realizes transient responses and is dominant at TSO setpoint changes. A large proportional gain gives fast transient response, but decreases damping capability and vice versa. Adding integral feedback in the controller minimizes steady-state tracking error. Response to disturbances is also reduced, which is relevant for maintaining the setpoint at varying wind speeds. In derivative feedback, the control signal is proportional to the rate of change of the system error. Derivative control improves closed-loop stability at the cost of noise response [31]. It is therefore disregarded for generator control.

Variable Structure PI Control

A variable structure PI is proposed in [32]. It is a variation of the standard PI controller. In this context, the term 'variable structure' refers to enabling or disabling the integrator part. The input of the controller is the error $e(t)$. For the PPM, this error equals the difference between the reactive power set point and the current value at PCC: $e(t) = \Delta Q_{PCC}(t) = Q_{s,PCC}(t) - Q_{PCC}(t)$. The output $u(t)$ of the VSPI controller is described by Equation 3.9.

$$u(t) = k_p \Big\{ e(t) + \int_0^t \Big[\frac{1}{T_i} \Big(e(\tau) \cdot \exp\Big(- \frac{e(\tau)^2}{2\beta^2 \cdot \sigma^2} \Big) \Big) \Big] d\tau \Big\} \tag{3.9}$$

The negative exponent in the integral is introduced and keeps the equation continuous. The magnitude of the error influences the amount of integral feedback. For large changes in the input signal, Equation 3.9 effectively becomes a proportional controller and when the error becomes small the integral action is enabled. This behaviour of the integral action is different from the standard PI controller.The variance $\beta^2\sigma^2$ are tuning parameters for the integral contribution.

The VSPI described has a quicker response with less overshoot in comparison with a classical PI as shown in [32]. The quick response could help with reaching a new set point from the TSO in a shorter amount of time. Moreover, the smaller overshoot could prevent operation outside the defined boundaries in the capability curves of the strings. Thus, it is beneficial to utilize a VSPI in reactive power control and therefore it shall be implemented in the design of the reactive power control for the control unit.

Control Scheme

The implemented control loop is shown in Figure 3.1.
The distribution coefficients $\beta_{q,i}$ each equal a fraction of the available power of the corresponding string. It conforms to the requirement of pro rata distribution of reactive power among strings.

$$\beta_{q,i} = \alpha_r \cdot Q_{a,i}, \quad i = 1,2,...,N, \quad 0 \leq \alpha_r \leq 1 \tag{3.10}$$

3.3.2 Tuning the VSPI

The VSPI is tuned using optimization of the following metrics:

- The time until Q_{PCC} reaches the set point $Q_{s,PCC}$ and becomes stable. By inspection, it was noticed that the response of the VSPI produces an oscillating behaviour around the set point. Thus, it came to our knowledge that when Q_{PCC} remains close to $Q_{s,PCC}$ (with a deviation of $\pm 2MVar$) for a few time steps it can be considered stable. This metric is chosen because minimizing it gives parameters that will lead to a shorter settling time which is desired since the set point has to be reached within a certain time period according to the requirements.

- The summation of the absolute error $|\Delta Q_{PCC}|$. Each time step ΔQ_{PCC} is calculated. This produces a vector: $\Delta Q_{PCC}[i] = Q_{s,PCC}[i] - Q_{PCC}[i]$ Thus, $\Delta Q_{PCC}[i]$ equals the i^{th} value of the vector obtained during simulation. Say i^{end} is the final index of this vector. Then the summation of the absolute error equals: $\sum_{i=1}^{i=i^{end}} \Delta_{PCC}[i]$. Minimizing this metric gives values that mostly reduce the steady-state error

- The summation of the error squared. Using the same notation as in the previous point, the summation of the error squared equals: $\sum_{i=1}^{i=i^{end}} (\Delta Q_{PCC}[i])^2$. Compared to minimizing the absolute error, minimizing this factor produces parameters that are more likely to decrease overshoot.

Before each optimization, via inspection and trial-and-error it is investigated which parameters seem to be more influential than others. The more influential parameters will be adjusted in smaller steps for each new iteration compared to the others in order to reduce optimization time.

Once a certain metric is optimized, the resulting parameters are used as a starting point for the next optimization. In the end a trade-off has to be found between settling-time and overshoot.

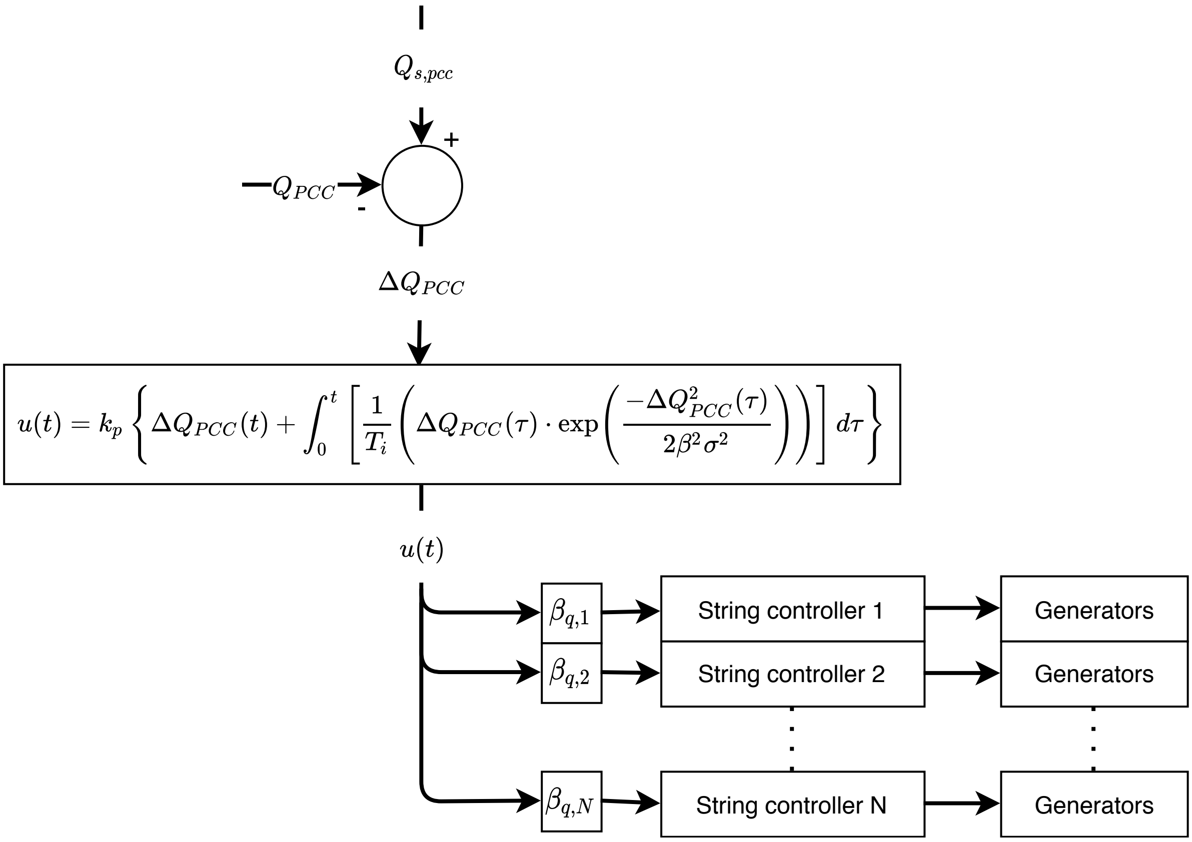

Figure 3.1: Control scheme used for reactive power control.

3.3.3 Design Reactive Power Control Mode: Voltage Sub-mode 1

The voltage droop constant R_u is defined as the ratio of the change in voltage to the change in reactive power. The voltage droop relation at PCC is determined by the modelling sub-group of this project [25]. The result is shown in Figure 3.2 and the corresponding droop is 0.014.

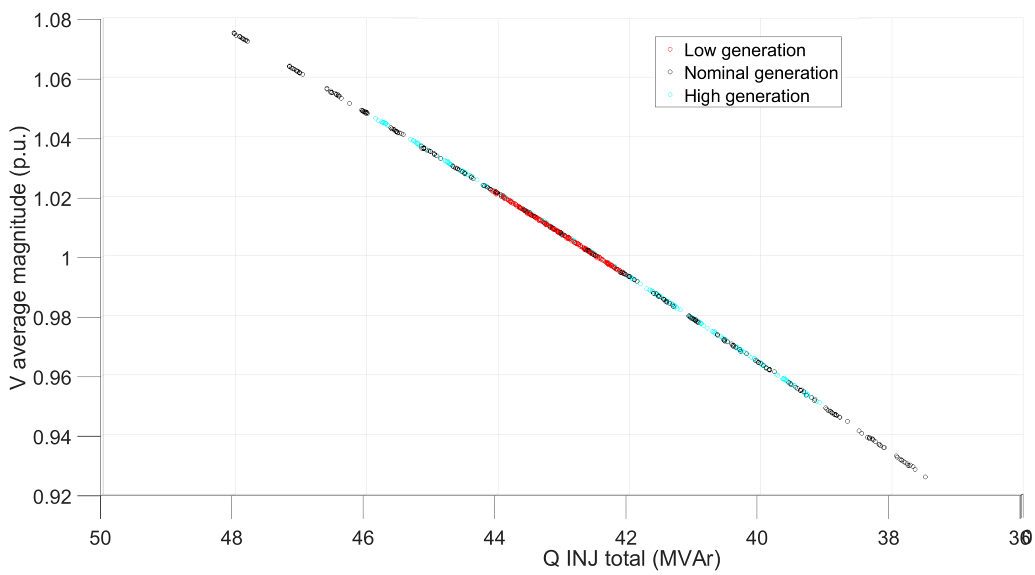

Figure 3.2: Droop relation at PCC [25]

The dynamic thresholds are set to +/- 10% and the disturbance thresholds are set to +/- 20%, according to the recommended values in Appendix B. Violation of the dynamic threshold causes a new voltage setpoint to be calculated. The new voltage setpoint is equal to the voltage corresponding to $\Delta Q_{PCC} \cdot R_u$, according to the droop relation. The voltage setpoint corresponds to a injection of reactive power, which is then implemented and maintained with the reactive power control mode. For initialization, the setpoint voltage is set to the current voltage at PCC. The corresponding reactive power output is determined according to the droop relation and is then implemented by the reactive power control mode.

It is determined to not have a control deadband, as deadbands are more appropriate to deal with fluctuations in real systems. For MATLAB implementation, control without deadband is more suitable. Violation of the disturbance threshold internally sets the reactive power setpoint to an unreachable value, such that the reactive power control mode maintains the maximum reactive power capacity.

The requirements do not specify how the system returns to the reference reactive power exchange after disturbance mode. However, as the TSO recovers the reactive power balance in the grid, the TSO should set a new value for $Q_{s,PCC}$. This will trigger the system to return to normal operation.

3.3.4 Insufficient Reactive Power Capability of Generators

Capability curves of WTGs show limited reactive power output near minimum or maximum active power output. The PPM can have insufficient reactive power capability in situations of low or high wind to satisfy the TSO setpoint. Yet, TSO requirements have to be fulfilled at all times. In such a boundary situation, reactive power must be controller by the OLTC and the 33 kV shunt reactor.

Shunt Reactor Disconnection and Re-Connection Conditions

Disconnection and re-connection conditions of the reactor have to be determined. The shunt reactor is generally connected to absorb reactive power generated by the cable network. It will be disconnected when the requested injection of reactive power into PCC can not be delivered by generators. That is when:
$0 < \sum_{i=1}^{i=N} Q_{a,i} < Q_{s,PCC}$. The reactor will be reconnected when the strings are capable of injecting at least $Q_{s,PCC}$+ 12 MVAR, because 12 MVAR will be absorbed by the reactor after re-connection. Fluctuations in wind- and solar profiles might fulfill the re-connection conditions. Therefore the conditions must be valid for a time period to avoid unnecessary switching. Wind speed profiles have more weight than irradiance profiles for determining the time period, considering that wind is generally the main contributor to reactive power injection (total capability of the turbines is way greater than solar capability for the PPM). From the wind profile in [33], a time period of 20 minutes is estimated to be appropriate. The sufficiency of the capability is only checked at the first instance the re-connection conditions are met and 20 minutes later. So, violating fluctuation in between do not reset the time period. Recoveries from in between violations must also be recorded and checked 20 minutes later, might the first period turn out to be violating the conditions. When the TSO decreases $Q_{s,PCC}$, re-connection conditions must be checked without consideration of the profiles.

OLTC Control for Reactive Power Support

The OLTC's primary function is to maintain the secondary side at 33 kV as the network voltage on the primary side fluctuates. That is to ensure proper operating conditions of the 33 kV equipment. However, a certain range of voltage deviations should be allowed for a certain time period. For the converters in the WTGs, the over- and undervoltage protection causes trips between 0.05 and 60 seconds if the voltage exceeds certain limits [34]. Trips due to OLTC control should be avoided as it disconnects generators. Figure 3.3 shows the relation between tripping times and voltage deviation. [34] specifies that the system can operate between 85% and 120% of the nominal voltage without tripping. That corresponds to the light grey area of Figure 3.3. Since voltage protection is not designed for the solar farm inverters, it is assumed to be identical. OLTC control is appropriate as the secondary voltage remains between these limits.

An additional functionality of OLTC is that it can aid in reactive power support at PCC. Adjustments of the OLTC tap positions changes the turn ratio. The changing reflected induced voltage affects the reactive power output of the OLTC. Appropriate tap positions can be determined by running power flow calculations for all generator conditions and for all tap positions, as is performed in [35]. Control actions can be based on this data. An other approach is to control according to the relation between tap position and dQ/dn. This relation is dependent on the R/X ratio of the lines and the wind speed (the active power output), as is derived in [36]. OLTC control can be performed according to this relation and by applying feedback from PCC. The

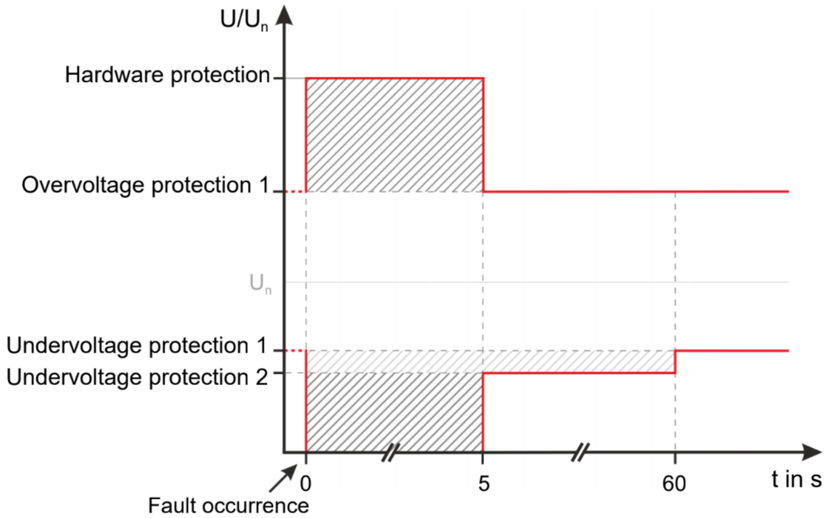

Figure 3.3: Over- and undervoltage protection and the tripping times of the wind energy converters [34].

latter approach is more appropriate as modeling errors do not affect the functionality of the control in a real system.

In situations where $\sum_{i=1}^{i=N} Q_{a,i} > Q_{s,PCC}$, the OLTC is controlled by maintaining the secondary voltage at 33 kV. It is appropriate to set a deadband for the secondary voltage, such that unnecessary control actions are avoided. Mechanical wear of the switching components increases maintenance [35]. When $\sum_{i=1}^{i=N} Q_{a,i} < Q_{s,PCC}$ and the reactor control has been performed, the OLTC taps change according to the dQ/dn relation. The OLTC tap changes are limited by the allowed secondary voltage of the wind energy converters. The tap changes are performed in steps of one tap change in order to check if the voltage limit will be reached at the next change. If ΔV_{sec} between two tap changes is larger than $|V_{limit} - V_{sec}|$ with the current tap, then further tap changes are not made. The OLTC control is considered at every instance of the reactive power control.

3.3.5 Communication With Optimisation Unit

The optimisation unit continuously calculates reactive power setpoints for strings with a time period of 15 minutes. At the initialization, the calculation of a setpoint valid for $t = 15$ minutes starts. This setpoint will be implemented at $t = 15$. The second setpoint is calculated between $15 \leq t < 30$ minutes and is implemented at $t = 30$. This process continues.

Active Power Prediction

An active power prediction is needed to determine future reactive power setpoints. The active power prediction is based on the active power controller, the initial active power output of strings, $P_{s,PCC}$, and the current- and expected wind speed and irradiance. Prediction of weather profiles is beyond the scope of this project, but is assumed to be available. The current- and expected wind speed and irradiance are linearly interpolated to obtain weather profiles. The predictor initializes the current active power string outputs. Active power control is executed with the profiles to maintain $P_{s,PCC}$. The final active power outputs of the strings serve as the prediction and are used in the optimisation algorithm. It should be pointed out that the final active power output can not directly be calculated. Eq. 3.3 depends on the available power and is therefore dependent on history.

Implementation Procedure of Optimisation Setpoint

Real-time control is necessary at a change of a $Q_{s,PCC}$ request. The change triggers a re-calculation of optimal setpoint. When the reactive power control reaches steady state and optimisation setpoints are available, the optimisation setpoint will be implemented. Stability is defined as the time duration $|\Delta Q_{s,PCC}|$ is between certain boundaries. Determination of the steady state boundaries and time duration is dependent on the simulation results and are described in Section 4.3.2. Violation of boundaries within the given time causes the stability check to be reset.

Chapter 4

Implementation and Validation

4.1 Wind Speed and Solar Irradiance Profile Generation

Wind speed and solar profiles are generated by taking a linear piecewise function of length t as a base line and adding noise. MATLAB's normrnd function generated a noise vector of length t/L from a normal distribution. The noise vector samples are smoothly interpolated with $L-1$ samples with MATLAB's intrpl1 function to match length t. For the wind speed, addition of one noise vector is adequate. Solar profiles require slow large and fast small variations and therefore two noise vectors are added. The frequency and magnitude of the generated wind speed profiles are similar to profiles generated in [33]. Similarly, the irradiance profiles match [37]. The resulting profiles are shown in Figure 4.1. Since the magnitude and frequency of the variations are realistic, the generated profiles are sufficient for testing and proof of concept.

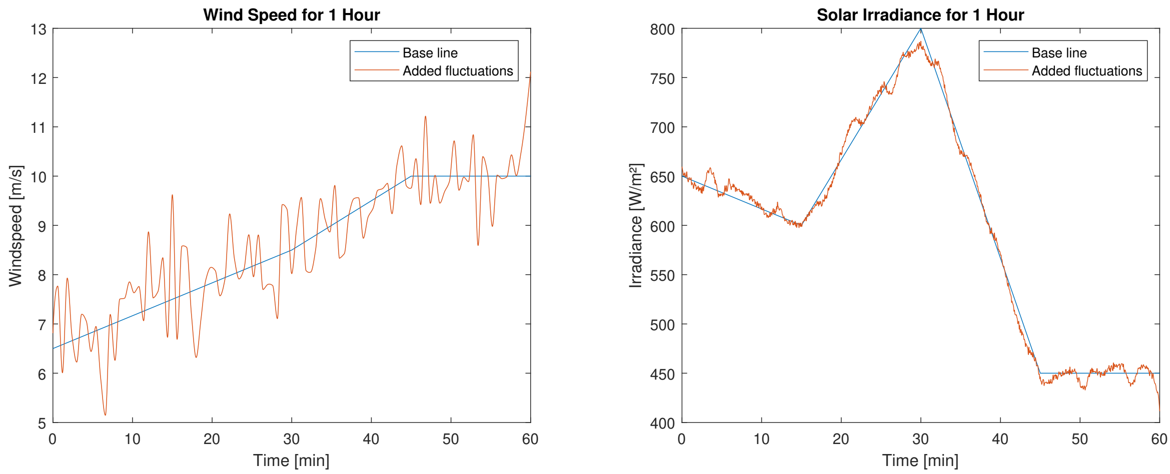

Figure 4.1: Wind speed and solar irradiance profile for testing of the complete CFC.

4.2 Testing Active Power Control

4.2.1 Implementation in MATLAB

The PPM which is being constructed by the company is modelled and simulated in MATPOWER. The equations in Section 3.2 are executed discretely in time steps.

In general, the flow of the code is as follows:

1. Calculate the available power based on the current wind speed and solar irradiance using the profiles from Section 4.1. The models used for calculating these values are given by [25].

2. Determine the difference between PCC set point and the current amount of active power delivered by the wind farm.

3. Based on this difference, the PCC set point, the available powers and the current amount of active power produced by the strings, use the framework given in Section 3.2 to calculate new set points for the strings.

4. Implement these set points by adjusting the generator values in the case file in MATPOWER. Run the power flow simulation to determine the new value at PCC. Repeat steps 1-4.

4.2.2 Results to Test Cases

The results for testing the active power control using the profiles given in Section 4.1 and the set points in Table 4.1 are shown in Figure 4.2.

Table 4.1: Active Power TSO Set Points used for simulation.

Active Power TSO Set Point [MW]	Time [s]
70	0
135	1800
100	2700

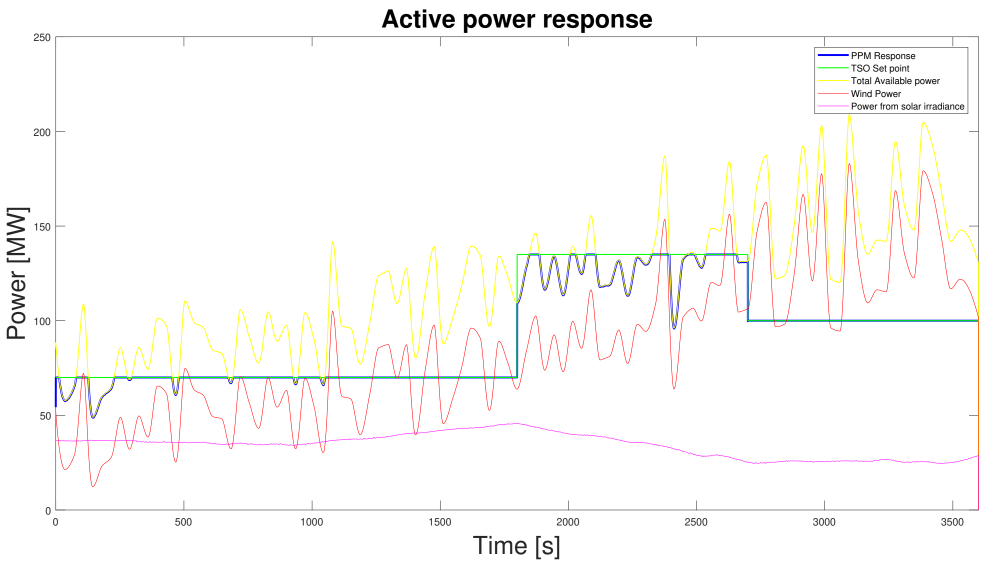

Figure 4.2: Active power tracking of the PPM given the profiles described in Section 4.1 and the set points shown in Table 4.1.

Regarding the test plan of Section 2.4.1, the active power control is able to implement and maintain set-points. Under- and overshoot are not visible and are therefore withing the maximum capacity of +/- 2%. Establishing the time period is problematic as the system tests is insensitive to α_p. Figure 4.2 also demonstrates that the maximum available power is maintained when it can not reach the setpoint. The system can therefore be operated at its maximum by setting an unreachable setpoint.

4.3 Testing Reactive Power Control Mode: Reactive Power

4.3.1 Implementation in MATLAB

The control loop mentioned in Section 3.3.1 is implemented in MATLAB discretely. The integral action is performed via the MATLAB function trapz.The active power outputs from the simulation in Section 4.2.2 are used to determine the available reactive power at each time instants via models given by [25]. The set points given by the optimization are only implemented once Q_{PCC} is stable and when the set points are within the capabilities of the strings. This procedure illustrates that reaching the set point is the top priority (according to the requirements).
Also, for this simulation the set points are implemented via a power flow simulation in MATPOWER to calculate the new Q_{PCC}. Based on the new Q_{PCC} the error $\Delta Q_{PCC} = Q_{s,PCC} - Q_{PCC}$ is calculated. Based on the error and the available reactive powers new set points are determined and the cycle continues. These relations between the different modules and the flow of the code are illustrated in Figure 4.3.

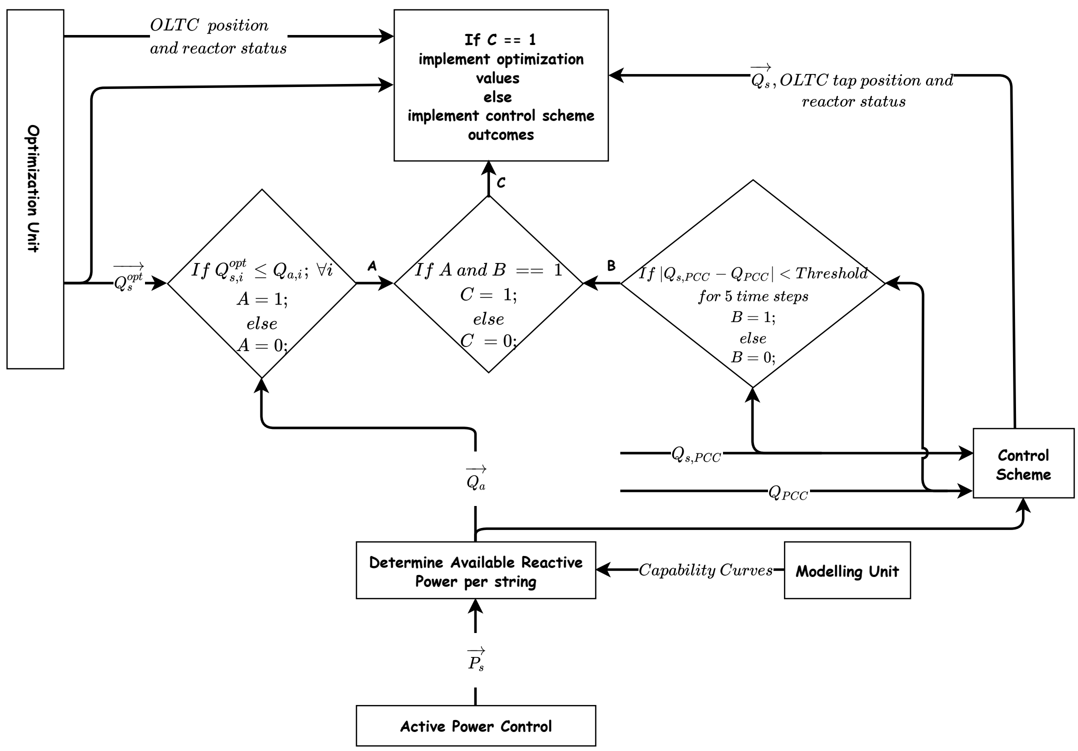

Figure 4.3: Flowchart showing the flow corresponding to the MATLAB implementation of the reactive power control in reactive power mode.

4.3.2 Results to Test Cases

The results for testing the reactive power control using the reactive power outputs from Section 4.2.2 are shown in Figure 4.4 and Table 4.2 below.

Table 4.2: Reactive Power TSO Set Points used for simulation.

Reactive Power TSO Set Point [MVar]	Time [s]
0	0
100	1800
-50	2700

Regarding the test plan of Section 2.4.2, the reactive power control mode is able to implement an increasing and decreasing setpoint and maintain setpoints. Figure 4.4 shows overshoot, but it is not possible to

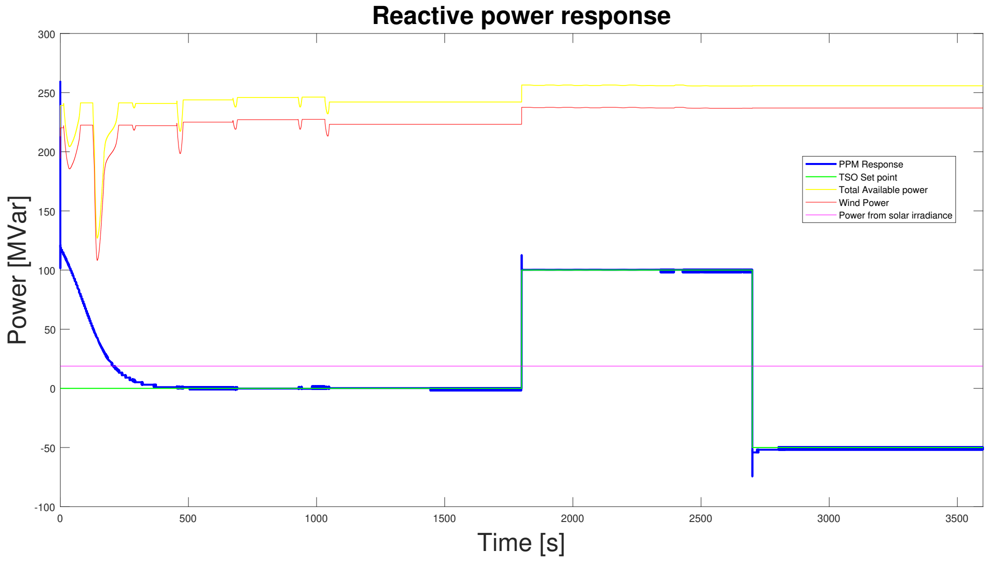

Figure 4.4: Reactive power tracking of the PPM given the active power output shown in the Section 4.2.2.

determine its adequacy as the maximum overshoot is undefined. The setpoint is maintained between +/- 2 MVAR in steady state. The first setpoint reaches steady state faster (in 1 second) than the second setpoint (in 30 seconds). That is due to the different magnitudes of $\Delta Q_{s,PCC}$. For the implementation of the optimisation set points this would imply that 1 second within steady state they are implemented. In the context of Figure 4.3, 1 second corresponds to 5 controller instances. An other remark about Figure 4.4 is the dip in available reactive power around 200 seconds. In Figure 4.1 this corresponds to a wind speed of 5 m/s. At wind speeds of 6 m/s much more reactive power is available. Tests for the implementation of an optimisation set point and reactor/OLTC control are not performed.

4.4 Testing Reactive Power Control Mode: Voltage Sub-mode 1

This reactive mode is not tested. More information on this will be given in Section 5.2.

4.5 Demonstration Program

A demonstrator program serves as a proof of concept and is aimed at a customer. A program is written in MATLAB App Designer where the codes of the controllers are implemented. The user can set the operation environment and the program will output the controller behaviour. The method for generating profiles is quick and flexible and is therefore useful for the demonstration program. Since the user can free experiment with the settings, the program is called Power Sandbox. User input settings include wind- and irradiance profiles types, selection of controller type and TSO setpoints changes. Output graphs are all shown in one output window. The graphs include the active- and reactive power exchange at PCC with setpoints, voltage at PCC, a few active- and reactive power string outputs with setpoints, OLTC tap position, shunt reactor state. Figure 4.5 shows the application window where the user can set the operating environment for a controller. The 'Run Simulation' will output the graphs, combined in one new window.

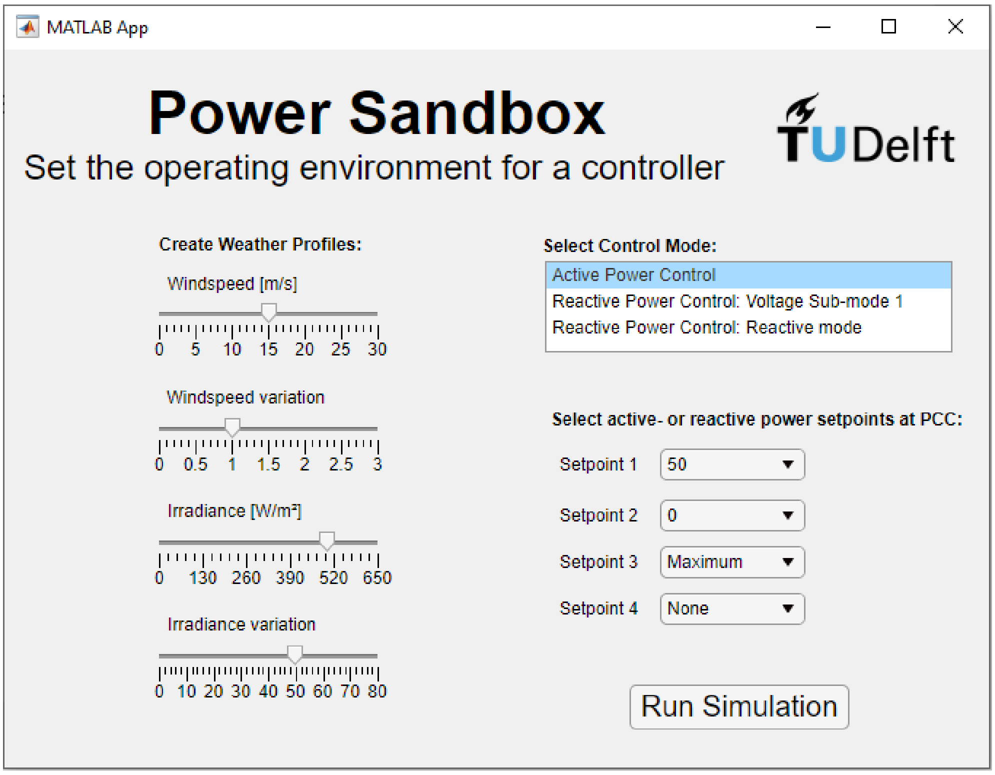

Figure 4.5: The application window where the user can set an environment for the controller.

Chapter 5

Conclusion

5.1 Validation of Requirements

The PoR from Section 2.1 is included in Appendix D. A validation comment is added after each requirement describing how the requirement is fulfilled. Most requirements are fulfilled by design. Validation of voltage sub-mode 1 requirements is not possible.

5.2 Conclusions for All Controller Types

Active Power Control

Looking at the results in Section 4.2.2, the active power control performs very well: When it's able to reach the set point it does and otherwise it follows the total available power quite closely. Furthermore, it can keep up with increasing or decreasing set points with little to no overshoot. However, when testing the control α_P appears to have a very small influence. Therefore, it is concluded that α_P doesn't require much attention when implementing the controller in a real PPM.

Reactive Power Control Mode: Voltage Sub-mode 1

Initially voltage sub-mode 1 is designed based on voltage droop from [29]. The design is insufficient for the requirements as the distribution of reactive power is not pro-rata and it does not internally change its voltage setpoint. This design can therefore not be included it the thesis, but is given in Appendix C.

Reactive Power Control Mode: Reactive power

The responses shown in Section 4.3.2 showcase that when the PPM in the reactive power control simulation is initialized with a Q production far from the set point it takes a few minutes before it reaches the set point. However, after those minutes it follows set point changes quickly but there are some overshoots. Furthermore, the tuning turned out to be quite complex since there are essentially three parameters to tune and their influence on the system is not straight forward.

5.3 Recommendation and Future Work

Physical realisation of the control unit and its implementation in a substation will be discussed in this section. IEC-60870-5 defines standards for power system automation systems. Communication of the controller with the TSO and string controllers is via the 104 protocol over fibre optic cables. The 104 protocol enables communication via TCP/IP (OSI layer 3-5) such that application data (OSI layer 7) can be delivered [38]. A signal list has to be set up listing all I/Os with their signal type, ranges and default value. All parties have to agree on the signal list. Communication procedures have to be specified during failures of communication modules. The hardware of the control unit consists of micro controllers which can be programmed in C according to the controller algorithms. Similarly, [32] has taken this approach to validate performance of the VSPI. The micro controllers need to be connected to communication units for the fibre optic cables, where A/D conversion occurs. All hardware needs to be organized in a cabinet for manageability of the substation building. A human-machine interface needs to be designed such that the control actions and device states can be moderated by the system operator. When the ATO is agreed, the controllers need to be tuned according to the given parameters. ENTSO-E RfG article 48 specifies testing requirements for the controllers [1]. This testing is performed in the real PPM. Despite that simulations have been performed for the controller designs, they are not required in practice.

A task that is simplified in this thesis is tuning. For a real system another tuning method is needed. Tuning based on the response of the real system instead of a MATLAB simulation is preferred to reduce the risk of obtaining non-optimal parameters for the controllers due to model inaccuracies. It is especially important for sensitive controllers such a the VSPI since their performance is quite sensitive regarding the tunable parameters. Executing this tuning can be done via the method specified in [12]. In [12], it is suggested to perform step-tests on the separate turbines. Using these measurements the frequency domain responses are determined and fitted with approximate (in [12] second order) transfer functions. These transfer functions can be combined to model the complete PPM and utilized to tune parameters of the controllers. This way, the tuning of the controller is based on the response of the real system.

Another simplification in this design is ignoring communication delays. For example the datasheet of the wind energy converters might list a certain time required for implementing a set point [34]. However, there is a communication delay when transmitting the set point signal from the CFC to the string controller. This is not taken into account for the simulations and therefore the real performance will probably will be less quick than expected compared to the simulation outcomes. Taking these delays into account and modelling them would make the simulations more accurate and thus more useful in determining whether the controller satisfies the requirements (such as rise-time requirements given by the TSO).

On a final note, many different tasks apply to the realization of a PPM. The automation engineering is only one part. When all works are finished, several Energisation Operational Notification steps have to be performed. Then the PPM will be ready to supply power to the grid. [redacted]

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Chapter A

Figures

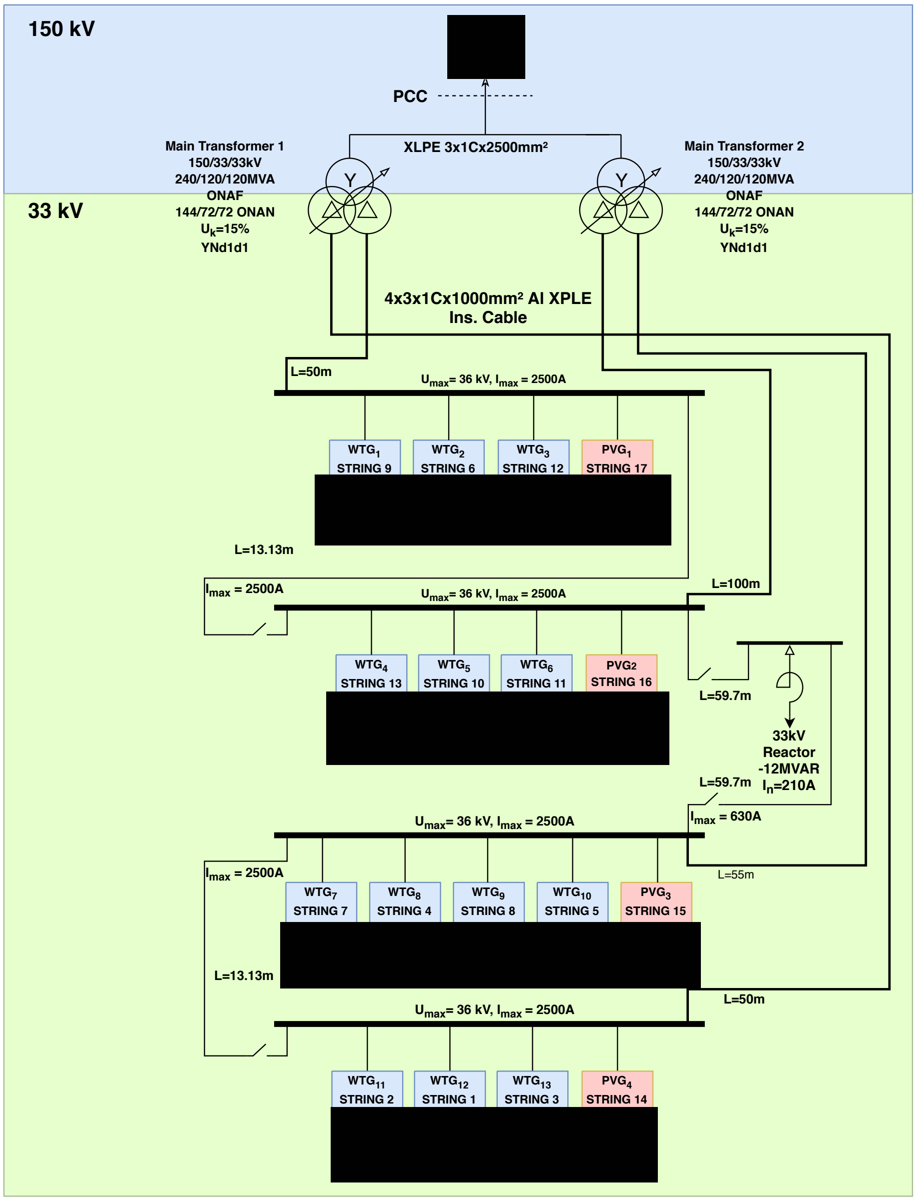

Figure A.1: A simplified SLD of the complete system.

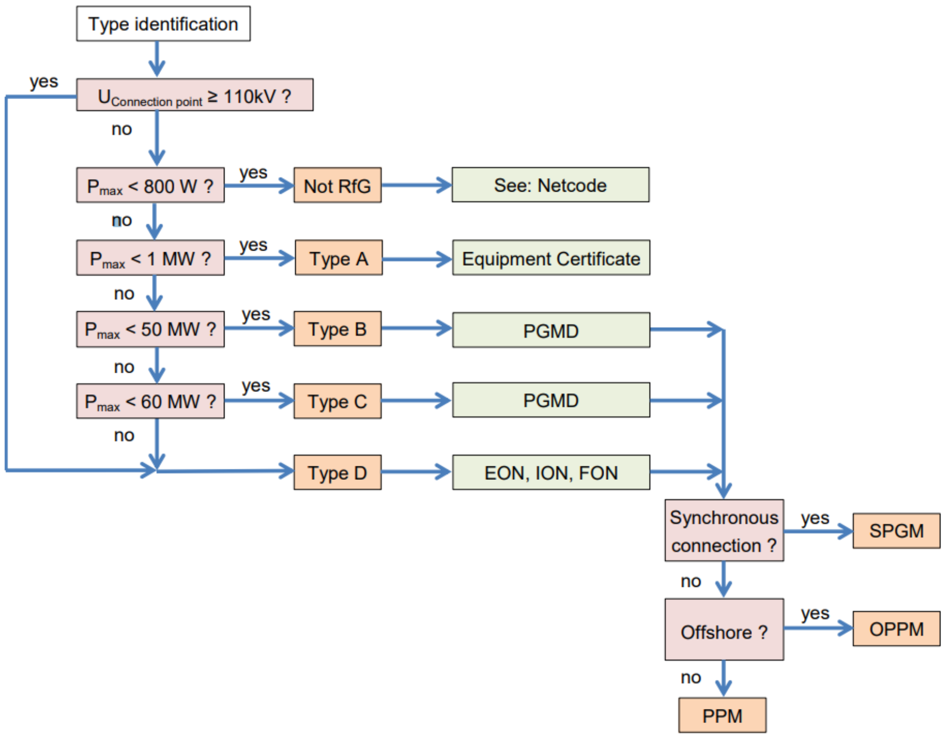

Figure A.2: Generator classification for RfG requirements [39].

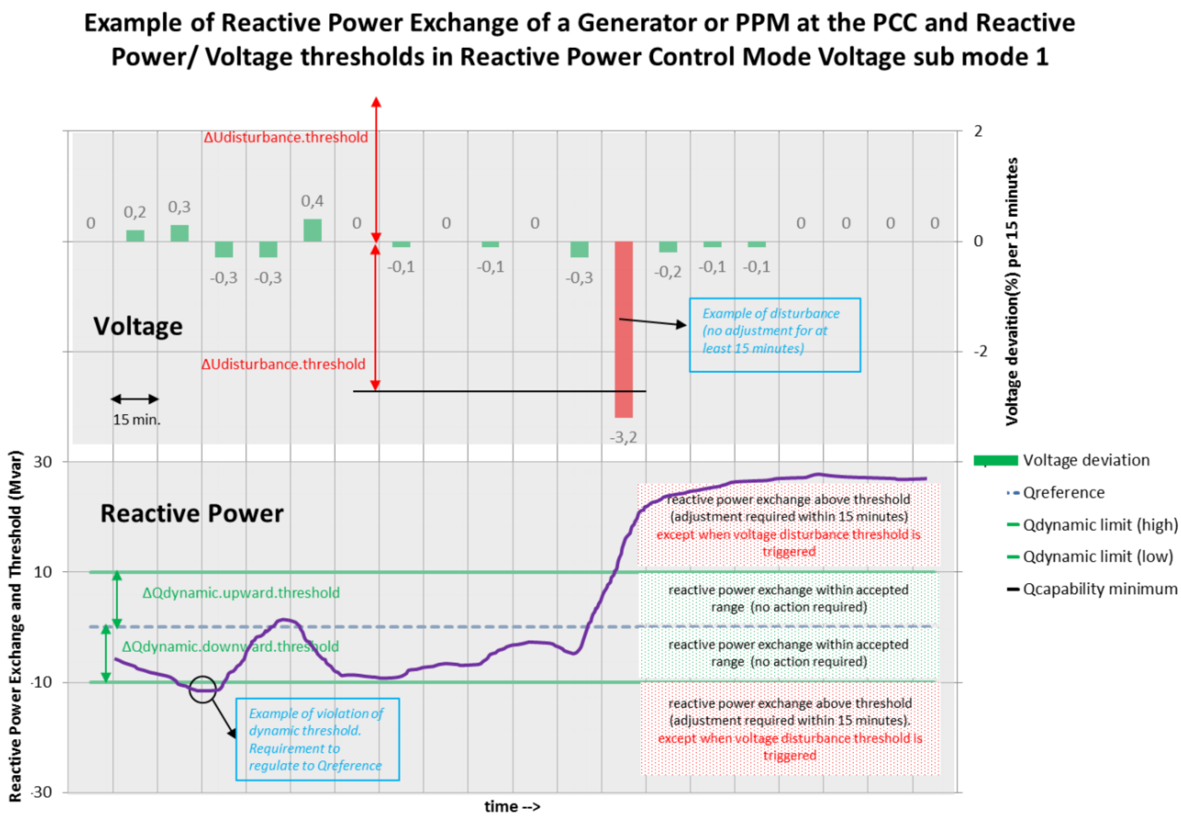

Figure A.3: Example of the reactive power exchange and corresponding voltage in relation to the thresholds in voltage sub-mode 1 [4].

Chapter B

Controller Parameters

Parameters for their controllers and their descriptions are given in this chapter and are from [4]. The following parameters hold for the voltage control. If applicable, their default values are given. Default values are bases on control characteristics of conventional generators.

- Default delay time for information. By default <0.5 second.
- t_1: time to reach 90% of the steady state values. By default 2.5 seconds.
- t_2: time required to settle at the steady state value. By default 7 seconds.
- Maximum voltage overshoot. By default 1%.
- Steady state reactive tolerance. By default < 5%.
- Steady state reactive power exchange. By default 0 MVAR, unless contractual arrangements are made.
- Δdynamic upper threshold. This value depends on the reactive power capability of the PPM and local network characteristics. It is typically set from 10% to 20% of Q_{max}.
- Δdynamic lower threshold is similar to Δdynamic upper threshold
- Frequency of violation of threshold voltage are checked continuously at least every 15 minutes.
- Estimated time and ramp rate to bring back the reactive power exchange to the reference value. This time is at least within 15 minutes and the ramp rate is dependent on time.
- Reference Tolerance for Reactive Power Exchange during adjustment of the voltage setpoint is +/- 1 MVAR.
- The selected base criterion is voltage or reactive power. By default it is reactive power.
- Δdisturbance upper threshold is given in MVAR or pu. It depends on the reactive power capability of the PPM and local network characteristics. Typically, it's value is above 20% of Q_{max} or is between 0.01 pu and 0.05 pu.
- Δdisturbance lower threshold is similar to Δdisturbance lower threshold.

Parameters for the reactive power control mode are not given in [4], but can be derived from the list of parameters for voltage sub-mode 1.

- Default delay time for information.
- t_1: time to reach 90% of the steady state values.
- t_2: time required to settle at the steady state value.
- Maximum reactive power overshoot.
- Steady state reactive tolerance.
- Steady state reactive power exchange. By default 0 MVAR, unless contractual arrangements are made.

Similarly to the reactive power control mode, parameters for the active power control can be set up.

- Default delay time for information.

- t_1: time to reach 90% of the steady state values.
- t_2: time required to settle at the steady state value.
- Maximum active power overshoot.
- Steady state tolerance.

Chapter C

Voltage Sub-mode 1 Design Based On Droop

[29] and [40] both propose a variable droop control scheme. In both cases, the proposed schemes seem to be able to improve voltage stability at the PCC. These results are important for the design of the controller in this thesis. The resulting voltage has to be stable at the PCC according to requirement RPC-VM-13. Thus, a variable droop control shall be considered for the design.

In [29], the control scheme was applied to determine reactive power set points for separate turbines. For this PPM, an adaptation shall be applied to determine set point for each string because looking from the outside in a string can also be considered as a generator. Therefore, the following equation applies:

$$Q_i - Q_{s,i} = \frac{-1}{R_i(V_{PCC} - V_{s,PCC})} \tag{C.1}$$

[29] proposes R_i to be proportional to $Q_{a,i}$. This is proposed because then the turbines with the highest available reactive power contribute more to the droop control compared to turbines with less available reactive power. Moreover, this reduces the possibility of reaching maximum operating limits of wind turbine converters which reduce wear outs to these inverters and reliability of the system.

In this thesis, an improvement of this control scheme is proposed. First of all, rewriting Eq. C.1 gives:

$$Q_{s,i} = Q_i + \frac{-1}{R_i} \cdot (V_{PCC} - V_{s,PCC}) = Q_i + \frac{-1}{R_i} \cdot \Delta V_{PCC} \tag{C.2}$$

The following formula for $\frac{-1}{R_i}$ is proposed:

$$\frac{-1}{R_i} \triangleq C_q \cdot \frac{Q_{a,i}^2}{Q_{a,i}^2 + \alpha_q} \cdot u(Q_{a,i} - Q_i) \triangleq C_q \cdot z_i \tag{C.3}$$

C_q will be the "normalization constant" and shall be dealt with expeditiously. z_i is the other part of the equation. This function is chosen because $\frac{-1}{R_i}$ and thus $Q_{s,i}$ increases when $Q_{a,i}$ of string i increases. This is appropriate since the strings with most capability at the time ought to contribute more to the droop compared to strings with less available power. The fraction is multiplied with the unit step function which equals 1 when $Q_{a,i} > Q_i$ and 0 when $Q_{a,i} \leq Q_i$. That is because a WTG should not produce more then its indicated maximum available power. Thus, when the turbine is performing at its maximum available power the control unit won't increase the set point.

Near the asymptote the function increases more slowly compared to a linear behaviour. This slow increase is more adequate since the set point reaches the limit less quickly. According to [29], wind turbines operating at maximum operating limits can increase wear outs of the converters and reducing the chances of reaching these limits improves the reliability. The quadratic behaviour was chosen because a higher order would change too fast. Thus, the function in Eq. C.3 is chosen to reduce the possibility of reaching the maximum operating limits.

α_P is a constant that can be tuned. Smaller α_P gives a more quick control since the function in Eq. 3.3 increases more rapidly. The opposite holds for a larger value. It can be tuned by simulating the active power response of the PPM to particular set points multiple times with varying α_P. For each simulation the rise-time + settling time and the overshoot can be determined. In this case rise-time + settling time indicates the time between detecting a set point and reaching it after a possible overshoot. The α_P required for a minimal rise-time + settling time and the α_P required for a minimal overshoot ought to be determined. Then, a trade-off has to be made between the two metrics to decide for an α_P with a reasonable performance for both rise-time + settling time and overshoot. The parameters requested by the TSO regarding these two have to be satisfied in the end in order to satisfy the requirements. α_P could be increased or decreased depending on the weather conditions. When the weather is quite volatile, it will have to be smaller to counter the quick deviations in the available power per string. If the weather doesn't deviate as much, this won't be necessary and a larger α_P will be chosen to reduce stress on the components by preventing fast changing set points.

According to [29], to ensure a droop of $-R_u$ at PCC, the following expression holds:

$$\sum_{i=1}^{i=N} \frac{1}{R_i} = \sum_{i=1}^{i=N} C_q \cdot \sum_{i=1}^{i=N} z_i = N \cdot R_u \Rightarrow C_q = \frac{N \cdot R_u}{\sum_{i=1}^{i=N} z_i} \tag{C.4}$$

Thus, $\frac{-1}{R_i}$ becomes:

$$\frac{-1}{R_i} = \frac{N \cdot R_u}{\sum_{i=1}^{i=N} z_i} \cdot z_i \tag{C.5}$$

Fig. C.1 The control scheme.

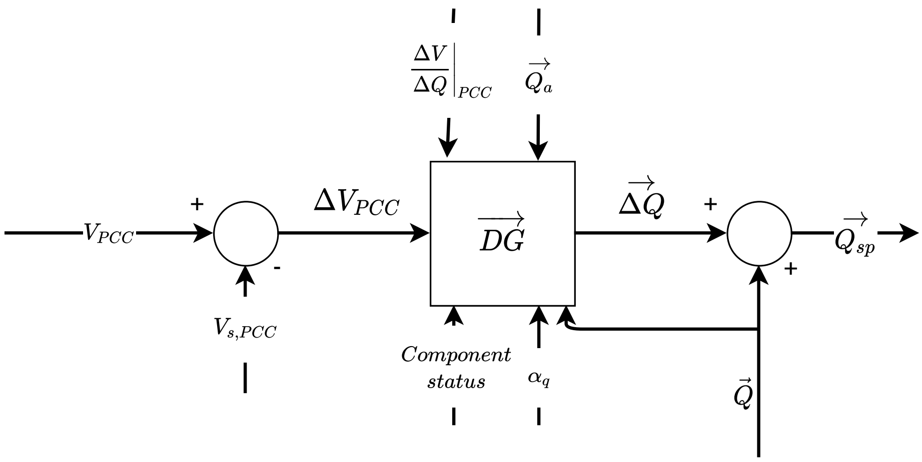

Figure C.1: Proposed droop control scheme.Component status indicates whether all strings are operational.

Chapter D

Validation of Requirements

Table D.1: Validation by means of comments of the PoR from Section 2.1 with requirements based on [1, 3, 4, 28].

Identifier	Requirement text	Source
Central farm control		
CFC-01	A central farm controller is required to ensure compliance to the grid codes and divide the load between generator strings. The central farm controller gives active- and reactive power setpoints to the controllers of the strings. The controllers on string-level are outside the scope of this project.	[28]
Validation Comment	Grid compliance is ensured by implementing the TSO's active- and reactive power setpoints by means of giving string setpoints. When the reactive power capability of the strings is insufficient, the shunt reactor and OLTC are employed.	
CFC-02	The measuring point for the central controller is at PCC. Response of the controller must be based on this measurement.	[28]
Validation Comment	The values at PCC are measured and function as feedback to the control.	
Active Power Control		
APC-01	With regard to active power controllability and control range, the Power-Generating Module control system shall be capable of adjusting an active power setpoint in line with instructions given to the Power-Generating Facility Owner by the relevant system operator or the relevant TSO. The relevant system operator or the relevant TSO shall establish the period within which the adjusted active power setpoint must be reached. The relevant TSO shall specify a tolerance (subject to the availability of the prime mover resource) applying to the new setpoint and the time within which it must be reached.	RfG Article 15.2.(a)
Validation Comment	According to the simulations, the active power control implements and maintains TSO setpoints. When the wind and irradiance is insufficient, power can not be delivered. However, TSO setpoints are always in the capability of the PPM [4]. Tuning of the period is which the setpoint is implemented proves to be difficult, as tuning parameter α_p does not affect the system much. The system maintains the setpoint very well, such that tolerance is no issue.	
APC-02	The Power-Generating Module is capable of receiving a setpoint of the active power and to follow it according to the instructions of the relevant TSO. The following conditions apply: a. The control range is between the minimum regulating level and the actual maximum capacity, unless otherwise agreed between the TSO and the connected party b. The time period within which the adjusted setpoint for the active power must be achieved is laid down in the Connection Agreement (ATO) c. The tolerance for the new reference value is +/-2% of the maximum capacity.	Netcode elektriciteit Article 3.24

Validation Comment	a. This is implied in the TSO setpoint b. The ATO is not available. The system reacts very fast, which could affect the grid frequency. The system seems untunable due to the insensitivity to α_p. c. The system maintains the setpoint very well, such that tolerance is no issue.	
APC-03	Absolute production constraint - The function must be able to limit the wind farm's active power production in the PCC's to a maximum specifically indicated active power reference value (MW).	[28]
Validation Comment	This is implied in setting the TSO setpoint.	
Reactive Power Control		
RPC-01	The following reactive control modes must be available: • Reactive power control - The function must control the reactive power output according to an indicated reactive power reference value (MVAr). • Voltage control – The purpose of this function is to regulate the reactive power output at PCC based on the voltage measurement, according to the requirements stated in the TSO grid codes. • Power Factor control - The function must control the reactive power output to have a constant power factor for varying active power production according to an indicated Cos(φ) value. However, Power Factor mode is omitted from the project.	RfG Article 21.3.(d).(i) and [28]
Validation Comment	Reactive power control is designed for reactive power control mode and voltage sub-mode 1. Power Factor mode is disregarded from the thesis as its sensitivity issues would be too farfetched. Voltage sub-mode 2 is disregarded because of its similarities to sub-mode 1. It would therefore add no value to the thesis.	
RPC-02	The default reactive power exchange at PCC is 0 MVAR. An capacitive or inductive offset in typical steps of 50 MVAR can requested by the network operator for a time interval. The time interval is typically one or several hours.	[4]
Validation Comment	The reactive power control is designed by taking the default of 0 MVAR with steps of 50 MVAR into account. These setpoints were taken as a guideline in the testing and in the demonstration program.	
RPC-03	Reactive power output cannot excess the limit of the wind farm reactive power capability.	[28]
Validation Comment	The reactive power is distributed within the limits of what is available corresponding to the string's active power output. By design, the reactive power limit of strings can not be exceeded.	
RPC-04	The controler can activate the 33 kV shunt reactor and OLTC according to the control strategy.	[28]
Validation Comment	The reactive power schemes employ the reactor and OLTC in case the turbine capabilities can not satisfy the TSO reactive power setpoint.	
RPC-05	The Network Operator determines the Reactive Power Control Mode (Voltage or Reactive Power).	[4]
Validation Comment	The control unit has a input signal for mode selection.	
RPC-06	Operation in the Forbidden Area (outside the park's power capability) is accepted in case it is caused by the parameters and control characteristics of the activated Reactive Power Control Mode.	[4]
Validation Comment	In the reactive power control overshoot can occur specifically.	

RPC-07	The Set Point type is coupled to the selected Reactive Power Control Mode.	[4]
Validation Comment	The reactive power control is based on the TSO reactive power setpoint. Voltage sub-mode 1 determines the voltage setpoint in relation to the reactive power setpoint.	
RPC-08	The Reactive Power Capability will apply pro rata to the amount of Generating Units In Service.	[4]
Validation Comment	All generator units inject or absorb reactive power in the same proportions of their capability, that is pro rata.	
Reactive Power Control Mode: Voltage Sub-mode 1		
RPC-VM-01	Voltage control (U-control) is characterized by Voltage Droop, Set Point Voltage and Control Speed.	[4]
Validation Comment	The PPM's voltage droop had been determined by [25] and is implemented in voltage sub-mode 1. The system can internally calculate a new voltage setpoint. Control speed is based on the VSPI in the reactive power control, which is integrated in voltage sub-mode 1.	
RPC-VM-02	Because the Reactive Power Control mode is Voltage the Reactive Power Exchange by the PPM at the PCC depends on the Voltage at the PCC.	[4]
Validation Comment	The voltage at PCC is an input of voltage sub-mode 1	
RPC-VM-03	The PPM must have the ability to determine locally the Set Point Voltage based on the Agreed Steady State Reactive Power Exchange at the PCC indicated by the Reference Steady State Reactive Power Exchange. The PPM must have the ability to process the Reference Steady State Reactive Power Exchange indicated by the Network Operator.	[4]
Validation Comment	Local determination of the setpoint is based on the droop relation and violation of the dynamic thresholds.	
RPC-VM-04	Every 15 minutes the Reactive Power Exchange at the PCC must be brought back by the PPM to the Agreed Steady State Reactive Power Exchange by adjustment of the Set Point Voltage (adjustment is only required in case the Reactive Power Exchange is outside a defined dead band).	[4]
Validation Comment	The VSPI can control the reactive power exchange sufficiently fast. A deadband is implemented	
RPC-VM-05	For the purposes of voltage control mode, the Power Park Module shall be capable of contributing to voltage control at the Connection Point by provision of reactive power exchange with the network with a setpoint voltage covering 0,95 to 1,05 pu in steps no greater than 0,01 pu, with a slope having a range of at least 2 to 7 % in steps no greater than 0,5%. The reactive power output shall be zero when the grid voltage value at the Connection Point equals the voltage setpoint. The default Voltage Droop is 10% at the PCC. This means that in case the Actual Voltage at the PCC drops with 10% the maximum Reactive Power Capability (100%) must be injected in the Network.	RfG Article 21.3.d.(ii) and [4]
Validation Comment		
RPC-VM-06	The PPM must determine the Set Point Voltage every time the Reactive Power Exchange has to be brought back to the Agreed Steady State Reactive Power Exchange.	[4]
Validation Comment	When Q_{PCC} becomes equal to $Qs,_{PCC}$, the voltage setpoint is adjusted to the corresponding value V_{PCC}	

RPC-VM-07	The setpoint may be operated with or without a deadband selectable in a range from zero to ± 5% of reference 1 pu network voltage in steps no greater than 0,5%.	RfG Article 21.3.d.(iii)
Validation Comment	Implementation of a deadband was not preferred, since its function does not fit a 'perfect' MATLAB environment. In a real design, a deadband would be more appropriate.	
RPC-VM-08	Following a step change in voltage, the Power Park Module shall be capable of achieving 90% of the change in reactive power output within a time t1 to be specified by the relevant system operator in the range of 1 to 5 seconds, and must settle at the value specified by the slope within a time t2 to be specified by the relevant system operator in the range of 5 to 60 seconds, with a steady-state reactive tolerance no greater than 5% of the maximum reactive power. The relevant system operator shall specify the time specifications.	RfG Article 21.3.d.(iv)
Validation Comment	These parameters are included in the ATO, which is unavailable. Tuning could have been performed according to the default values, but the system is only tuned to obtain a reasonable looking result.	
RPC-VM-09	Regarding Voltage control sub-mode 1: • In case the reactive power exchange at the Connection Point has exceeded the predefined Dynamic Threshold (solid green lines in the figure 4.14), but has not exceeded the predefined Disturbance Threshold, the setpoint voltage must be adjusted by the PPM to re-establish the agreed steady state reactive power exchange at the Connection Point within 15 minutes (this is a slow control function over the voltage control). • In case the reactive power exchange at the Connection Point or the voltage deviation at the Connection Point exceeds the predefined Disturbance Threshold (solid red lines in the figure 4.14), the reactive power support of the PGM must be maintained for at least 15 minutes (this is a standard voltage control functionality).	Netcode elektriciteit Article 3.26.12
Validation Comment	Implementation of the thresholds is performed and the behavior is implemented in the design.	
RPC-VM-10	When initiating Reactive Power Control Mode Voltage the Set Point Voltage must be made equal to the Actual Voltage at the PCC.	[4]
Validation Comment	The voltage is initialized to the initial measured value of V_{PCC}	
RPC-VM-11	The Set Points and Slope (Voltage Droop) must be adjustable, during normal operation.	[4]
Validation Comment		
RPC-VM-12	Adjustment of the Operating Point of the Slope must be possible within 15 minutes, to adjust the reactive power exchange a the PCC.	[4]
Validation Comment		
RPC-VM-13	During adjustment of the Set Point Voltage the Reactive Power Control Mode must remain Voltage.	[4]
Validation Comment	It remains voltage mode.	
RPC-VM-14	The Reactive Power Control Mode Voltage must result in a stable and damped behaviour of the voltage at PCC.	[4]
Validation Comment	Stability and damping are emphasized by using a VSPI in the control rather than a PI.	
Reactive Power Control Mode: Reactive Power Control		

RPC-RC-01	Reactive Power control (Q-control) is characterized by its Set Point Reactive Power and Control Speed.	[4]
Validation Comment	Reactive power mode takes the TSO reactive power request as input. Control speed can be tuned with the variables of the VSPI.	
RPC-RC-02	The PPM must have the ability to process the Set Point Reactive Power indicated by the Network Operator.	[4]
Validation Comment	Reactive power mode takes the TSO reactive power request as input.	
RPC-RC-03	During normal operation (Reactive Power regulation at the PCC) the controller must periodically check for changes of the Set Point reactive Power indicated by the Network Operator.	[4]
Validation Comment	The controller checks for setpoint changes at every instance.	