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B A C H E L O R   T H E S I S

Topic: Technical Requirements for Wind Power Plants Connected to the Electrical Grid in Finland and Market Analysis for Services of M.O.E.

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Declaration

I hereby declare that this bachelor thesis has been written only by the undersigned and without any assistance from third parties. Furthermore, I confirm that no sources have been used in the preparation of this thesis apart from those mentioned in the list of references.

Itzehoe, 29.07.15
Place, Date

Möller
Signature

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Sven Ole Möller

Abstract

The energy transition from conventional to a more sustainable energy production leads to increasing requirements for grid integration of power generating facilities from renewable resources. At the same time, grid codes become more important and complex. This thesis analyses the technical requirements for grid integration of wind power plants in Finland and compares these with the requirements in Germany. Furthermore, it evaluates market chances for services of M.O.E. in Finland.

In particular, the requirements in the Finnish grid code VJV2013 and the German VDE-AR-N 4120 are examined while considering the development of wind power in both countries. At present, wind power does not significantly influence the Finnish energy production and the technical requirements for grid integration of wind turbines in Finland are reasonable according to the currently installed wind power capacity. In specific parts, such as power quality and plant modelling, the VJV2013 is more stringent, but generally the requirements are not as extensive as in the German equivalent. Especially in terms of the upcoming European grid code NC RfG, the Finnish requirements will have to undergo further changes.

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1 Introduction

In Europe the renewable power capacity is continuously increasing. Forcing a change in the European energy production not only results in a lot of advantages but also provides new challenges. Changes in the pattern of energy production —from conventional power plants to decentralised renewable power plants—is based on the idea of creating a more sustainable environment by reducing greenhouse gas emissions. A very important topic referring to the change in energy production is the integration of renewable power plants into the electrical grid.

In the past, most renewable energy power plants were shut down during grid instabilities and conventional power plants were responsible for re-establishing the defined quality. Since more and more renewable power capacity is being integrated into the electrical grid, it is important that renewable power plants should remain connected to the grid during unexpected events or failures. A shutdown of such plants in case of an electrical failure nowadays will cause a large shortage of power in the electrical grid and most probably result in a major blackout. This is because the electrical backup capacity does not cover the installed power capacity from renewable power plants in countries with a high share of renewable energy production. For example, Germany was providing approximately 93 GW of its total electricity capacity from renewable energy sources in 2014 [1], whereof a maximum of approximately 40 GW were in operation at the same time in December 2014 [2]. The backup capacity was only around 3 GW in the same year [3], which means that even partial shutdowns of more than 3 GW will cause massive problems. For this reason, technical requirements for renewable energy plants have been developed. The requirements for electrical grid connections are defined in specific grid codes, laws and technical guidelines, and they usually vary from one country to another.

M.O.E. is specialised in grid integration of wind power plants to confirm the compliant behaviour in electrical grids. At present, M.O.E. focuses on the German market but is also contemplating providing its services to other European countries. Therefore, it is interested in improving its expert knowledge in Finnish regulations and to explore the requirements to integrate wind power plants into the Finnish grid.

This thesis considers technical standards to integrate wind power plants into the electrical grid as well as economic aspects in terms of the development of wind power and market chances for M.O.E. in Finland. Chapter 2 illustrates the development of wind power plants in the European Union and, in particular, wind power in Finland and Germany to give an overview of the current situation. To understand the central points of integrating renewable power plants into the electrical grid, the relevant electrical characteristics and the corresponding technical requirements in Finland and Germany are considered in Chapter 3. The specific technical requirements in terms of grid integration of wind power plants into Finland's electrical grid are mentioned in Chapter 4. These requirements are then compared with the German standards. In addition, the differences between Finnish and German standards are critically reviewed. Finally, this thesis explores possible business areas for M.O.E. in Finland, considering its potential customers, economic potential, barriers, and chances in the Finnish energy market.

2 Comparison of Wind Power Development

The European Union is actively promoting the energy transition and has set ambitious climate targets for 2020. Referring to the initiative '20-20-20', the European Union has agreed to increase the total energy consumption produced from renewable resources to 20 %. To fulfil this objective, every EU country must commit to specific action plans [4].

The following figure illustrates the huge growth of wind power in the European electric power capacity since 2000.

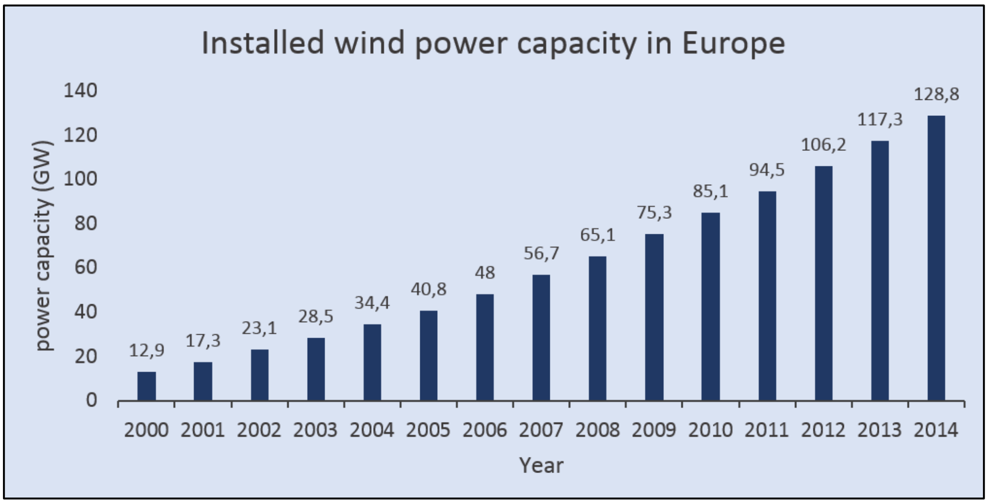

Figure 1: Installed wind power capacity in Europe [5].

Renewable energy power plants have accounted for more than 50 % of the newly installed power capacity per year since 2007. In particular, wind power has continuously increased during the illustrated period of time. In 2014, wind power reached 14.1 % of the market share and is still growing at the expenses of the oil, coal, and nuclear power industries [5]. For this reason, technical requirements and obligations to integrate renewable energy power plants into the electrical grid are important and necessary.

2.1 Wind Power in Finland

The share of renewable energy production in Finland is already one of the highest in Europe. At the end of 2013, 36 % of Finland´s electricity generation was from renewable resources.

Finland, one of the most forested countries in Europe, generates around 16 % of its power from wood-based energy sources such as black liquor, a waste product of the pulp industry. In addition, hydropower accounts for another 19 % of Finland´s power generation. In 2013, less than 1 % of the Finnish power capacity was provided by wind power plants and other yield-dependent energy sources [6]. The target for 2020, set by the Finnish government, is to reach a share of 38 % of renewable energy sources to comply with the European energy programme '20-20-20'. Since wind power did not have a significant influence in Finland´s power generation until the European energy programme came into effect, it is now considered as one of the main technologies to raise the country's share of renewable power generation even more. The action plan of Finland to fulfil the European energy programme´s target —submitted in 2010—includes the development of wind power towards a power generation of 6 TWh in 2020 [7]. This means a growth in the Finnish wind power capacity towards approximately 2,500 MW [8]. To realise this objective, the 'Act on Production Subsidy for Electricity Produced from Renewable Energy Sources' established a feed-in tariff system in 2011 [9]. Wind power in Finland has been growing since 2010 due to the relatively new targets in the Finnish energy politics. The increase of wind power is illustrated in Figure 2.

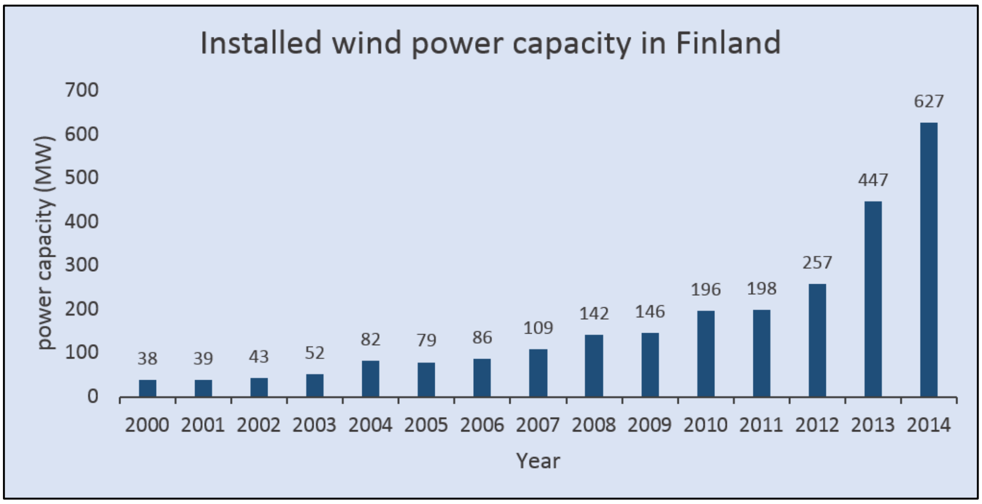

Figure 2: Total wind power capacity in Finland [10].

2.2 Wind Power in Germany

Germany established the renewable energy law (EEG) in 2000 to force the energy transition. The EEG was adjusted several times to adapt to specific market situations and reach defined political targets. Since the EEG is in force, the share of renewables stepped up from 7 % in 2000 to 25.8 % by the end of 2014. A fixed compensation for electricity fed into the grid and a guaranteed purchase are the key factors in Germany´s major growth in the renewable electrical power capacity [11].The target, set by the German government, is to reach a share of renewables in Germany's power capacity of 40–45 % in 2025 and more than 80 % in 2050 [12].

The installed wind power at the end of 2014 was 38,115 MW. Referring to the total power capacity in Germany, wind power provides 8.6 % of the entire electricity generation, and it accordingly accounts for the highest share in Germany´s power capacity from renewable energies. Furthermore, wind energy is constantly increasing since the EEG came into effect. Figure 3 illustrates the development of wind energy from 2000 to 2014 in Germany [13].

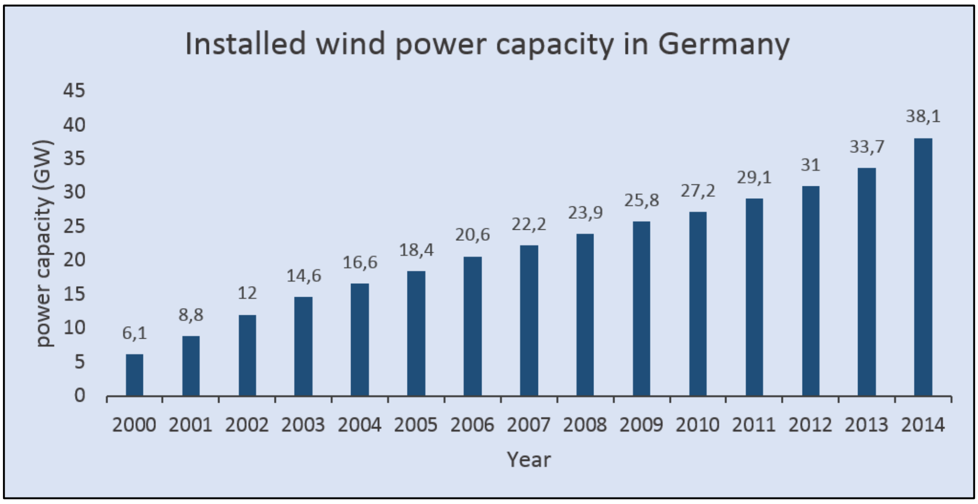

Figure 3: Total wind power capacity in Germany [13].

Compared to other European countries, Germany has the largest installed wind energy capacity (30.4 %), followed by Spain (17.9 %) and the UK (9.7 %), related to the total share of wind power in Europe [5].

3 Standardisation for Grid Integration of Renewable Energies

Technical frame conditions are necessary to secure grid stability, a reliable power supply, and continuous power quality. Nearly every country has set specific requirements in this regard. According to M.H.J. Bollen [14], there are three main reasons for standardisation in grid integration:

- specify nominal values for defined parameters
- specify a certain method for measurements and test
- reduce the quantity of disturbances, failures, and other problems.

Several critical electrical characteristics and safety devices are relevant for fulfilling these standards.

3.1 Relevant Electrical Characteristics and Protection Devices

Figure 4 illustrates an overview of the central points to ensure a stable electrical grid and a defined power quality.

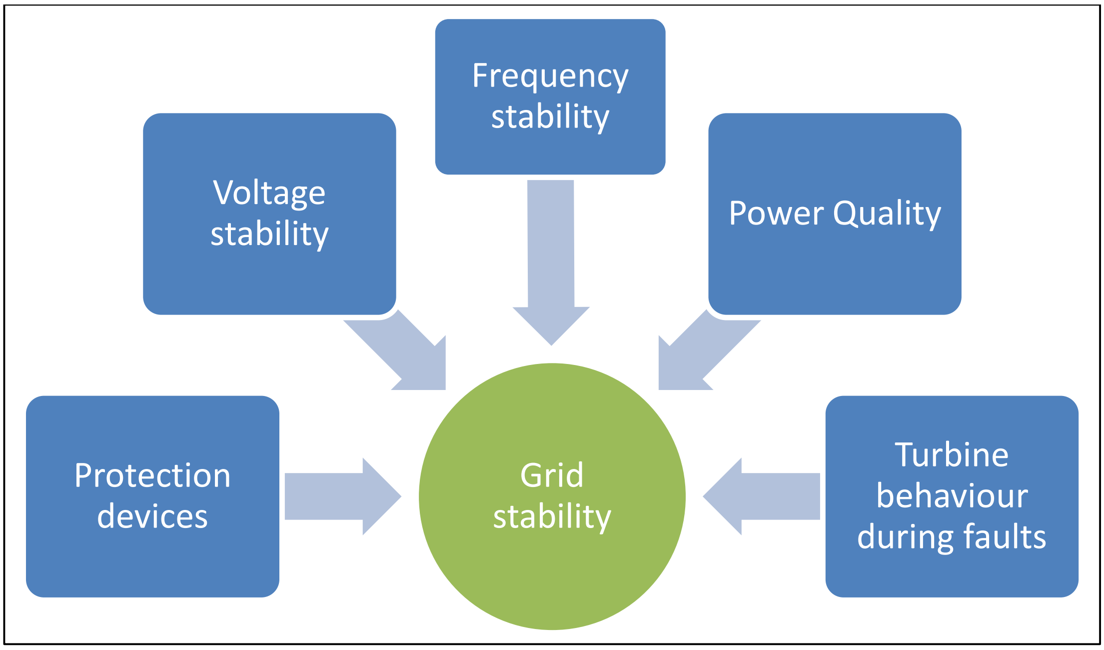

Figure 4: Central points to ensure a stable electrical grid and a defined power quality.

3.1.1. Voltage Stability

Ideally, the voltage level in electrical grids should be constant (for example, 110 kV). In practice, the voltage level varies slightly due to changes in load and energy production, tap changing of transformers, switching operations of capacitors and reactors, and line losses. The provision of reactive power in electrical grids is essential to maintain a steady voltage level. Therefore, power plants should be able to provide capacitive and inductive reactive power, depending on the demand in the electrical grid.

3.1.2. Frequency Stability

The nominal frequency of the interconnected grid in Europe is 50 Hz. Maintaining a constant frequency in the electrical grid is important with regard to the damaging effects for power-generating and power-consuming machines connected to the grid. In general, deviations from the nominal frequency are caused by energy supply and consumption imbalances. Therefore, it is important to adjust the electricity production continuously. In fact, wind power plants should be able to change their active power feed-in for this purpose.

3.1.3. Turbine Behaviour during Faults

The occurrence of voltage dips in electrical grids is not avoidable. Several circumstances—for example, short circuits, lightning strikes, or a simultaneous connection of large-scale power consumers—can be responsible for voltage dips. If there happens to be a huge amount of installed wind power, it would be fatal to shut down such power plants in the above-mentioned cases. For this reason, wind power plants should stay connected to the electrical grid during voltage dips and remain the active power feed-in after fault finding. The technical declaration for this process is FRT (Fault-Ride-Through) [15]. Furthermore, power-generating units are meant to support the electrical grid by reactive current feed-in, in order to re-establish the nominal voltage level during grid faults.

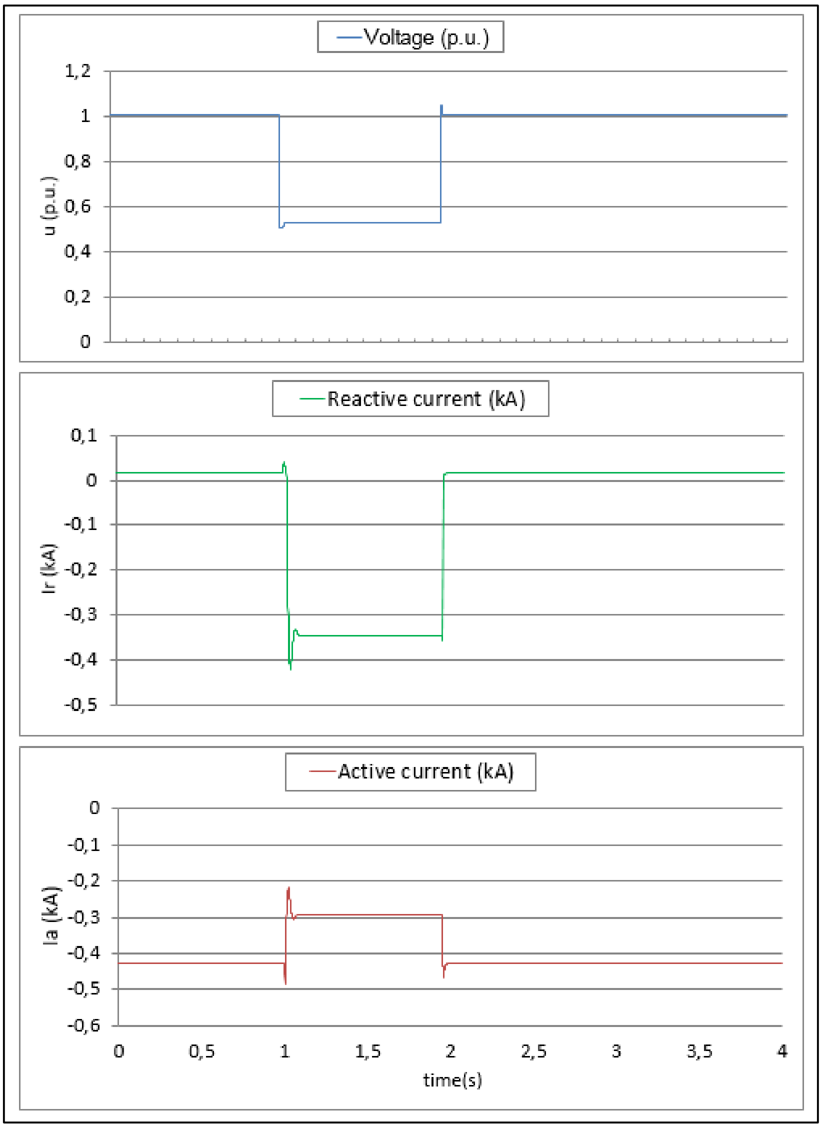

Figure 5: Results of a LVRT simulation and the reactive current feed-in.

Figure 5 illustrates the results of a voltage drop simulation. The simulation was made in *DigSilent Powerfactory*, including realistic data and dynamic turbine models provided by a wind turbine manufacturer. The illustration presents a voltage drop to 50 % of the nominal voltage for 1 s. During the fault, the power plant operates in the LVRT mode (Low-Voltage-Ride-Through). The active current decreases, while the reactive current increases to support the electrical grid.

3.1.4. Protection Devices

Protection modules are necessary to prevent power plants and electrical grids from any damage that may happen due to unreasonable operating conditions. With reference to the TC 2007 [16], such unreasonable operating conditions are for example:

- short circuits
- over-voltage / under-voltage
- over-frequency / under-frequency
- asynchronous operation
- others.

Specific safety parameters have to be defined for such operating conditions by grid operators and turbine manufacturers to avoid risks. At wind power plants, protection modules are usually integrated into every power-generating unit, distribution station, and transformer station.

3.1.5. Power Quality

Harmonics and inter-harmonics, flicker, and fast voltage drops due to switching operations are generally considered to be the main voltage disturbances. Therefore, boundary values are necessary to ensure a safe operation of electrical components and to limit flicker. Such impacts are usually measured by wind turbine manufacturers for the relevant turbine types and are given in specific values to utilise them for different types of connection points. For fast voltage drops of a power-generating facility, a load flow simulation is necessary to assess the influence.

3.2 Technical Regulations in Finland

In Finland, the electricity transmission grid is run as a monopoly. The national transmission grid operator (≥ 110 kV) is Fingrid Oyj. In addition, there are many small distribution grid operators. The Finnish Energy Market Authority imposes all responsibilities in terms of the national grid system on Fingrid and continuously observes the market [17]. Therefore, Fingrid sets all technical requirements for grid connections. The relevant documents are:

- YLE2013 [18]
  Describes main principles and general connection terms.

- VJV2013 [19]
  Describes specific technical requirements for power-generating facilities.

All power plants with an installed power capacity above 0.5 MW and connected to the electrical grid in Finland have to fulfil these requirements. The power plant operator is required to prove compatibility when the generating units are directly connected to Fingrid's connection lines. Wind power plants are usually connected to medium-voltage grids. In this case, the distribution grid operator is obligated to prove the compatibility of the wind power plant at the connection point [20]. Technical requirements are almost completely described in the VJV2013 [19] and hence essential for this elaboration.

3.3 Technical Regulations in Germany

Germany is one of the pioneers in the energy transition and already provides more than 35,000 MW of power capacity from wind power plants. There are a lot of important regulations in Germany because of this reason and an open market structure. There are up to 900 different grid operators acting in the German medium and high-voltage grid system. The essential regulations are listed in the following:

- SDLWindV [21]
  It describes the specific technical requirements for wind power plants to receive EEG feed-in tariffs enforced by the EEG [12]. In most of its requirements the SDLWindV refers to the BDEW MSR 2008 [22] for connections to medium-voltage grids and with intensive changes to the TC 2007 [16] for connections to high-voltage grids.

- BDEW MSR 2008 [22]
  It describes the technical requirements for power plants connected to the medium-voltage grid in Germany.

- TC 2007 (Transmission Code 2007) [16]
  It describes the technical requirements for power plants connected to the high and highest-voltage grid in Germany.

- VDE-AR-N 4120 (TAB high voltage) [23]
  The VDE-AR-N 4120 will replace the TC 2007. It is already in force since 1 January 2015 but provides a transition period of two years. This guideline was composed together with several interest groups, such as grid operators and power plant operators, as well as with independent electrical engineers.

The mentioned regulations are the most important ones in Germany. In addition, there are more recommendations and technical guidelines for specific characteristics, measurements, and certification. Furthermore, there are specific regulations published by every grid operator.

4 Grid Code Comparison

The Finnish requirements, set by Fingrid, are related to the high-voltage transmission grid. Therefore, it is reasonable to compare the Finnish regulations with the recently established regulations described in the VDE-AR-N 4120 [23] in Germany.

The VDE-AR-N 4120 refers to two types of power-generating units: type one describes synchronous generators with direct coupling to the electrical grid, while all other power-generating units belong to type two. Modern wind power plants are exclusively units of type two. For this reason, power-generating units of type one are not considered further in this thesis.

The Finnish grid code VJV2013 covers the voltage levels of 110 kV, 220 kV, and 400 kV. There are no essential differences in the technical requirements for power plants in accordance with the voltage level. Therefore, values on a percentage basis are converted for a voltage level of 110 kV to compare them with those mentioned in the VDE-AR-N 4120. In addition, the VJV2013 refers to different power classes for several requirements. The power classes are listed in the following:

- Power Class 1: 0.5–10 MW
- Power Class 2: 10–25 MW
- Power Class 3: 25–100 MW
- Power Class 4: > 100 MW

4.1 Range of Operation

The operational area of a power plant describes the range of voltage and frequency within which the plant must be able to operate without being disconnected from the electrical grid.

Requirements in accordance with VJV2013 [19]

According to the Finnish grid code, power plants have to operate permanently within the voltage range of 99 kV to 115.5 kV and a frequency range of 49 Hz to 50.3 Hz without any change in the active or reactive power capacity. Beyond this range, power plants have to operate at least for a specific time, as described in Figure 6.

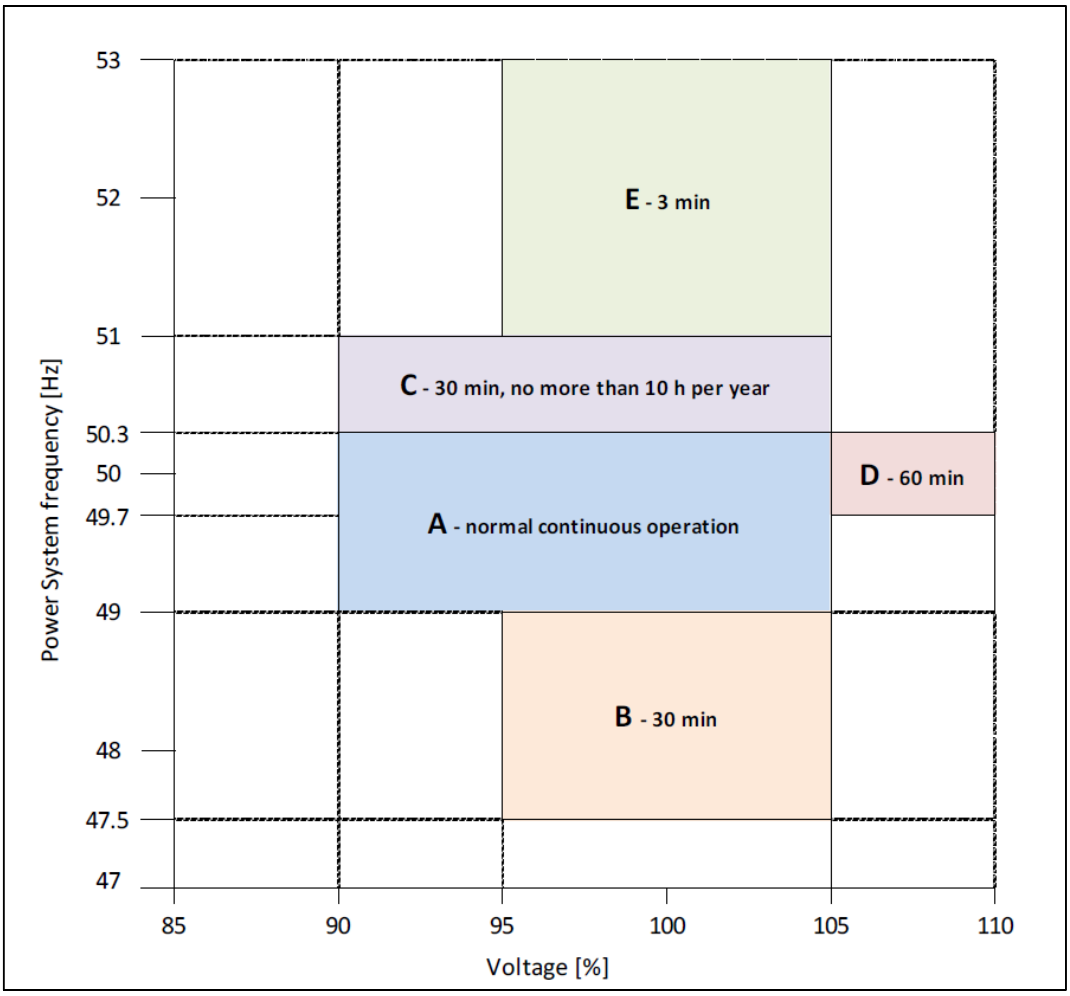

Figure 6: Continuous operation range (VJV2013) [19].

Apart from the normal operating range (A), a decrease in the active power feed-in is allowed in defined limits.

For frequencies below 49 Hz down to 47.5 Hz (B), a linear reduction from 100 % to 85 % is permitted. From 50.3 Hz to 51 Hz (C), a power decrease of 10 % is allowed if the power plant can operate with the initial power capacity, in case the frequency falls below 50.3 Hz. During over-frequencies from 51 Hz to 53 Hz (E), a rapid decrease in power generation is applicable.

While the voltage level is between 115.5 kV and 121 kV (D), power plants are allowed to decrease the active power feed-in by 10 %.

Outside such operating ranges, immediate disconnection from the electrical grid is not desired, and the power plants should continue to operate while considering the technical limits.

Requirements in accordance with VDE-AR-N 4120 [23]

Referring to the VDE-AR-N 4120, power plants connected to the high voltage grid in Germany have to operate without any limitation from 96 kV to 123 kV and 49 Hz to 50.5 Hz. Similar to the Finnish requirements, there are time limits for deviations from the normal range of operation. Figure 7 illustrates such requirements.

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Figure 7: Continuous operation range (VDE-AR-N 4120) [23].

For a supply voltage below 96 kV, power plants are required to operate normally for at least three minutes. Below 93.5 kV, power-generating plants are allowed to disconnect immediately for quasi-stationary operating conditions.

The power-generating facility has to remain connected to the electrical grid while the voltage is above 123 kV for a minimum of 30 minutes. If the increased voltage persists for more than 30 minutes or the voltage is higher than 127 kV, it is allowed to immediately disconnect for quasi-stationary operating conditions.

For frequencies above 50.5 Hz up to 51.5 Hz, power plants must stay connected to the grid for at least 30 minutes. However, the requirement for under-frequencies between 49 Hz and 47.5 Hz is in staggered intervals. Power-generating plants have to maintain the connection for 30 minutes between 49 Hz to 48.5 Hz, 20 minutes for 48.5 Hz to 48 Hz, and at least 10 minutes for 48 Hz to 47.5 Hz.

For safety reasons and to maintain the connection for as long as possible, power plants are allowed to reduce the active power beyond the range of continuous operation. Outside the ranges that are illustrated in Figure 7, power plants are allowed to disconnect immediately from the electrical grid for quasi-stationary operating conditions.

Comparison and remarks

In both grid codes the range of operation is described in detail. The requirements referring to the VDE-AR-N 4120 cover a wider voltage range than the VJV2013. Figure 8 compares both ranges.

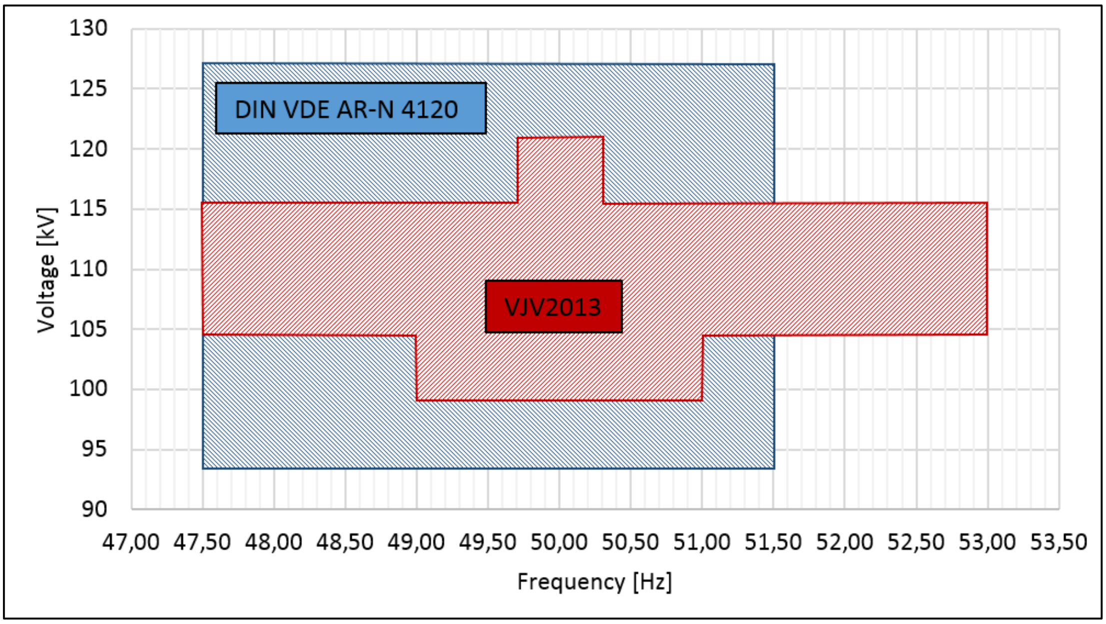

Figure 8: Continuous operating range (VJV2013 in red, VDE-AR-N 4120 in blue).

The difference in terms of the operating range is reasonable since there is a huge amount of decentralised power plants in Germany, and, therefore, an early shutdown due to deviations from the nominal conditions would cause massive problems in the electrical grid. In general, the electrical grid and the power generating plants have to be more flexible in order to generate more energy from yield-dependent renewable energy sources like solar and wind power. At present, the share of such energy sources in Finland is rather low. As more flexibility in the electrical grid means more costs in terms of grid and plant development, the requirements set by Fingrid are sufficient at the moment. Increasing the share of wind and solar power plants remarkably would change the situation and be an argument to extend the range of continuous operation. Modern wind power plants already cover a wider range.

The wider frequency range in the VJV2013 up to 53 Hz is reasonable for electrical grids with a low short-circuit capacity and hence bigger fluctuations of the frequency. Experts in Germany are also considering enlarging this range for a new guideline in terms of the medium-voltage grid.

The VDE-AR-N 4120 and the VJV2013 refer to minimum requirements in terms of the operating range. In general, disconnection from the electrical grid is only desired when there are risks for operational safety of the corresponding power plants or the relevant grid operator requires disconnecting at earlier stages by considering their electrical grid structures.

Furthermore, the VJV2013 allows a linear reduction in active power generation of 15 % during under-frequencies—from 49 Hz to 47.5 Hz. A decrease in the active power generation in this case is absolutely unintentional and refers to direct coupling to the electrical grid due to the frequency-dependent generators of big power plants. More active power is needed to stabilise the frequency, and standby power plants are normally put into operation. Usually, wind power plants are connected to the electrical grid with electric power converters and hence the turbine does not depend on the grid's frequency. It means that a reduction of the active power feed-in is not desired and would not be applicable for wind power plants during under-frequencies.

4.2 Voltage Stability

To stabilise and influence the voltage level, power plants should be able to generate inductive and capacitive reactive power. The reactive power value must be controllable within defined ranges by the grid operator to guarantee a safe operation of the electrical grid.

Requirements in accordance with VJV2013 [19]

Referring to the reactive power capacity and the control mechanism of wind power plants, there are different requirements for the separate power classes.

There are no requirements for wind turbines of Power Class 1 (0.5–10 MW) in terms of the reactive power capacity. For this type of wind turbines, Fingrid imposes the relevant network operator to set plant-specific requirements.

For wind power plants of Power Class 2 (10–25 MW), the requirement for the reactive power capacity at the connection point is a power factor cos φ of 0.995 under-excited when the voltage is between 99 kV and 110 kV, and a power factor cos φ of 0.995 over-excited when the voltage is between 110 kV and 115.5 kV. There is no requirement for the reactive power capacity below the minimum output of the wind turbine. The minimum output is turbine-specific and describes the smallest possible active power feed-in without any time limitation measured at the connection point. Figure 9 illustrates these requirements.

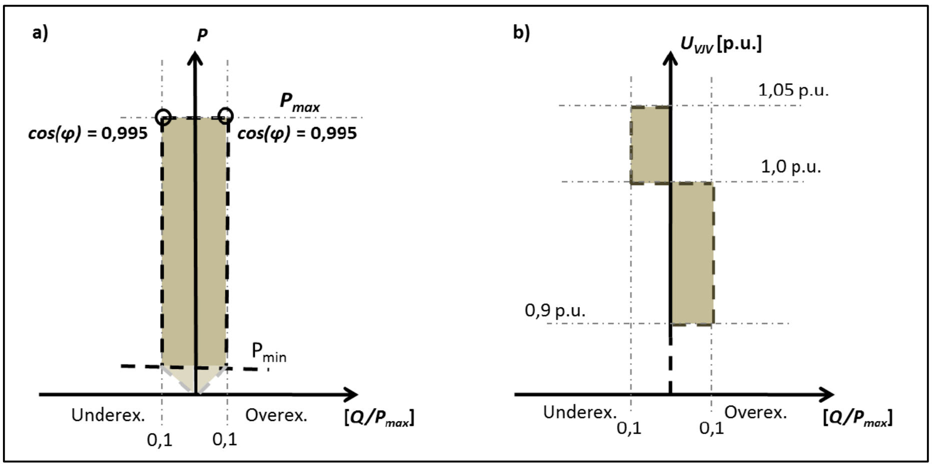

Figure 9: Requirements for the reactive power capacity of wind turbines of Power Class 2 (VJV 2013) [19].

The mentioned power factor of cos φ of 0.995 under and over-excited means a reactive power capacity of ± 10 % in accordance with the maximum power capacity of the wind turbine.

Larger wind power plants in terms of Power Classes 3 and 4 (> 25 MW) require a wider range of the reactive power capacity. A power factor cos φ of 0.95 under and over-excited is required at the maximum power output. For lower outputs than the maximum, the requirement decreases linearly until a power output of zero megawatt. The voltage range is not changing compared to the turbines of Power Class 2. Figure 10 illustrates these requirements.

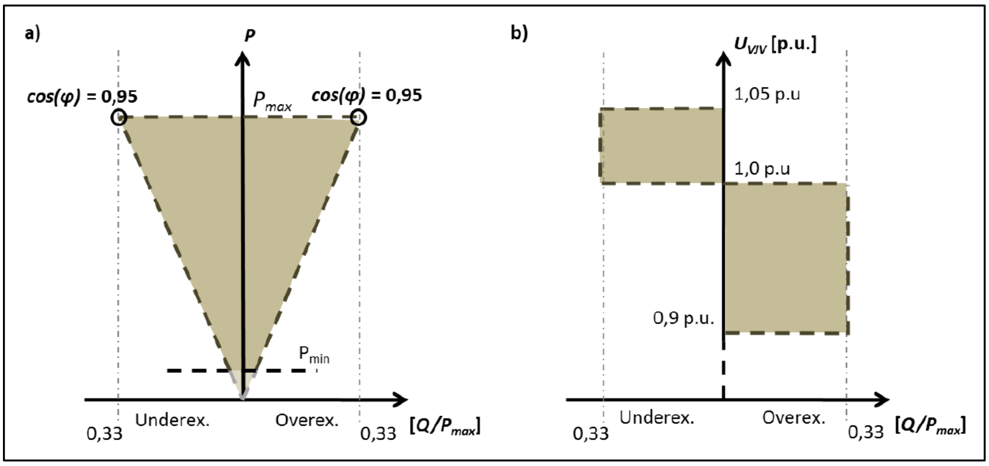

Figure 10: Requirements for the reactive power capacity of wind turbines of Power Classes 3 and 4 (VJV2013) [19].

The extended range of the power factor equals a reactive power capacity of ± 33 % of the maximum power feed-in.

Power plants of Power Class 1 are generally allowed to operate with a constant power factor of cos φ of 1 at the connection point. The generating facilities of Power Classes 2, 3, and 4 must be equipped with a voltage and reactive power control unit to fulfil the requirements. There are three different control modes in accordance with the VJV2013:

- Constant reactive power control

Direct control of the reactive power at the connection point. The step-size of the control unit must not exceed 1 Mvar.

- Constant power factor control

Direct control of the power factor at the connection point. The step-size of the control unit must not exceed 0.01 between the power factor of cos φ of 0.95 under and over-excited.

Remark:

The power factor control range with cos ϕ of 0.95 over and under-excited is not consistent with the requirement for the reactive power capacity of power-generating facilities of Power Class 2.

- Constant voltage control

Direct control of voltage at the connection point within the range of continuous operation (cf. Chapter 4.1). The maximum step-size is 0.01 p.u. The slope of the voltage control should be linear and controllable within a range of 10 % from the nominal voltage. For changes in the voltage level below 0.05 p.u., the wind turbine has to respond with the following speed:

  - 90 % of the total change in reactive power must be reached within 1 s.
  - The step response must not overshoot the measured reactive power by more than 15 %.
  - The reactive power must settle to the set value within 3 s.

The control unit is meant to work in the same way irrespective of whether it is controlled locally or through a remote control. Furthermore, mode changes must not cause significant changes in power plant operation (e.g., oscillations or changes in the rated capacity).

The same control modes are required for wind power plants of Power Class 4, but advanced analyses in terms of the controller settings are necessary due to the big impact for the electrical grid system.

Requirements in accordance with VDE-AR-N 4120 [23]

For the reactive power capacity of power-generating units, the relevant network operator can predetermine one of three variants in accordance with Figure 11. The relevant grid operator will choose one of these options, considering its specific grid requirements. For grid integration of the power plant, the chosen variant must be fulfilled at the connection point. The illustrated requirements refer to the installed active power capacity of the power plant $P_{b,inst}$.

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Figure 11: Requirements for the reactive power capacity of power plants during nominal operation in different variations (VDE-AR-N 4120) [23].

Variant 1 equals a cos φ of 0.975 under-excited up to 0.9 over-excited, Variant 2 equals a cos φ of 0.95 under-excited up to 0.925 over-excited, and Variant 3 equals a cos φ of 0.925 under-excited up to 0.95 over-excited.

In addition to the requirements for the nominal active power feed-in, the VDE-AR-N 4120 also describes requirements for the reactive power capacity for part load operation. The illustrated characteristic curves in Figure 12 point out the requirements in accordance with the same variations given in Figure 11.

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Figure 12: Requirements for the reactive power capacity of power plants during part load operation according to the variations in Figure 11 (VDE-AR-N 4120) [23].

In part-time load, there are no requirements for the supply of reactive power at the grid connection point when the active power is below 10 %. However, when the power-generating facility operates below 10 % of its maximum power capacity, it is not allowed to generate more reactive power than 5 % of the maximum agreed active power capacity. Above 20 % of the nominal output, the full reactive power capacity in accordance with the specific variant must be available.

Furthermore, the grid operator can demand several options to control the reactive power capacity with reference to specific parameters.

- Q(U) characteristic

The power plant must adjust the reactive power feed-in as a function of the voltage level at the grid connection point. The required reactive power must be provided within a time range of 5 s to 60 s (settling time). For certain situations, the relevant grid operator is allowed to dictate a time between 2 s and 5 s. In this case, the power plant operator must be timely notified.

The reactive power must settle to the set value within 3 s plus the settling time. Figure 13 illustrates an example for a Q (U) characteristic.

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Figure 13: Example of a Q (U) characteristic (VDE-AR-N 4120) [23].

The relevant grid operator can dictate the following parameters for the characteristic:

- dead-band between ± 0 kV and ± 2.5 kV
- gradient between 3 % and 12 % per kV
- upper voltage limit between 118 kV and 123 kV
- lower voltage limit between 96 kV and 110 kV.

- Q (P) characteristic

This control mode generates a specific reactive power, depending on the current active power feed-in of the wind turbine. The relevant grid operator can dictate 10 basic values. In between these basic values the interpolation must be linear. The settling time must not exceed four minutes. This control mode must be disengageable to operate the power plant with a power factor of 1.

- Constant reactive power control

The control unit directly controls the reactive power output of the power plant. It can be either a fixed value or variable by remote control. The relevant grid operator dictates the set point in accordance with the installed power capacity. Otherwise, the default value should be 0 %. The settling time must not exceed four minutes, and the reactive power value must be adjustable in steps of at least 1 %.

- Constant power factor control

Direct control of the power factor is set in such a way that the ratio of active and reactive power feed-in remains constant. The minimum step size must be 0.005, and the settling time must not exceed four minutes. Also, for this option, the relevant grid operator dictates the set point remotely. Otherwise, the default value should be 1.

In general, the tolerance between the measured reactive power value and the set point value is a maximum of 5 % of the maximum power capacity of the generating facility.

Comparison and remarks

It is to be noted that the Finnish grid code does not require smaller power plants below 25 MW to take part in the continuous static voltage stability, since there are only minor requirements for the reactive power capacity of power plants in Power Class 2 and none for power plants of Power Class 1. The VDE-AR-N 4120 does not differentiate in terms of the nominal power feed-in of power plants. Therefore, small wind power plants have to comply with those requirements in Germany. Overall, the requirements described in the VDE-AR-N 4120 are much higher than those in Fingrid's VJV2013 in terms of the range of the power factor and the voltage ranges. Figure 14 compares both ranges.

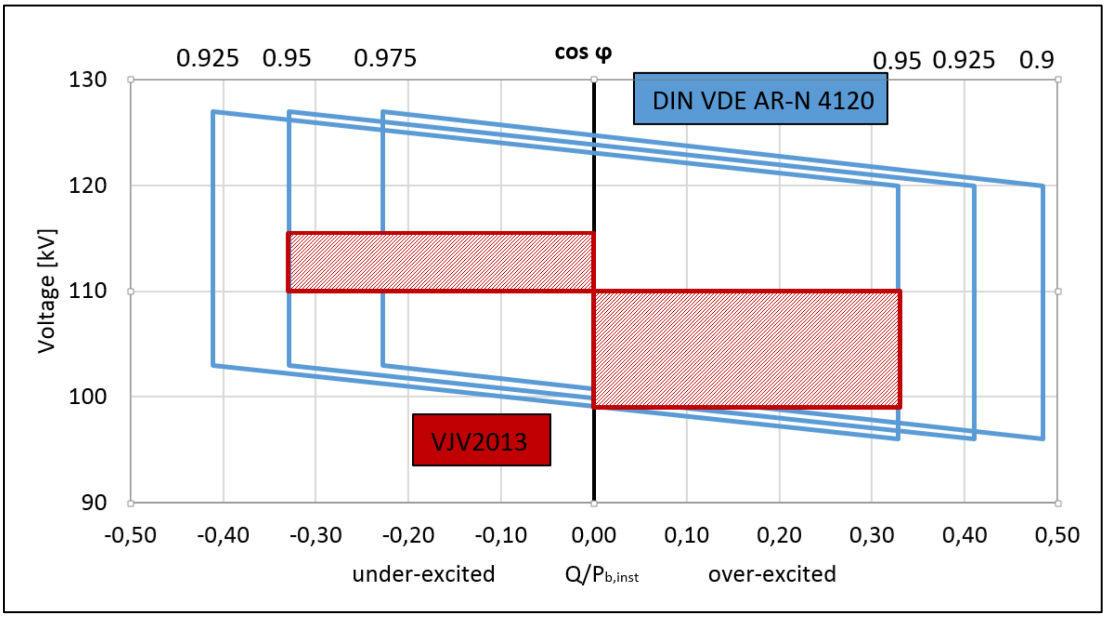

Figure 14: Reactive power capacity ranges (VJV2013 in red, VDE-AR-N 4120 in blue).

The dimensioning of the transformer station is a key factor to accomplish a wide voltage range. Modern transformer stations are able to adjust to the actual voltage due to automatic step positioning. This must be considered during the planning phase. Also, the requirements for part load operation are stricter in accordance with the VDE-AR-N 4120. While the requirements in the Finnish VJV2013 decrease with reduced power feed-in, the VDE-AR-N 4120 only softens the requirements below 20 % of the maximum power capacity. The reason is a fixed power factor in the requirements referring to the VJV2013. In contrast, the VDE-AR-N 4120 requires a fixed reactive power capacity.

Furthermore, the relevant grid operator can choose between three different variations for the reactive power range in accordance with the VDE-AR-N 4120. This allows for additional flexibility, and, therefore, grid operators can integrate new power plants easier in terms of the specific needs of their electrical grid systems. In addition, there are more specific requirements for the control mechanism of power plants in Germany. Especially, parameters for characteristic curves are given in more detail. In Germany, a lot of decentralised power-generating units are connected to the grid. This leads to stronger voltage fluctuations and hence to stricter requirements for the reactive power capacity and the control units.

4.3 Frequency Stability

The balance between generated and consumed active power is the most important point in terms of frequency stability. Therefore, it is important to be able to reduce the power generation during over-frequencies and increase it during under-frequencies.

Requirements in accordance with VJV2013 [19]

The VJV2013 describes its requirements in the context of the continuous operation range (cf. Chapter 4.1). For this reason, Table 1 summarises the requirements.

Table 1: Summary of the active power requirements in terms of frequency deviations.

Frequency range [Hz]	Voltage range [kV]	Active power requirement
49–50.3	99–115.5	No change in active power allowed
49.7–50.3	115.5–121	A reduction of 10 % is allowed
50.3–51	99–115.5	A reduction of 10 % is allowed when the power plant is able to operate with the initial output if the frequency decreases below 50.3 Hz
51–53	104.5–115.5	Rapid decrease of the active power feed-in allowed
49–47.5	104.5–115.5	Linear reduction of the active power feed-in from 100 % to 85 % is permitted

Remark:

A reduction of the active power feed-in for under-frequencies is only reasonable for direct-coupled generators. Therefore, it is assumed that the allowed linear reduction in the active power feed-in during under-frequencies in the VJV2013 only refers to direct-coupled generators.

Requirements in accordance with VDE-AR-N 4120 [23]

The VDE-AR-N 4120 requires a change in the active power feed-in whenever the frequency is above 50.2 Hz. This is shown by Figure 15.

PROTECTED CONTENT

Figure 15: Requirements for the active power feed-in depending on the frequency.

Within a frequency range of 50.2 Hz to 51.5 Hz in the electrical grid, power plants must reduce or increase the active power feed-in linearly with a gradient of 40 %/Hz.

The momentary active power feed-in at the time the frequency exceeds 50.2 Hz is relevant for the calculation. The following equation describes the active power behaviour between 50.2 Hz and 51.5 Hz. Within the mentioned range, the active power feed-in depends on the frequency. Above 51.5 Hz, an immediate shutdown of the power plant is required.

$$\Delta P = 20\, P_m \frac{50.2Hz - f_{grid}}{50Hz} \tag{1}$$

A step size of 10 % is sufficient for the active power reduction. In addition, power plants must be able to reach the set point with a gradient of 20 % of the installed power per minute. Furthermore, if the frequency falls below 50.2 Hz and the available primary energy is higher than at the point of exceeding 50.2 Hz, the active power increase must not exceed 10 % per minute. A reduction of at most 20 % during under-frequencies is only allowed for direct-coupled power plants.

Comparison and remarks

The requirements in the VDE-AR-N 4120 are given in more detail. While the VJV2013 requires a rapid power decrease for over-frequencies above 51 Hz and a decrease of 10 % from 50.3 Hz to 51 Hz, the VDE-AR-N 4120 requires a defined active power adjustment whenever the frequency is above 50.2 Hz. A detailed account of the meaning of rapidly decreasing the active power is missing in the requirements of Fingrid.

Owing to the given formula in the VDE-AR-N 4120 and the related characteristic curve, power plants are able to react very flexibly in terms of frequency deviations.

Furthermore, both grid codes consider the active power reduction of direct-coupled power plants for under-frequencies. Due to the lower frequency, direct-coupled generators operate with a lower number of revolutions and therefore a lower active power feed-in. In general, wind power plants are connected to the electrical grid via power converters. For this reason, a reduction of the active power feed-in during under-frequencies is not applicable.

A revision of the requirements in terms of frequency stability, mentioned in the VJV2013, is reasonable to clarify the behaviour of power plants during over and under-frequencies. The VDE-AR-N 4120 provides a good example of these requirements.

4.4 Turbine Behaviour during Faults

Temporary voltage interruptions due to faults in electrical grids are unavoidable. Therefore, it is important to set specific requirements for the behaviour of power plants in such situations.

Requirements in accordance with VJV2013 [19]

Power plants of Power Classes 1, 2, and 3 are not allowed to disconnect during short-time voltage problems. This has been referred to in Figure 16.

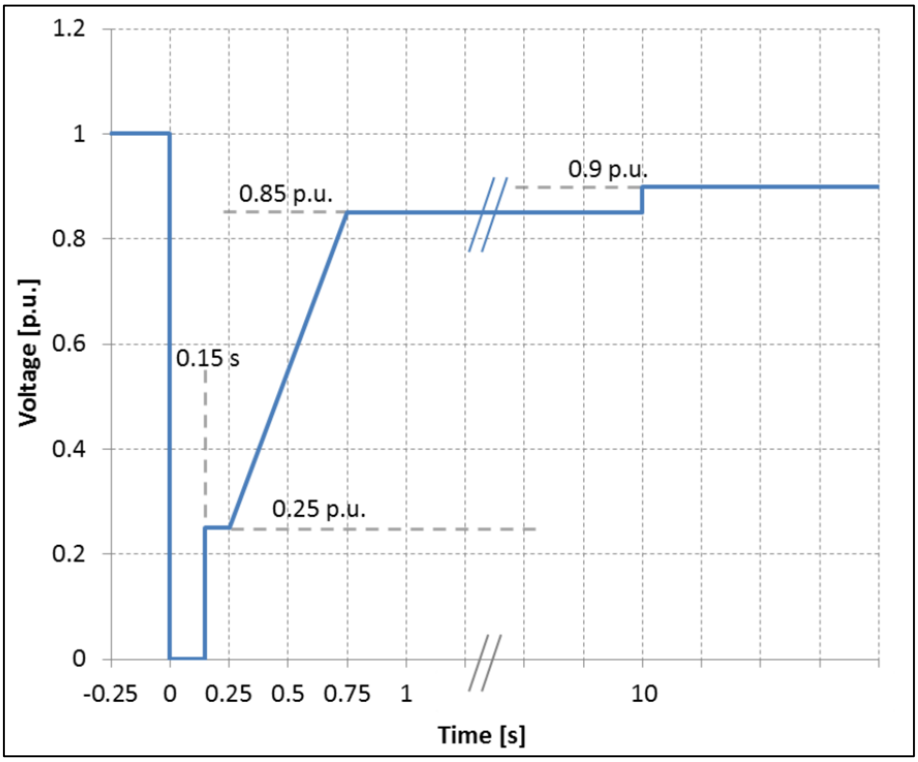

Figure 16: Requirements for power plants to withstand grid faults (VJV2013) [19].

According to Figure 16, power plants have to stay connected to the electrical grid during voltage drops to zero for at least 150 ms. Above 0.25 p.u., the limiting curve is linear with a minimum time of 250 ms and a maximum time of 750 ms for a voltage drop to 0.85 p.u. Between 0.85 p.u. and 0.9 p.u., power-generating facilities have to maintain the connection for at least 10 s. Outside these ranges, power plants are allowed to disconnect to avoid damaging effects.

For power plants of Power Class 4, the requirements are slightly stricter since these power plants have to withstand voltage drops to zero for at least 250 ms.

In addition, the VJV2013 requires dynamic simulations before commissioning of the power plant to secure a compliant behaviour during voltage problems. For these simulations, a dynamic model of the power plant is necessary, which has to be given to Fingrid.

For the requirement of additional electrical current feed-in into the electrical grid during momentary voltage problems, the VJV2013 refers to the relevant grid operator without setting a frame.

Requirements in accordance with VDE-AR-N 4120 [23]

The VDE-AR-N 4120 differentiates between two-phase and three-phase short-circuits. Figure 17 illustrates these requirements.

PROTECTED CONTENT

Figure 17: Requirements for power plants to withstand voltage disturbances (VDE-AR-N 4120) [23].

During three-pole short-circuits, power plants have to maintain the connection for at least 150 ms for voltage drops to zero. From there, the required time is growing linearly up to voltage drops of 80 % of the nominal voltage. For two-pole short-circuits, voltage drops to zero must not be a problem for 220 ms and the linear growth up to 80 % of the nominal voltage is more flat. Up to 85 % of the nominal voltage, power plants have to stay connected for a minimum of 3 s in both short-circuit scenarios. In addition, the VDE-AR-N 4120 sets a limit for over-voltages.

The connection must be maintained for 100 ms during over-voltages up to 130 % and one minute up to 125 % of the nominal voltage.

Furthermore, power plants have to support the electrical grid by injection of additional reactive current during grid faults. For this behaviour, the VDE-AR-N 4120 uses the k-factor, thereby describing the correlation between the voltage dip and the required additional reactive current support.

$$k = \frac{\Delta i_B}{\Delta u} \tag{2}$$

This parameter must be adjustable in every power-generating unit in steps of 0.5 between two and six. The relevant grid operator can choose a k-factor in this range. After fault correction, power plants must be able to increase the active current feed-in with a minimum rate of 20 % per second up to the value before the disturbance occurred. In addition, the VDE-AR-N 4120 refers to different short-circuit scenarios. During three-pole short-circuits only the positive-sequence must be considered due to the even voltage drop in all phases. In terms of two-pole short circuits, the negative-sequence must also be considered and the reactive current must be fed into the damaged phase.

<u>Comparison and remarks</u>

The requirements during voltage dips are stricter with reference to the VDE-AR-N 4120. This is mainly caused by the general wider operation range in Germany. The requirement to operate during voltage problems is getting more important, depending on the number of decentralised power-generating facilities, to avoid a chain reaction in shutdowns of power plants. Furthermore, the VDE-AR-N 4120 also sets a limit for over-voltages, while the VJV2013 does not consider this scenario.

Moreover, the VJV2013 does not set requirements for the reactive current injection during momentary voltage problems and refers to the relevant grid operator. This behaviour of power plants is clearly regulated in the VDE-AR-N 4120 by a specific parameter frame, while the relevant grid operator still has the chance to choose between different variations. Modern wind power plants fulfil this requirement by different modes, and a more detailed description will be useful for the Finnish grid code.

The required consideration between the positive-sequence and the negative-sequence in the VDE-AR-N 4120 is very future-oriented, and it will require new measurements and simulation models for wind turbines. This consideration is advantageous in terms of asymmetric faults due to selective reactive current feed-in. Currently, only the positive-sequence is considered during faults in Germany.

4.5 Protection Devices

Requirements in accordance with VJV2013 [19]

There are no specific requirements for protection devices set in the Finnish grid code. The VJV2013 refers to the owner of the power-generating facility to arrange suitable protection modules to avoid damage from the electrical grid and prevent damage from the power plant. The concept should be coordinated with the relevant grid operator. Furthermore, Fingrid imposes all responsibilities in terms of correct planning and realisation to the power plant owner.

The protection modules must not cause conflicts with other requirements such as the behaviour during faults and the operating range.

Requirements in accordance with VDE-AR-N 4120 [23]

The VDE-AR-N 4120 recommends the following protection devices.

- Grid protection devices

Grid protection devices provide operational safety for the electrical grid of the relevant grid operator. Therefore, a digital protection device is necessary to measure and continuously observe the grid impedance. This method allows accurate detection of the error location and different initiation time-frames, depending on the error distance.

- Short-circuit protection devices

Short-circuit protection devices interrupt the grid connection in case of short-circuits in the power-generating facility. The concept has to be agreed upon with the relevant grid operator, but at least an over-current protection has to be realised to disconnect the power-generating units after a specific time. In the protection range of the power transformer, the maximum time of an over-current must not exceed 150 ms. For the low-voltage side of the power transformer, the maximum time limit is 1 s.

- Uncoupling devices

In terms of uncoupling devices, there is a difference between different locations of the protective functions. In addition to the grid connection point, the protective function of the uncoupling device must be realised at the high-voltage side of the power transformer and in every power-generating unit. The functions of the uncoupling device must include:

  - voltage protection
  - Q-U protection (only at the high-voltage side of the power transformer)
  - frequency protection.

The voltage protection function disconnects the power-generating facility in terms of high or low voltage levels. The measurement must consider all three phases and the line-to-line value on the high voltage side of the power transformer. Also, the measurement at the power-generating unit must consider line-to-line or line-to-earth voltage, depending on the connection symbol of the unit transformer and the relevant low-voltage grid configuration. The device must disconnect the power-generating unit or facility whenever one phase crosses the critical value.

In contrast, the Q-U protection only disconnects the power plant when all three phases are below 85 % of the agreed supply voltage and the power plant is operating under-excited. This is important to avoid incorrect behaviour of the power plant during and after failures in the electrical grid.

The frequency protection disconnects the power-generating units in terms of unacceptable over or under-frequencies in the electrical grid.

The following illustration is an example of a concept of the uncoupling devices.

PRTOTECTED CONTENT

Figure 18: Example of the protection concept of a power-generating facility (VDE-AR-N 4120) [23].

Figure 18 also illustrates the recommended values for the protective functions.

To maintain the protective functions of all protection devices, separate battery backups must be installed. For power-generating units, the backup capacity must provide electricity for 6 s. For the relevant functions of the generating facility, electricity must be provided for at least 8 h.

Comparison and remarks

The VJV2013 does not provide specific requirements for protection devices. All responsibilities are transferred to the power plant owner and the relevant grid operator. The VDE-AR-N 4120 gives recommendations for the protection devices and also ranges for the settings.

The handling for protection devices is, therefore, quite similar in both grid codes. This is reasonable because only the relevant grid operator can set requirements for protective functions in accordance with the structure of the relevant electrical grid. A defined range is recommended to avoid unreasonable requirements by distribution grid operators.

Wind turbine manufacturers already consider the protective functions in their power plants to comply with specific requirements set by grid operators. The adjustment ranges for the settings of those modules vary between different manufacturers, but, in general, all modern wind turbines can fulfil the requirements set by the relevant grid operator.

A battery backup to maintain the protective functions during electricity supply problems is very important to guarantee a safe operation of power plants. In case of an outage of the backup storage, the power switch of the generating facility or turbine must open immediately in Germany.

4.6 Power Quality

Requirements in accordance with VJV2013 [19]

Fingrid transfers the responsibility to set requirements for the power quality characteristics to the relevant grid operator. Furthermore, the power plant owner has to deliver the required information and reports to the grid operator for further calculations. For measurements of these reports, the VJV2013 refers to the international standard IEC 61400-21 ‘Measurement and assessment of power quality characteristics of grid connected wind turbines’ [24].

Requirements in accordance with VDE-AR-N 4120 [23]

The VDE-AR-N 4120 sets specific boundary values for the following voltage disturbances. The basis for these values is specific turbine measurements in accordance with the FGW TR3 [25] and the IEC 61400-21 [24].

- Voltage drops in order to switching operations

Voltage deviations caused by switching operations must not exceed 2 % for the whole power-generating facility. For single power-generating units, the boundary value is 0.5 %, or 2 % divided by the number units in case of less than four units.

- Flicker

The maximum flicker intensity is separated into long and short-term intensity. The boundary values are:

$$P_{lt} = 0.35$$

$$P_{st} = 0.5$$

- Harmonics and inter-harmonics

For harmonic and inter-harmonic currents, the VDE-AR-N 4120 sets specific boundary values and a calculation scheme.

$$I_{\nu Azul} = i_{\nu Azul} \cdot S_{kV} \cdot \sqrt{\frac{S_A}{S_0}} \tag{3}$$

Formula (4) calculates the maximum allowed harmonic or inter-harmonic current in accordance with the related boundary value for the specific harmonic number listed in Table 2 with:

$I_{\nu Azul}$	Permitted absolute harmonic current
$i_{\nu Azul}$	Permitted relative harmonic current
S_{kV}	Short-circuit power of the electrical grid at the connection point

S_A Connected power of the power plant

S_0 Maximum power, which can be connected to the specific grid section

Table 2: Permitted relative harmonic currents related to the short-circuit power of the electrical grid.

PROTECTED CONTENT

Comparison and remarks

Power plants can influence the grid negatively due to the feed-in of an electrical current. It is important to set boundary values to secure that all power plants connected to a grid connection point do not cause problems concerning the power quality. These requirements should avoid the increases in further 'pollution' of the power quality due to an increased amount of power electronics.

In general, such impacts are measured in appropriate measurement stations for prototype turbines. Therefore, it is important for wind turbine manufacturers to know about specific standards in different countries.

The VDE-AR-N 4120 sets requirements in tune to the mentioned impacts and also describes relevant calculation schemes. In contrast, the VJV2013 transfers the responsibility to set boundary values to the relevant grid operator. This is not problematic due to the relevant grid operator's knowledge about their electrical grid. In general, calculations in terms of electrical emissions made by the relevant grid operator are more accurate since they are able to consider all generating facilities and consumers.

The VJV2013 requires additional commissioning tests (cf. Chapter 4.7.2), including power quality measurements for the generating facility, while these impacts are only theoretically analysed in Germany and measurements are only required whenever the theoretical calculation exceeds the relevant boundary values. The regulation with regard to the VJV2013 is therefore more accurate and delivers exact values. As a result, the requirements in terms of power quality in the VJV2013 are more reasonable than the German requirements mentioned in the VDE-AR-N 4120.

4.7 Others

4.7.1. Modelling of the Power-Generating Unit and System

Requirements in accordance with VJV2013 [19]

The VJV2013 requires simulation models for wind power plants of Power Classes 2, 3, and 4. These models must describe the real operating behaviour and impacts of the wind turbine. Already during the planning phase, the specific models must be delivered to Fingrid with the general data of the power-generating facility. The models must include:

- static behaviour
    - power flow
    - voltage profile
    - different operation modes
    - fault currents
- dynamic behaviour
    - changes in voltage amplitude and phase angle
    - electromechanical oscillations
    - fast transients (momentary voltage disturbances, FRT).

The model must be verified by comparing the results of the simulation with the results of the commissioning test (cf. Chapter 4.7.2).

Furthermore, the simulation model should be delivered and compiled in a single equivalent generator. The model should preferably be compatible with the simulation environment *Siemens PSSE 33.5* used by Fingrid, or it should be delivered as a detailed block diagram in connection with the parameter list by using another simulation software as long as the data is sufficient to implement the model to the simulation environment of Fingrid. In addition, the model must come with some documentation, including instructions for the handling of the model, the project-specific parameter list, and a block diagram level description.

<u>Requirements in accordance with VDE-AR-N 4120</u> [23]

The VDE-AR-N 4120 requires specific unit certificates for every turbine type. The unit certificate includes all technical information about the power-generating unit and also the validation of the required simulation model to check the grid code compliant behaviour. For the process of unit measurements and model validation, the VDE-AR-N 4120 refers to the FGW TR 3 [25] and FGW TR 4 [26]. Furthermore, the process of unit certification is described in the FGW TR 8 [27]. In addition, the relevant grid operator can demand specific power plant models.

4.7.2. Verification process

Requirements in accordance with VJV2013 [19]

Fingrid requires compliance testing for wind power plants. The power plant operator has to initiate such measurements after commissioning of the relevant power plant.

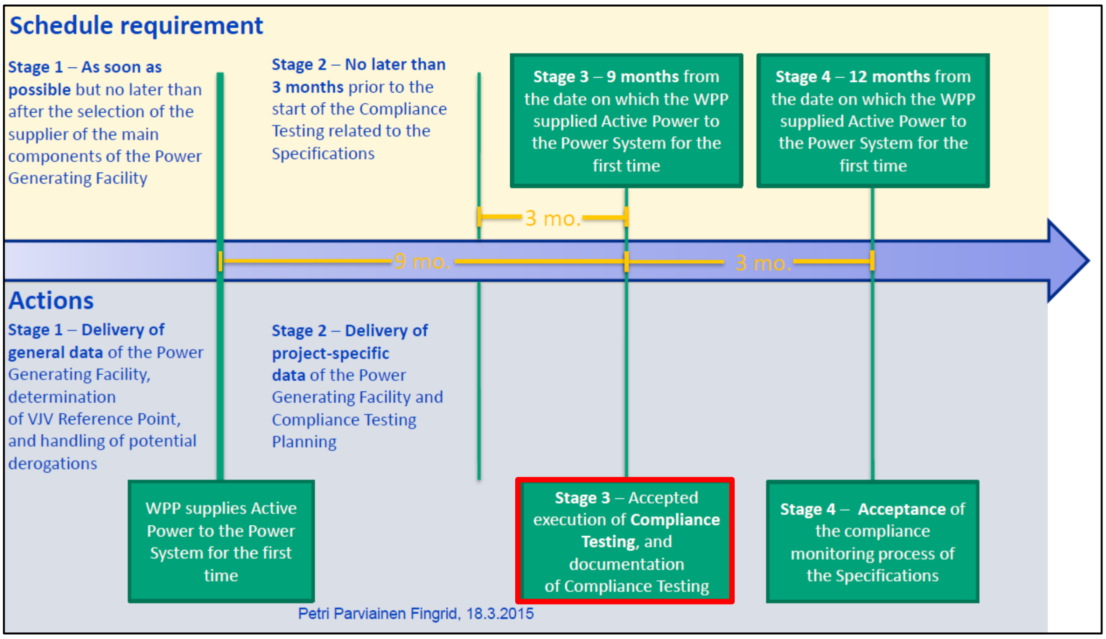

Figure 19: Schedule requirement for the compliance testing [28].

Figure 19 illustrates the schedule for the whole construction of a wind power plant in Finland. The compliance test must be executed within nine months after commissioning.

The following tests must be included in the compliance testing:

- operation at minimum capacity
- start and shut-down of the wind power plant
- reactive power capacity
- voltage and reactive power control functions
- active power and frequency control functions
- power quality
- power plant behaviour during faults.

The measurements are less extensive for wind power plants of Power Class 1.

Requirements in accordance with VDE-AR-N 4120 [23]

The VDE-AR-N 4120 requires a verification process of the electrical behaviour of power plants.

As already mentioned in Chapter 4.7.1, the VDE-AR-N 4120 requires unit certificates for every turbine type. The unit certificate is valid for all units of the same model. Furthermore, the VDE-AR-N 4120 requires a verification of the compliant behaviour of the relevant power plant. This verification process must already be started during the planning phase of the power plant.

Currently, this process is divided into the project certificate and the compliance report after commissioning. The project certificate includes an evaluation report with simulations of the whole power plant, which analyses the behaviour in normal operation mode as well as the behaviour at the assigned connection point during grid faults. In addition, the dimensioning of the components and the tripping of protective relays get checked for plausibility.

The compliance report confirms the correct realisation of the power-generating system after commissioning. The installed components and the adjusted parameters are compared with the project certificate. Moreover, the results of executed protection tests are considered. The whole process is described in the FGW TR8 [27] in detail.

The verification process must be executed by an independent certification body that has been accredited in accordance with DIN EN ISO/IEC 17065.

Comparison and remarks

Both grid codes require specific simulation models. This is reasonable in order to calculate the impacts of a wind power plant and to prove the compliant behaviour. Fingrid requires a validation of the delivered model with the measurements of the compliance testing. The VDE-AR-N 4120 requires unit certificates, including validated models of the wind turbines, to prove the compliant behaviour by independent experts. In addition, the VDE-AR-N 4120 also gives grid operators the opportunity to demand a specific model of the power plant for grid studies. However, the opportunity to request specific power plant models is still unspecified in the VDE-AR-N 4120. This should be adjusted in an upcoming revision. While the validation for turbine models with prototype measurements is reasonable, the validation of the whole power plant model is recommended after commissioning. In general, all wind turbine manufacturers are able to deliver validated simulation models for their turbine types.

Before construction of the wind power plant, general data and simulation models must be provided to Fingrid by the power plant operator. Assuming that Fingrid checks the compliance with the general data before construction, it would be a huge amount of work when more and more decentralised power plants are developing. In Germany, independent accredited certification bodies are responsible for securing the grid compliance during the planning phase. This is advantageous because of their independence—there are more than 800 grid operators in Germany—and, of course, due to the focused expert knowledge of these certification bodies leading to less problems during grid integration and a defined quality in the electrical grid.

An investigation of the certified projects in 2013, executed by six certification bodies in Germany, with a total of 3.5 GW installed power from renewable energies, has shown that in more than 80% of the projects the provided documents and settings had to be improved in order to receive a certificate. These numbers show the large impact of the certification on the quality of the connected renewable power-generating facilities and therefore on the performance, stability, and safety of the electrical grid. In addition, conflicts between power plant developers, power plant owners, and grid operators have been reduced [29].

A detailed compliance verification is essential in this regard. Already during the planning phase of wind power plants, this process is reasonable to secure grid stability and compliant behaviour after commissioning. The consultation of independent experts is recommended, especially when there are a lot of different distribution grid operators and manufacturer-specific knowledge is required.

5 Market Chances for Services of M.O.E.

M.O.E. is specialised in grid integration of renewable energies. The company is continuously developing and considering new business areas in other European countries.

5.1 Possible Business Areas

5.2 Potential Customers

5.3 Economic Potential

5.4 Barriers

5.5 Chances and Key Factors

5.6 Conclusion

6 Summary and Outlook

This thesis illustrates a big difference in the development of wind power plants as well as technical requirements between Finland and Germany. While Germany is one of the leaders in the establishment of wind turbines, Finland has just started to invest in this sector due to the general European climate targets. The technical requirements mentioned in the VDE-AR-N 4120 are higher and more detailed than in Fingrid's VJV2013. Especially in terms of the new European grid code NC RfG, Fingrid has to replace or rework the existing grid code. Therefore, Fingrid has already announced a new version of their grid code at the end of 2017. The VDE-AR-N 4120 already covers a lot of requirements in terms of the NC RfG. This fact and also the big difference in the installed power capacity of wind power plants explain the discrepancy between the German and the Finnish grid code. Wind turbines designed for the German market should not face general problems in accordance with the Finnish requirements as long as there are no massive additional requirements from the relevant distribution grid operators (their requirements were not a part of this thesis). In general, there are different software versions for power converters released by turbine manufacturers to comply with the regulations in different countries.

Appendix

A.1 Abbreviations

BDEW	Bundesverband der Energie- und Wasserwirtschaft (Association of Energy and Water Industries)
VDE-AR-N 4120	Technical Requirements for the Connection and Operation of Customer Installations to the High Voltage Network
EEG	Erneuerbare-Energien-Gesetz (Renewable-Energy-Law)
EU	European Union
FGW	Fördergesellschaft Windenergie (Society for the Promotion of Wind Energy)
FRT	Fault-Ride-Through
LVRT	Low-Voltage-Ride-Through
M.O.E. GmbH	Möller Operating Engineering GmbH
MSR 2008	Technical Guideline: Generating Plants Connected to the Medium-Voltage Network
NC RfG	Network Code for Requirements for Grid Connection applicable to all Generators
SDLWindV	Verordnung zu Systemdienstleistungen durch Windenergieanlagen (Ordinance on System Services by Wind Energy Plants)
TC2007	TransmissionCode 2007
TR3	Technical Guideline: Determination of the Electrical Characteristics of Power-Generating Units and Systems
TR4	Technical Guideline: Requirements for Modelling and Validating Simulation Models of Electrical Characteristics of Power-Generating Units and Systems
TR8	Technical Guideline: Certification of the Electrical Characteristics of Power-Generating Units and Farms in the Medium, High, and Highest-voltage Grids

VJV2013	Specification for the Operational Performance of Power Generating Facilities
YLE2013	Fingrid OYJ´s General Connection Terms

A.2 Symbols

cos (φ)	Power factor
f	Frequency
f_{grid}	Momentary grid frequency
I_a	Active current
I_r	Reactive current
I_{vAzul}	Permitted absolute harmonic current
i_{vAzul}	Permitted relative harmonic current
P	Active power
P_{AV}	Agreed active power capacity of the power plant with the network operator
$P_{b,inst}$	Installed active power capacity of the wind power plant
P_{lt}	Long-term flicker intensity
P_m	Active power feed-in at the point of exceeding the boundary value
P_{max}	Maximum active power output of the wind park
P_{mom}	Momentary active power feed-in
P_{st}	Short-term flicker intensity
Q	Reactive power
Q_{vb}	Required reactive power capacity
S_A	Connected power of the power plant
S_{kV}	Short-circuit power of the electrical grid at the connection point
S_0	Maximum power, which can be connected to the specific grid section
t	Time
U	Voltage
ü	Transmission ratio of the transformer
$u_{(t)}$	Voltage at a specific point of time
U_b	Voltage during normal operation
U_C	Agreed supply voltage with the network operator

U_{MS}	Voltage at the medium-voltage side of the unit transformer
U_N	Nominal voltage
U_{NS}	Voltage at the low-voltage side of the unit transformer
U_{VJV}	Voltage at the connection point

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A.5 References

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A.6 Data Disc

The attached data disk includes this bachelor thesis in a digital format.