Analysis of the availability of power plant system services of a cluster based on its configuration

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LIST OF ABBREVIATIONS

AC	Alternating Current
ANN	Artificial Neural Network
AS	Ancillary Services
Cluster	Wind Farm Cluster
CR	Contingency Reserve
CSC	Current Source Converter
DC	Direct Current
DFIG	Doubled-Fed Induction Generator
DoW	Description of Work
DSO	Distribution System Operator
DTOC	Design Tool for Offshore wind farm Clusters
ENTSO-E	European Network of Transmission System Operators for Electricity
EERA	European Energy Research Alliance
EU	European Union
EWEA	European Wind Energy Association
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
FSCG	Full Scale Converter Generator
GFS	Global Forecast System
HVDC	High Voltage Direct Current
IWES	(Fraunhofer) Institut für Windenergie und Energiesystemtechnik (Institute for Wind Energy and Energy System Technology)
NC	Network Code, also may be called as grid code
NC RfG	ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators
NWP	Numerical Weather Prediction system
PMSG	Permanent Magnet Synchronous Generator
PCC	Point of Common Coupling
POI	Point of Interconnection
RR	Replacement Reserve
SCIG	Squirrel Cage Induction Generators
SO	System Operator (indistinctly TSO or DSO)
SS	System Services
SSVC	Steady-State Voltage Control
Tn.m	Task number n.m
TS	Transmission system
TSO	Transmission System Operator
TYPE 3	Variable speed, double-fed asynchronous generators with rotor-side converter
TYPE 4	Variable speed generators with full converter interface
VSC	Voltage Source Converter
WF	Wind Farm
WFC	Wind Farm Controller
WP2	Work Package 2
WPP	Wind Power Plant
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine

1 INTRODUCTION

1.1 Motivation

This deliverable D2.7 describes the tool and procedure developed in Task T2.4 to analyze the availability of power plant system services according to EERA-DTOC [1] DoW, presenting the assumptions adopted to achieve the objectives.

1.2 Objectives

The overall objective of Work Package 2 (WP2) is to develop a design tool and procedure for the optimization of the electrical design of offshore wind farm clusters, including the **provision of power plant system services** by the cluster.

Specifically, T2.4 aims to perform the analysis of the availability of power plant system services[1] of a cluster and its main objectives are:

- To develop a simulation tool for the provision of power plant system services;
- To analyze the availability of power plant system services of a cluster in dependence of its configuration (network layout and different wind farm aggregation criteria).

The P**ower plant system services** are different supporting actions provided by WPP to maintain the grid operation in correct (or even optimum) level. Some of those services are the so-called *ancillary services*[2], as well as congestion detection/ management support and balancing power supply.

1.3 Background

According to projections by EWEA [2] the cumulative offshore wind power capacity in EU member states will increase from 5.3 GW in 2012 to 40.0 GW in 2020 and further to 150 GW in 2030. In terms of electricity production, this amounts to about 4.1 % of EU electricity consumption in 2020 and 13.9 % in 2030.

The high penetration of offshore wind power will create an increased demand of ancillary services to keep the balance on the European interconnected grid [3] . Those services could be provided by the offshore connected wind farm clusters themselves if the grid design and cluster locations are planned with this aim.

Several projects are investigating the provision of ancillary services from renewable energy sources, and more specifically from wind, as in the EU-funded REServices project [5] . Therefore, it is part of this task to analyze and understand the impact of the cluster connections and the grid design in the provision of system services.

1.4 Approach and Methodology

The evaluation of the provision of power plant system services is based on the long-term power output time series simulation of the clusters including all wind farms. Those time series are either a) provided by the CorWind model [7] , or b) by the variability and predictability module[3], which is based on CorWind time series as long as GFS weather prediction and provides time series of available power and forecasted power output values. The offshore grid layout and the grid within

[1] See "*1.5 General definitions*" (pp. 11) where the general term definitions are presented.

[2] Id.

[3] See [7]

the cluster and its connection(s) to shore is provided either by NET-OP model [8] and further user inputs or by another software[4] providing a PSSE grid description in Raw file format.

This simulation consists of the cluster behavior and the cluster control. The cluster simulation is a steady-state load flow simulation of the wind farms, their connections to offshore substations (POI) and the connections to the grid on land (by HVAC or HVDC technology). The cluster control provides the intrinsic required control commands (setpoints) for the individual wind farms within the cluster in order to fulfill requirements for power plant system services at the connections point(s) on land.

For the provision of power plant system services, the forecast based on the GFS [10] NWP and a forecaster based on ANN and its uncertainty are considered, as provided by the variability and predictability module [7] . Also, the influence of the cluster grid and connection to shore is included in the calculation.

1.5 General definitions

1.5.1 System and ancillary services[5]

The **power plant system services** are different supporting actions provided by a power plant (in this case specifically WPP) to maintain the grid operation in correct levels. Some of those services are the so-called ancillary services[6], as well as congestion detection/ management support and balancing power supply.

Sync. Area	Process	Product	Activation	Local/Central	Dynamic/ Static	Full Activation Time
BALTIC	Frequency Containment	Primary Reserve	Auto	Local	D	30 s
Cyprus	Frequency Containment	Primary Reserve	Auto	Local	D	20 s
Iceland	Frequency Containment	Primary Control Reserve	Auto	Local	D	variable
Ireland	Frequency Containment	Primary operating reserve	Auto	Local	D/S	5 s
Ireland	Frequency Containment	Secondary operating reserve	Auto	Local	D/S	15 s
NORDIC	Frequency Containment	FNR (FCR N)	Auto	Local	D	120 s -180 s
NORDIC	Frequency Containment	FDR (FCR D)	Auto	Local	D	30 s
RG CE	Frequency Containment	Primary Control Reserve	Auto	Local	D	30 s
UK	Frequency Containment	Frequency response dynamic	Auto	Local	D	Primary 10 s / Secondary 30 s
UK	Frequency Containment	Frequency response static	Auto	Local	S	variable
BALTIC	Frequency Restoration	Secondary emergency reserve	Manual	Central	S	15 Min
Cyprus	Frequency Restoration	Secondary Control Reserve	Auto/Manual	Local/Central	D/S	5 Min
Iceland	Frequency Restoration	Regulating power	Manual	Central	S	10 Min
Ireland	Frequency Restoration	Tertiary operational reserve 1	Auto/Manual	Local/Central	D/S	90 s
Ireland	Frequency Restoration	Tertiary operational reserve 2	Manual	Central	S	5 Min
Ireland	Frequency Restoration	Replacement reserves	Manual	Central	S	20 Min
NORDIC	Frequency Restoration	Regulating power	Manual	Central	S	15 Min
RG CE	Frequency Restoration	Secondary Control Reserve	Auto	Central	D	≤ 15 Min
RG CE	Frequency Restoration	Direct activated Tertiary Control Reserve	Manual	Central	S	≤ 15 Min
UK	Frequency Restoration	Various Products	Manual	D/S	N/A	variable
BALTIC	Replacement	Tertiary (cold) reserve	Manual	Central	S	12 h
Cyprus	Replacement	Replacement reserves	Manual	Central	S	20 min
Iceland	Replacement	Regulating power	Manual	Central	S	10 Min
Ireland	Replacement	Replacement reserves	Manual	Central	S	20 Min
NORDIC	Replacement	Regulating power	Manual	Central	S	15 Min
RG CE	Replacement	Schedule activated Tertiary Control Reserve	Manual	Central	S	individual
RG CE	Replacement	Direct activated Tertiary Control Reserve	Manual	Central	S	individual
UK	Replacement	Various Products but the main one is Short Term Operating Reserve (STOR)	Manual	D/S	N/A	from 20 min to 4 h

Figure 1. ENTSO-E Working Group. Survey on Ancillary Services[7] (Source: ENTSO-E).

[4] At the moment of writing this report, the utilization of the eeFarm II software from ECN is investigated.

[5] According to [4]

[6] cf. [6]

[7] According to [27]

According to [6] , there are different definitions of ancillary services depending on the country and market, varying some parameters from one to the other, like maximum activation times, minimum possible offer and time to keep the provision, among others (see Figure 1). In the context of the WP2 and the project, an inline with the DoW, the definitions suggested by ENTSO-E [12] [13] as they are addressed in [6] were adopted for sake of clarity and uniformity:

- **System services** are all services provided by some system function (such as a system operator or a grid/network operator) to users connected to the system.
- **Ancillary services** are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality.

Besides the ancillary services, WPP are able to provide more system services, like congestion management (mainly by managing the reactive power provision to the grid allowing a more efficient voltage control) and balancing power. A detailed definition of each investigated system service is presented in section 2.1 *Considered Power Plant System Services* (pp. 22).

1.5.2 Conversion concepts

This report adopted the main definitions provided by REserviceS Project [5] regarding conversion technologies, following the wind turbine conversion typology according to the new standard IEC 61400-27: Types 1, 2, 3 and 4; commented in [16] . Complementary descriptions of the technology can be found in [17] and [18] .

Modern wind turbines are mainly from Type 3 and 4, as presented in Figure 2 and Figure 3, and they are the assumed types for actual and -moreover- for future wind turbine configuration[8].

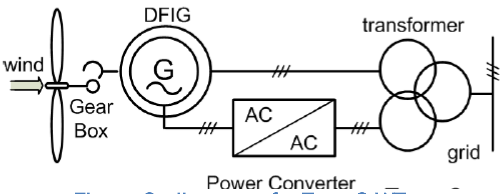


Figure 2: diagram of a Type 3 WT.

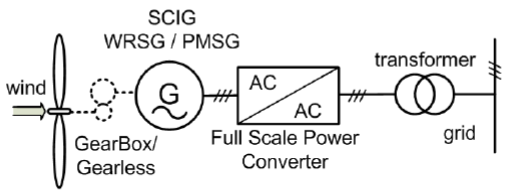


Figure 3: diagram of a Type 4 WT.

1.5.3 Wind Power Plant concepts and related concepts

Related topics with the WPP structure are:

- **Point of Interconnection (POI)** or **Point of Connection (POC):** the point at which the Wind Farm's electrical system is connected to the public electricity system. The POI is shown in Figure 5.
- **Point of Common Coupling (PCC):** the point on the public electricity network at which other customers are, or could be, connected. Not necessarily the same location as point of connection. According to ENTSOE [28] , the PCC is the interface point between the Power Generating Facilities equipment and the Network Operators equipment.
- **Wind Farm Controller (WFC):** the management system that implements the control strategies and coordinates the operation of several wind turbines. The functions of a WFC are the control and supervision of the WT.

[8] It is expected on future scenarios to implement turbines of 5, 7, 10 and even 20 MW, assuming that the implemented technologies will by either type 3 or 4.

- **Voltage system:** symmetrical positive sequence three-phase voltage source.

The hierarchy of wind power technologies analysed in is this report is:

- **Wind Turbine (WT):** a single wind converter machine connected to the grid or to a wind farm controller that transforms the kinetic energy of the wind in mechanical energy and then, by means of an electrical generator, in electrical energy.

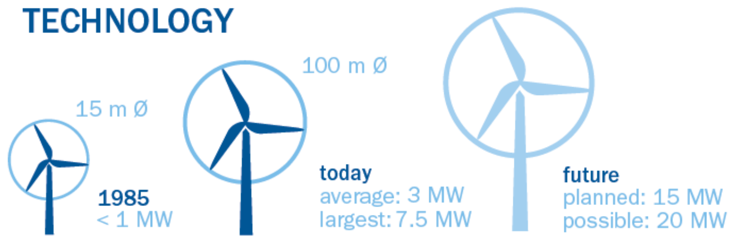


Figure 4: historical sizes of wind turbines and trends for the future [19]

The average size of a wind turbine today and the trend for the future years is given in Figure 3.

- **Wind Farm (WF):** defines the aggregation of a number of WTs connected to the same substation (or collector system station), and controlled by only one autonomous WFC. A graphical description of a wind farm is presented in Figure 5. A WF has only one POI and one WFC.

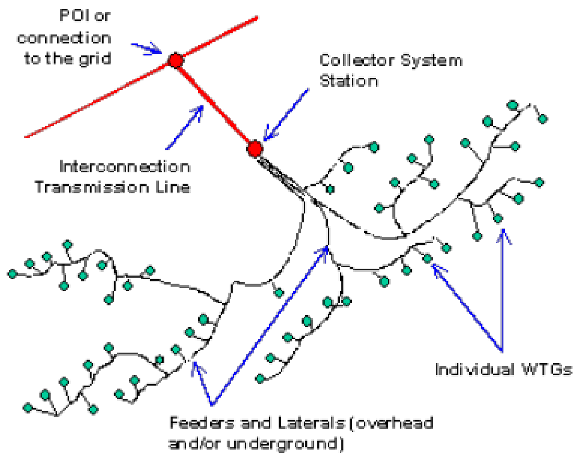


Figure 5. Typical WF/WPP topology [20]

- **Wind Power Plant (WPP):** a set of independent WF controlled by a unique WFC which operates and manages the entire set of WF as a power plant. A WPP could have one or more POIs but only one WFC.
- **Wind Farm Cluster (Cluster):** set of independent WF/WPP controlled by their own WFC that are jointly managed by a special control system operating each single WF/ WPP in a coordinated manner through their own WFC. The pooling (aggregation) of several large wind farms to clusters up to the GW range facilitates the integration of large amounts of variable generation into electricity supply systems. Cluster management includes the aggregation of geographically dispersed wind farms according to various criteria, for the

purpose of an optimized network management and optimized generation scheduling. The scope and size of a Cluster is mainly limited by the services provided, namely:

- In case of frequency control, the WF/WPP integrating the Cluster could be dispersed and far away from each other;
- When providing voltage control, due to the local character of the service, integrating WF/WPP must either be connected to the same POI or located nearby to effectively provide the intended service.

Generation Group Cluster	**Requirements: Profile Based Operation Mode** • uninfluenced operation • power limitation • energy compliance • constant power output • supply of control energy
Generation Group	**Requirements:** • maximum power limitation (dynyamic threshold values) • short circuit current • emergency cut-off (disconnection) by network outages • coordinated start-up and shut-down procedures (gradients limitation)
Single Generator	**Requirements:** • safe and reliable operation • maximum energy yield

Figure 6: Wind Farm Cluster Management [21]

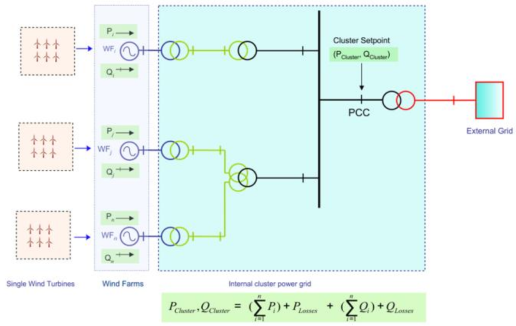


Figure 7: typical cluster layout, with the individual wind farms and the connecting grid until the POI [11] .

1.5.4 *Frequency and Voltage Support Services*

- **Frequency Restoration Reserve (FRR):** its activation modifies the active power set points/adjustments of reserve providing units in the time-frame of seconds up to typically 15 minutes after an incident. Activated centrally and has automatically activated and manually activated parts. It is managed by each TSO and coordinated through the control of transits between TSO's area of responsibility. It constitutes the Secondary Response.

- **Replacement Reserve (RR):** manually activated, with activation time from 15 minutes to hours. Replacement reserves are activated manually and centrally at the TSO control centre in case of observed or expected sustained activation of FRR and in the absence of a market response. It constitutes the Tertiary Response.

For a complete description of the FRR and RR, please refer to [6] and [13]

- **Balancing Power/ Energy:** power/ energy used to correct imbalances in the electricity grid in real time in cases where normal generation differs from electricity consumption. By using balancing power, transmission system operators can ensure a stable frequency in their balancing zone. Demand for balancing power can result from deviations between actual and forecast electricity consumption and from power plant shutdowns or unexpectedly high wind energy generation[9].

  Balance Energy is the volume of electricity required for each billing unit to balance the difference between the effective import (or delivery) according to metered values and the

[9] Cf. RWE annual report 2008 (online: http://rwecom.online-report.eu/2008/ar/servicepages/welcome.html)

import (or delivery) according to the schedule for a specific time unit to create a zero balance billing unit (for the Swiss control area)[10].

- **Reactive power contribution to onshore nodes (steady-state reactive power contribution/ Voltage Control):** controlling voltage node profile to a target value or within a target range. This control is commonly achieved by injecting or absorbing reactive power at a voltage controlled node by means of synchronous sources, static compensation, tap changing transformers in the substations, transmission lines' switching, virtual power plants including demand facilities and if necessary load shedding. The system operator dispatches the reactive power using the active and passive reactive power sources [ref] that belong to different levels: generation, transmission and distribution, using Optimal Power Flow methods.
- Schedule: a reference set of values representing the Generation, consumption or exchange of electricity between actors for a given time period.
- Generation Schedule: a Schedule representing the Generation of electricity of a Power Generating Module or a group of Power Generating Modules.

1.5.5 *System Management Support*

- **Congestion Management:** are the procedures and actions taken in order to prevent or mitigate a physical congestion, which means any network situation, either described in a Common Grid Model[11], or occurring in real time, where power flows has to be modified to respect Operational Security [22]

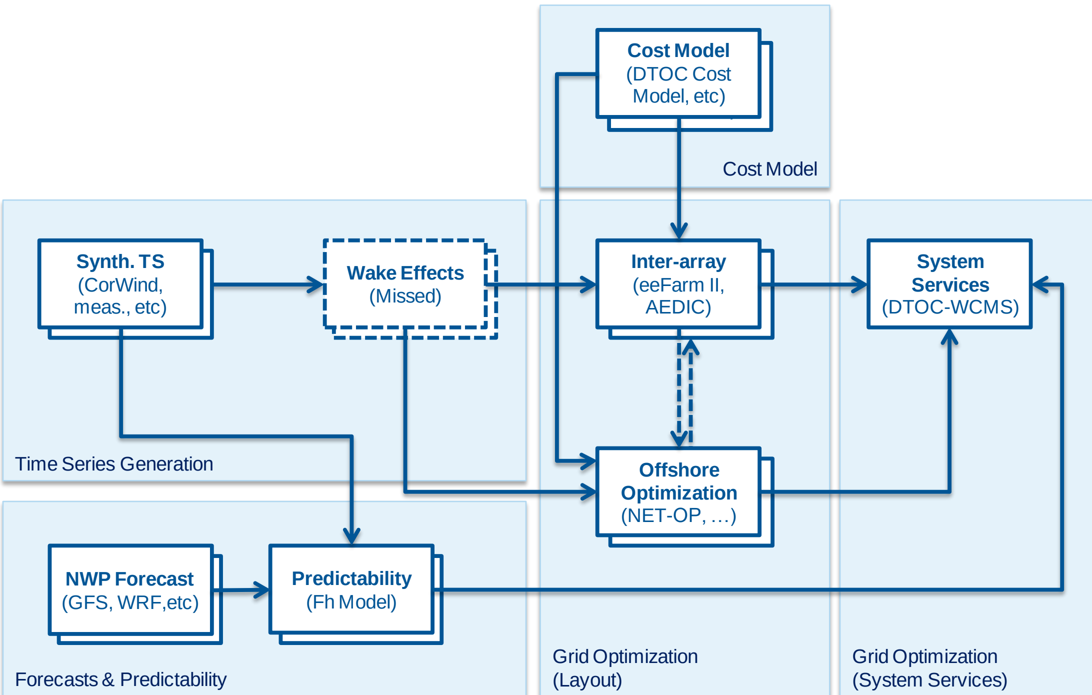


Figure 8. Basic diagram depicting the relationships among different models in WP2.

[10] According to the Swiss electricity market glossary (in "ENTSO-E Definitions and Acronyms", https://emr.entsoe.eu/glossary/bin/view/GlossaryCode/GlossaryIndex)

[11] Common Grid Model: European-wide or multiple-System Operator-wide data set, created by the European Merging Function, through the merging of relevant data from individual grid models.

1.6 The Wind Farm Cluster Manager System (WCMS) in EERA-DTOC

The Wind Farm Cluster Manager System (WCMS) is an operational tool developed by Fraunhofer IWES in 2009 in the frame of the EU-funded Wind on the Grid Project [11] . It is the basis of the new DTOC-WCMS (Design Tool for Offshore Clusters- Wind Farm Cluster Modelling & Simulation), which was developed in MATLAB as a simulation tool.

The tool allows the simulation of the operation of clusters providing power plant system services. It consists on a module that calculates the state of the electrical grid (cluster grid and connection to shore from T2.2 and T2.3) based on the wind farm locations, the input of the wind power output time series and the control commands for the clusters. It simulates the provision of system services by the clusters based on the predictability of T2.1, as it is depicted on Figure 8.

The technical specifications of wind farms and wind farm clusters are taken from the integrated design specification of the project via interfaces defined in T5.2, following the adopted standards in T4.1.2 of the DoW. This includes the description of a verified electrical design developed in T2.2 and T2.3.

The considered power plant system services are depicted in page 22, in Table 1.

1.7 New developments and features on the DTOC-WCMS

Due to the proposed offshore grid concepts, HVDC technology had to be implemented within the DTOC-WCMS grid calculation module. The necessary steps as well as background information is given below.

1.7.1 Current Source Converter HVDC Transmission

The CSC-HVDC transmission link is based on line-commutated thyristor converter technology. Two converters can be connected either directly in Back-to-Back configuration or via DC line in Point-to-Point Configuration. Between the AC connection point and the converter transformer equipped with tap-changer is placed, which plays an important role in the control scheme of the complete arrangement. Figure 9 presents the control scheme of the rectifier side of the CSC-HVDC transmission link.

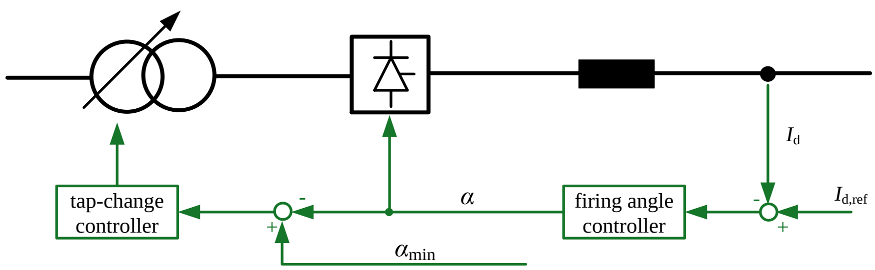


Figure 9. Control scheme of the rectifier side of the CSC-HVDC.

The CSC control scheme is based on two degrees of freedom at each side:

- Tap-change control and firing angle control for rectifier,
- Tap-change control and excitation angle control for inverter

Controlling the firing/extinction angle is used for rapid control after changing an operation point. After a certain delay, the tap-changer of the transformer will be adjusted to remain controller reserve for the firing/extinction angle control. However, since line-commutated converters are not able to control reactive power independently of active power set-points, firing/extinction angle are also affecting reactive power demand of the HVDC transmission. Therefore, another reason for tracking the tap-changer is to limit reactive power demand. To define a certain operation point in terms of active or reactive power at steady-state condition, the tap position and the firing/extinction angle are needed. Both quantities at each side can be interpreted as state-variables for the whole transmission system in this case. Figure 15 summarizes all needed quantities for power flow calculation and highlights a state-variable that need to be known fully describing the steady-state. Note, that consumer oriented sign conventions are used for AC and DC side. The control is working in such a way, that after all dynamic processes accomplished, the DC current magnitude is at a constant value, which is a parameter of the CSC-HVDC transmission link.

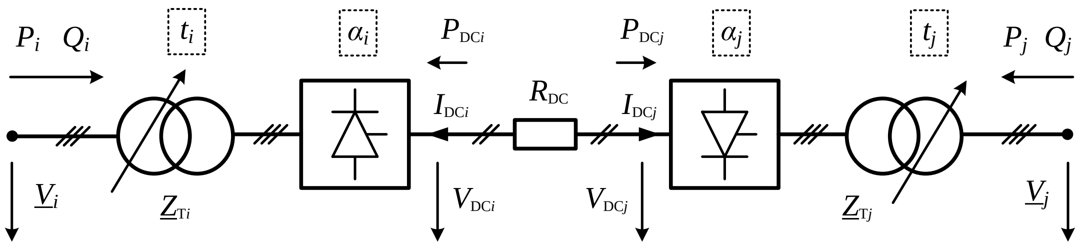


Figure 10. Summary of all needed quantities for power flow calculation.

Eq.1 and Eq. 2 describe the active and reactive power behavior to the AC node *i* depending on the state-variables tap-position and firing angle,

$$P_{\text{CSC}i} = V_i t_i \frac{\sqrt{6}}{\pi} I_{\text{DC}i} \cos \alpha_i - \sqrt{3/2}\,\frac{\sqrt{6}}{\pi} X_{\text{T}i} I_{\text{DC}i}^2 \qquad \text{Eq. 1}$$

$$Q_{\text{CSC}i} = V_i t_i \frac{\sqrt{6}}{\pi} I_{\text{DC}i} \sin\left(\cos^{-1}\left(\text{sign}(I_{\text{DC}i})\cos \alpha_i - \frac{X_{\text{T}i}|I_{\text{DC}i}|}{\sqrt{2} t_i V_i}\right)\right) \qquad \text{Eq. 2}$$

Where X_T is the imaginary part of the complex transformer impedance $\underline{Z}_T$, while the transformer resistance is neglected.

Voltage Source Converter HVDC Transmission

The VSC-HVDC transmission link is based on self-commutated converter technology. Figure 11 presents the control scheme of one converter. In contrast to the CSC technology, active and reactive power can be controlled independently. Based on the reference value of both quantities reference values for an inner current controller is calculated. Due to the coupling between both axes feed-forward decoupling circuits are used depending on the transformer reactance. The power and current control takes place in grid synchronous rotating coordinates. Therefore, the grid voltage angle is tracked. By means of the same angle the set voltage of the converter is transformed back before the PWM function calculates the switching states for gate control. Lowercase description denotes that per-unit quantities are used within the control scheme to gain numerical accuracy within limited bit range.

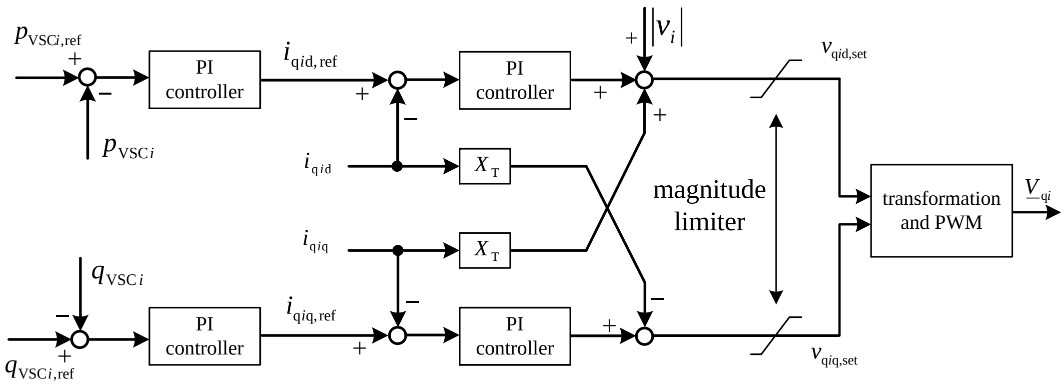


Figure 11. Control scheme of one converter.

However, for steady-state calculation after all dynamic processes are decayed, only the source voltage of the converter is necessary to calculate the power flow in a hybrid DC/AC environment. Since the source voltage is a complex quantity, two state-variables are necessary, which are the source voltage magnitude and the source voltage angle for power flow calculation in polar coordinates. Figure 12 summarizes all needed quantities for power flow calculation and highlights a state-variable that need to be known fully describing the steady-state. Note, that consumer oriented sign conventions are used for AC and DC side. The control is working in such a way, that after all dynamic processes accomplished, the DC voltage magnitude is at a constant value at one side, where the converter is in charge of achieving the power balance of the link. This DC voltage magnitude is a parameter of the VSC-HVDC transmission link.

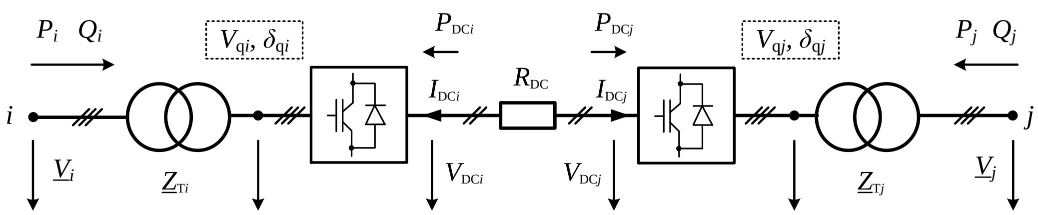


Figure 12. Summary of all needed quantities for power flow calculation.

Eq. 3 and Eq. 4 describe the active and reactive power behavior to the AC node *i* depending on the state-variables source voltage magnitude and source voltage angle,

$$P_{\mathrm{VSC}i} = \frac{V_i^2}{Z_{\mathrm{T}}}\cos\varphi_Z + \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}}\cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 3}$$

$$Q_{VSCi} = \frac{V_i^2}{Z_{\mathrm{T}}}\sin\varphi_Z + \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}}\sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 4}$$

Where φ_Z is the angle of the complex transformer impedance $\underline{Z}_{\mathrm{T}}$, where the transformer resistance is considered. Since the converters can be represented by source voltages, the equations are equal to the power flow equation between two AC nodes, where the node voltages are known.

1.7.2 Modified Newton-Raphson Load Flow Calculation

Classical Newton-Raphson algorithm

The Newton-Raphson load flow calculation is well known iterative method for calculating the steady-state operation point of a power system. The aim is to determine all complex node voltages, e.g. in terms of voltage magnitude and voltage angle for the algorithm working in polar coordinates. If every complex node voltages are known and the topology and the impedance of all passive grid components are given, the system state is fully described. Therefore, AC nodes can be interpreted as state-variables for the classic Newton-Raphson algorithm. Furthermore, AC nodes can be of three different types depending on which state-variable or active/reactive nodal powers are known. This has to be considered within the iteration by eliminating certain columns and lines in the linearized Jacobian Matrix. The fundamental structure before eliminating is shown in Eq. 5.

$$\begin{pmatrix} \Delta V_1 \\ \vdots \\ \Delta V_k \\ \Delta\delta_1 \\ \vdots \\ \Delta\delta_k \end{pmatrix} = \begin{bmatrix} \left[\left[\frac{\partial P_i}{\partial V_j}\right]\right]_{\text{iter}} & \left[\left[\frac{\partial P_i}{\partial \delta_j}\right]\right]_{\text{iter}} \\ \left[\left[\frac{\partial Q_i}{\partial V_j}\right]\right]_{\text{iter}} & \left[\left[\frac{\partial Q_i}{\partial \delta_j}\right]\right]_{\text{iter}} \end{bmatrix}^{-1} \cdot \begin{pmatrix} P_{1,\text{spec}} - P_{1,\text{iter}} \\ \vdots \\ P_{k,\text{spec}} - P_{k,\text{iter}} \\ Q_{1,\text{spec}} - Q_{1,\text{iter}} \\ \vdots \\ Q_{k,\text{spec}} - Q_{k,\text{iter}} \end{pmatrix} \qquad \text{Eq. 5}$$

By the deviation at each iteration step of nodal power to former specified nodal power demand, the vector of state-variables is corrected at each step. The step-size for this correction is determined by the Jacobian Matrix.

Expansion of algorithm

Since the interpretation of node voltages as state-variables is already in place, the state-variables of the HVDC power equations could also be integrated, which seems to be likely. From a structural point of view, this can be done by expanding the Newton-Raphson method in such a way, that the nonlinear system of equations remains determinable. The principle is illustrated in Eq. 6 for the example of on VSC-HVDC transmission link with the associated state variables.

$$\begin{pmatrix} \Delta V_1 \\ \vdots \\ \Delta V_k \\ \Delta\delta_1 \\ \vdots \\ \Delta\delta_k \\ \Delta V_{n\mathrm{q}} \\ \Delta V_{m\mathrm{q}} \\ \Delta\delta_{n\mathrm{q}} \\ \Delta\delta_{m\mathrm{q}} \end{pmatrix} = \begin{bmatrix} \mathbf{J}_{\mathrm{AC}} + \mathbf{J}_{\mathrm{UL}} & \mathbf{J}_{\mathrm{UR}} \\ \mathbf{J}_{\mathrm{LL}} & \mathbf{J}_{\mathrm{LR}} \end{bmatrix}_{\mathrm{iter}}^{-1} \cdot \begin{pmatrix} P_{1,\text{spec}} - P_{1,\text{iter}} \\ \vdots \\ P_{k,\text{spec}} - P_{k,\text{iter}} \\ Q_{1,\text{spec}} - Q_{1,\text{iter}} \\ \vdots \\ Q_{k,\text{spec}} - Q_{k,\text{iter}} \\ \Delta F_{\mathrm{VSC1}} \\ \Delta F_{\mathrm{VSC2}} \\ \Delta F_{\mathrm{VSC3}} \\ \Delta F_{\mathrm{VSC4}} \end{pmatrix} \qquad \text{Eq. 6}$$

As already denoted, to make sure the system remains solvable after the HVDC state-variables are included. The Jacobian Matrix $\mathbf{J}_{\mathrm{AC}}$ need to be extended by four sub-matrices: $\mathbf{J}_{\mathrm{UL}}$, $\mathbf{J}_{\mathrm{UR}}$, $\mathbf{J}_{\mathrm{LL}}$, $\mathbf{J}_{\mathrm{LR}}$ (UL: upper left; UR: upper right; LL: lower left; LR: lower right). Furthermore, the vector with deviations of specified active and reactive power and iterative results of nodal powers need to be expanded with additional mismatch equations representing the control goals of the controllable transmission link.

Concept of mismatch equations based on control mode

The mismatch equations can be formulated according to the set-points, which will be allocated to the controllable devices. While for CSC-HVDC it is only possible to define active power, VSC-HVDC can be specified in active and reactive power and are even able to provide voltage control to their connection point. For both systems, active power set-point can only be reached for the converter of one connection point (master converter), while the other has to before a balancing operation (slave converter). The mismatch equation for both systems master converter is given in Eq. 7 and Eq. 8 supposing the converter at node i perform as master.

$$\Delta F_{\mathrm{CSC1}} = P_{\mathrm{CSC}i,\mathrm{spec}} - P_{\mathrm{CSC}i,\mathrm{iter}} \qquad \text{Eq. 7}$$

$$\Delta F_{\mathrm{VSC1}} = P_{\mathrm{VSC}i,\mathrm{spec}} - P_{\mathrm{VSC}i,\mathrm{iter}} \qquad \text{Eq. 8}$$

Supposing the converter at node j is in slave mode, leads to the two mismatch equation describing the balancing of the DC link by compensating the DC link losses. Eq. 9 shows the balancing for the CSC-HVDC, since the DC link current will remains constant due to the control behaviour, the parameter can be used instead.

$$\Delta F_{\mathrm{CSC2}} = P_{\mathrm{CSC}i,\mathrm{spec}} - P_{\mathrm{CSC}i,\mathrm{iter}} + P_{\mathrm{CSC}j,\mathrm{iter}} + R_{\mathrm{DC}} I_{\mathrm{DC}j}^2 \qquad \text{Eq. 9}$$

Eq. 10 shows the balancing mismatch equation for the VSC-HVDC, instead of the DC current, the DC voltage is used in contrast to CSC-HVDC. This due to the control behaviour of this technology and the DC link voltage parameter can be used in this equation.

$$\Delta F_{\mathrm{VSC2}} = P_{\mathrm{VSC}i,\mathrm{iter}} + P_{\mathrm{VSC}j,\mathrm{iter}} + V_{\mathrm{DC}j}^2 R_{\mathrm{DC}}^{-1} \qquad \text{Eq. 10}$$

Note, that for power flow purposes, the balancing equations show the only link between to AC nodes that are only connected via HVDC transmission.

Since for VSC-HVDC systems also the reactive power is controllable, the two remaining mismatch equations with their reactive power behavior. Suppose the converter at node *i* is performing a specified reactive power provision to its AC connection node Eq. 11 is valid.

$$\Delta F_{\mathrm{VSC3}} = Q_{\mathrm{VSC}i,\mathrm{spec}} - Q_{\mathrm{VSC}i,\mathrm{iter}} \qquad \text{Eq. 11}$$

Supposing the converter at node j is even providing voltage control to its AC node, the mismatch equation can be formulated according to Eq. 12.

$$\Delta F_{\mathrm{VSC4}} = U_{j,\mathrm{spec}} - U_{j,\mathrm{iter}} \qquad \text{Eq. 12}$$

For the development of the two remaining mismatch equations for the CSC-HVDC, a boundary condition for the control scheme can be used. Since the tap-change control tries to keep the reactive demand as low as possible and therefore keeps the firing/extinction angle as close to its minimum value as possible, Eq. 13 and Eq. 14 can be used for the mismatch formulation at both connection nodes.

$$\Delta F_{\mathrm{CSC3}} = \alpha_{i,\mathrm{min}} - \alpha_{i,\mathrm{iter}} \qquad \text{Eq. 13}$$

$$\Delta F_{\mathrm{CSC4}} = \alpha_{j,\mathrm{min}} - \alpha_{j,\mathrm{iter}} \qquad \text{Eq. 14}$$

Derivatives based on applied technology

The elements of the Jacobian sub-matrix J_{UL} describe the dependency between reactive/active power of each converter and the conventional state-variables of the AC power system namely node voltage magnitude and node voltage angle. Those are as follows for the CSC-HVDC:

$$\partial P_{\mathrm{CSC}i}/\partial V_i = t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos\alpha_i \qquad \text{Eq. 15}$$

Analogously, the terms for reactive power can be formulated. The same equations are valid for the converter connected to node *j*. Furthermore, there is no dependency between node voltage magnitude and node voltage angle and the active/reactive power of the CSC-HVDC.

For the VSC-HVDC the terms for the sub-matrix $\mathbf{J}_{\mathrm{UL}}$ are as follows considering active power at node *i*:

$$\partial P_{\mathrm{VSC}i}/\partial V_i = \frac{2V_i}{Z_{\mathrm{T}}} \cos\varphi_Z + \frac{V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 16}$$

$$\partial P_{\mathrm{VSC}i}/\partial \delta_i = -\frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 17}$$

In contrast to the CSC-HVDC, the dependency between active power and node voltage angle need to be represented. The same formulations are valid for the active power derivatives at node *j*. Analogously, the terms for reactive power can be formulated. They are given in Eq. 18 and Eq. 19.

$$\partial Q_{\mathrm{VSC}i}/\partial V_i = \frac{2V_i}{Z_{\mathrm{T}}} \sin\varphi_Z + \frac{V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 18}$$

$$\partial Q_{\mathrm{VSC}i}/\partial \delta_i = \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 19}$$

The elements of the Jacobian sub-matrix $\mathbf{J}_{\mathrm{UR}}$ describe the dependency between reactive/active power of each converter and the specific state-variables of the used technology. For the CSC-HVDC this results in Eq. 20 and Eq. 21 for active power at node *i*.

$$\partial P_{\mathrm{CSC}i}/\partial \alpha_i = V_i t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \sin\alpha_i \qquad \text{Eq. 20}$$

$$\partial P_{\mathrm{CSC}i}/\partial t_i = V_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos\alpha_i \qquad \text{Eq. 21}$$

For the VSC-HVDC Eq. 22 and Eq. 23 are valid for active power derivatives and node *i*.

$$\partial P_{VSCi}/\partial \delta_{iq} = \frac{V_i V_{iq}}{Z_T} sin(\delta_i - \delta_{iq} - \varphi_Z) \qquad \text{Eq. 22}$$

$$\partial P_{\mathrm{VSC}i}/\partial V_{i\mathrm{q}} = \frac{V_i}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 23}$$

Analogously, the terms for reactive power can be formulated. They are given in Eq. 24 and Eq. 25.

$$\partial Q_{\mathrm{VSC}i}/\partial \delta_{i\mathrm{q}} = -\frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 24}$$

$$\partial Q_{\mathrm{VSC}i}/\partial V_{i\mathrm{q}} = \frac{V_i}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \qquad \text{Eq. 25}$$

The elements of the Jacobian sub-matrix $\mathbf{J}_{\mathrm{LL}}$ describe the dependency between the formulated mismatch equations and the conventional state-variables of the AC power system namely node voltage magnitude and node voltage angle. For CSC-HVDC systems master converter Eq. 26 is valid supposing the converter at node *i* performs as master.

$$\partial \Delta F_{\mathrm{CSC1}} / \partial V_i = -t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos \alpha_i \quad \text{Eq. 26}$$

For VSC-HVDC system Eq. 27 and Eq. 28 are valid supposing the converter at node *i* perform as master.

$$\partial \Delta F_{\mathrm{VSC1}} / \partial \delta_i = \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 27}$$

$$\partial \Delta F_{\mathrm{VSC1}} / \partial V_i = -\frac{2V_i}{Z_{\mathrm{T}}} \cos \varphi_Z - \frac{V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 28}$$

Since the second mismatch equation in both technologies is representing the active power coupling between two AC nodes that are connected via HVDC transmission link, the derivatives have to be formulated with respect to node *i* and node *j*. Supposing the converter at node *j* performs as slave results in two equation for the CSC-HVDC (Eq. 29 and Eq. 30) and four equations for the VSC-HVDC (Eq. 31, Eq. 32, Eq. 33 and Eq. 34). All equations are given below.

$$\partial \Delta F_{\mathrm{CSC2}} / \partial V_i = -t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos \alpha_i \quad \text{Eq. 29}$$

$$\partial \Delta F_{\mathrm{CSC2}} / \partial V_j = -t_j \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}j} \cos \alpha_j \quad \text{Eq. 30}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial \delta_i = \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 31}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial V_i = -\frac{2V_i}{Z_{\mathrm{T}}} \cos \varphi_Z - \frac{V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 32}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial \delta_j = \frac{V_j V_{j\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_j - \delta_{j\mathrm{q}} - \varphi_Z) \quad \text{Eq. 33}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial V_j = -\frac{2V_j}{Z_{\mathrm{T}}} \cos \varphi_Z - \frac{V_{j\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_j - \delta_{j\mathrm{q}} - \varphi_Z) \quad \text{Eq. 34}$$

The third and fourth mismatch equation of CSC-HVDC system is neither a function of node voltage magnitude nor node voltage angle. However, for VSC-HVDC systems both mismatch equations are dealing with the behavior of the converter in terms of reactive power. If the converter at node *i* is performing a specified reactive power provision to its AC connection node Eq. 35 and Eq. 36 are valid.

$$\partial \Delta F_{\mathrm{VSC3}} / \partial \delta_i = -\frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 35}$$

$$\partial \Delta F_{\mathrm{VSC3}} / \partial V_i = -\frac{2V_i}{Z_{\mathrm{T}}} \sin \varphi_Z - \frac{V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 36}$$

Supposing the converter at node *j* is providing voltage control to its AC node, the derivative with respect to the fourth mismatch equation can be formulated according to Eq. 37.

$$\partial \Delta F_{\mathrm{VSC4}} / \partial V_j = -1 \quad \text{Eq. 37}$$

The elements of the Jacobian sub-matrix $\mathbf{J}_{\mathrm{LR}}$ describe the dependency between the formulated mismatch equations and the specific state-variables of the used technology. For CSC-HVDC systems master converter Eq. 38 and Eq. 39 are valid supposing the converter at node *i* performs as master.

$$\partial \Delta F_{\mathrm{CSC1}} / \partial t_i = -V_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos \alpha_i \qquad \text{Eq. 38}$$

$$\partial \Delta F_{\mathrm{CSC1}} / \partial \alpha_i = V_i t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \sin \alpha_i \qquad \text{Eq. 39}$$

For VSC-HVDC system Eq. 40 and Eq. 41 are valid supposing the converter at node *i* perform as master.

$$\partial \Delta F_{\mathrm{VSC1}} / \partial \delta_{i\mathrm{q}} = -\frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin\left(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 40}$$

$$\partial \Delta F_{\mathrm{VSC1}} / \partial V_{i\mathrm{q}} = -\frac{V_i}{Z_{\mathrm{T}}} \cos\left(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 41}$$

Again the derivatives for the second mismatch equation have to be formulated with respect to node *i* and node *j*. Supposing the converter at node *j* performs as slave results in two equation for the CSC-HVDC (Eq. 42, Eq. 43, Eq. 44 and Eq. 45) and four equations for the VSC-HVDC (Eq. 46, Eq. 47, Eq. 48 and Eq. 49). All equations are given below.

$$\partial \Delta F_{\mathrm{CSC2}} / \partial t_i = -V_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \cos \alpha_i \qquad \text{Eq. 42}$$

$$\partial \Delta F_{\mathrm{CSC2}} / \partial \alpha_i = V_i t_i \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}i} \sin \alpha_i \qquad \text{Eq. 43}$$

$$\partial \Delta F_{\mathrm{CSC2}} / \partial t_j = -V_j \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}j} \cos \alpha_j \qquad \text{Eq. 44}$$

$$\partial \Delta F_{\mathrm{CSC2}} / \partial \alpha_j = V_j t_j \frac{\sqrt{6}}{\pi} I_{\mathrm{DC}j} \sin \alpha_j \qquad \text{Eq. 45}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial \delta_{i\mathrm{q}} = -\frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}} \sin\left(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 46}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial V_{i\mathrm{q}} = -\frac{V_i}{Z_{\mathrm{T}}} \cos\left(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 47}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial \delta_{j\mathrm{q}} = -\frac{V_j V_{j\mathrm{q}}}{Z_{\mathrm{T}}} \sin\left(\delta_j - \delta_{j\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 48}$$

$$\partial \Delta F_{\mathrm{VSC2}} / \partial V_{j\mathrm{q}} = -\frac{V_j}{Z_{\mathrm{T}}} \cos\left(\delta_j - \delta_{j\mathrm{q}} - \varphi_Z\right) \qquad \text{Eq. 49}$$

The third and fourth mismatch equations of CSC-HVDC system depend only on the firing/extinction angle. Therefore, the derivatives for both converter at node I and node j can be formulated according to Eq. 50.

$$\partial \Delta F_{\mathrm{CSC3}} / \partial \alpha_j = \partial \Delta F_{\mathrm{CSC4}} / \partial \alpha_j = -1 \qquad \text{Eq. 50}$$

Considering specified reactive power provision of converter at node *i* to its AC connection node, Eq. 51 and Eq. 52 can be formulated for the VSC-HVDC.

$$\partial\Delta F_{\mathrm{VSC3}}/\partial\delta_{i\mathrm{q}} = \frac{V_i V_{i\mathrm{q}}}{Z_{\mathrm{T}}}\cos(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 51}$$

$$\partial\Delta F_{\mathrm{VSC3}}/\partial V_{i\mathrm{q}} = -\frac{V_i}{Z_{\mathrm{T}}}\sin(\delta_i - \delta_{i\mathrm{q}} - \varphi_Z) \quad \text{Eq. 52}$$

Supposing the converter at node j is providing voltage control to its AC node, the derivative with respect to the fourth mismatch equation can be formulated according to Eq. 53 due to the voltage loop of the HVDC source voltage and the node voltage magnitude of the connected AC node.

$$\partial\Delta F_{\mathrm{VSC4}}/\partial V_{j\mathrm{q}} = -1 \quad \text{Eq. 53}$$

Since the elements of the Jacobian and therefore the whole load flow calculation are depending on the applied control modes, a methodology for choosing those control modes is necessary.

Selection of control mode

In the framework of EERA-DTOC, the study case Kriegers Flak is shown in Figure 13. The offshore structure consists of two areas, which are marked in green respectively red. HVDC connections are in yellow while AC branches are in blue color.

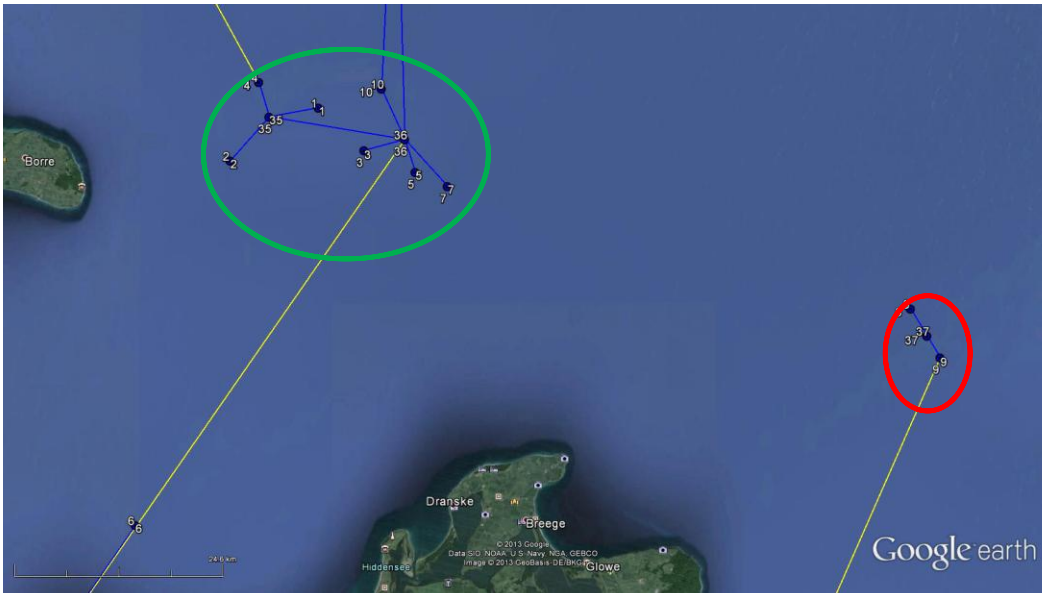


Figure 13. Kriegers Flak Offshore structure.

For the matter of simplicity, only VSC-HVDC systems are considered in the study case. Considering the red part, the HVDC connection has to provide voltage control with its seaside converter so the wind farms are able to synchronize to the offshore grid voltage. In terms of active power, the set-point of the HVDC depends on the active power production of the connected wind farms. Therefore, the HVDC has to operate in slack mode operation. During the first load flow iterations, the AC offshore connection node of the HVDC is treated as slack or swing bus. The injected active and reactive power at this node is calculated via the AC branch power values connected to this bus. Those values are then given to the HVDC mismatch equations as set-points. In this case, the offshore converter has to perform as master. Considering the green part, all HVDC connections are providing voltage control to the offshore grid with their converter at offshore side. The reason for this is the same as considering the red area. However, the active power set-point is calculated due to onshore target values. This can be done either by the demand of onshore node during normal operation or due to reserve provision to the national grids. In this case, the onshore converter station of each HVDC connection performs as master, so at offshore site losses are always considered. For the green area, the onshore node of Sweden is always set as slack bus due to its AC connection to the offshore grid. However, since in each via HVDC coupled AC grids a slack have to be present to balance active and reactive power, every land connection point is set as slack. To treat the problem in a universal way, a checking routine scans the grid structure and sets slack busses or HVDC systems in slack mode operation. All converters at land side of HVDC system are set to reactive power provision by fixed values. Here, the converter capabilities are the only limit for reactive power provision to onshore nodes.

General remarks

Even though the VSC-HVDC systems are the preferred technology for offshore grids due to their capabilities in voltage control and islanding operation, CSC-HVDC systems are manageable if the grid strong enough e.g. due to meshed AC connections to an onshore grid, like in the study case presented. Thereby the reactive power demand has to be met and other components like wind farms have to take over the voltage control responsibility. Since the decision for AC or DC connection is mainly based on cost and therefore based on a critical distance, CSC-HVDC become beneficial if critical size in terms of power is also considered. At a certain transport level of power, switching losses of VSC-HVDC system are a major cost factor and the efficiency of CSC-HVDC system gain importance.

2 POWER PLANT SYSTEM SERVICES

In this section the considered power plant system services are presented and defined as well as the general rules applied to their simulation.

The results provided by the tool should be considered as technical solution due to the fact the DTOC-WCMS is simulating what it is technically possible to achieve in terms of system services without any consideration about the markets and their rules.

Moreover, procurement rules for services are sometimes different in different European countries[12]. Those rules are here simplified and some basic assumptions are made. In the coming pages those assumptions are presented and explained.

2.1 Considered Power Plant System Services

The **power plant system services** are different supporting actions provided by a power plant (in this case specifically WPP) to maintain the grid operation in correct (or even optimum) level. Some of those services are the so-called ancillary services, as well as congestion management support and balancing power supply.

According to the DoW, *"the availability of power plant system services of a cluster is analyzed, especially: the reserve power provision and balancing, the reactive power supply and voltage control, and the dependence of the capability of a cluster to provide such services generator types and cluster grid connections - on its configuration is investigated. AC as well as HVDC connections are considered"*.

Then, the considered power plant system services are organized as they are depicted in Table 1:

Category	Service	Description
Frequency Support	Reserve	FRR (like Secondary Reserve) as defined in [13] .
		RR (like Minute Reserve) as defined in [13] .
	Balancing Power	Balancing power supply [14] .
Voltage Support	Reactive power contribution to onshore nodes	Reactive power provision of the cluster (if connected with AC) or by HVDC links to onshore nodes [15] .
System Management	Congestion Detection/Management	Maximum load flow into the grid due to congestions on land [15] or overloaded electrical components.

Table 1. Analyzed power plant system services.

2.2 Clusters of wind farms

The impact of wind power variability[13] on the provision of system services can be significant, especially at individual wind farms level. In order to overcome this, it is possible to use the smoothening effect that geographical spreading of WFs has on the wind power production. Moreover, it is shown that there is an almost linear relation between variability and predictability

[12] See Figure 1 in page 10.

[13] Please, refer to [7]

or forecast quality (Figure 15). The latter means that the uncertainty level – crucial in delivering frequency support services – can be reduced by geographical spreading.

A further reduction of the uncertainty can be achieved by using probabilistic forecast, being able to reach confidence intervals that are similar to the conventional power plants. Therefore, the use of probabilistic forecasts -together with pre-qualification methods adapted to the characteristics of wind power- are issues that need to receive more attention in the future.

The advantages of analyzing the variability and predictability on wind farm clusters have been clearly established in [7] . In the mentioned document, a comprehensive study of the correlation between the variability (wind power fluctuations) and predictability (forecast quality) for a single wind farm (Figure 14) and for clusters of wind farms (Figure 15). The results show that in both cases, the correlation between the Mean Absolute Gradients (MAG) of the measured 1h-power time series, defined as the absolute difference between the power in each time step, and the Root Mean Square Error (RMSE), normalized with the installed capacity, is very good.

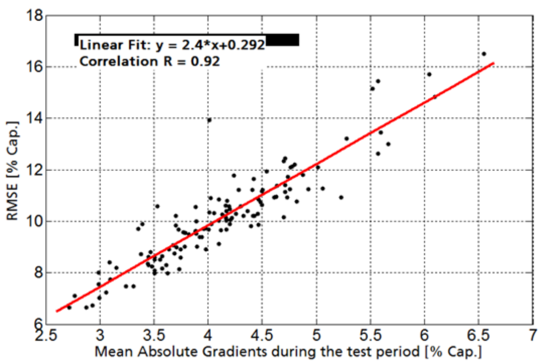


Figure 14: correlation between RSME and MAG [23]

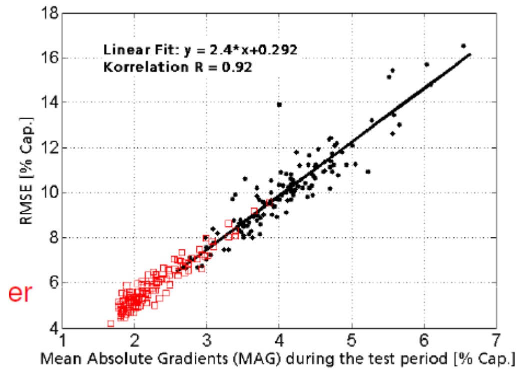


Figure 15: the correlation between RMSE and Meand Absolute Gradients (MAG), proving an excellent correlation of 0.92 [23]

Therefore, **minimizing the wind power variability will result in better predictability**. The analysis showed that wind power fluctuations are influencing the quality of the power forecast more than the NWP grid resolution.

The main outcomes are:

- Linear dependency between the RMSE of wind farm/portfolio power forecasts and the mean absolute 1h-gradients of the power time series.
- Minimizing the power fluctuations of the wind farm portfolio leads to a better forecast quality.

These notions are the basis behind the aggregation (portfolio) of wind farms and WPP in wind farm clusters and is presented in the next chapter how the provision of system services based on forecasts are improved due to clustering (and the improvement of forecast) and reducing the variability if those phenomena is analyzed at planning (for grid and wind farms) stage.

2.3 Power Plant System Services Analysis with the DTOC-WCMS

2.3.1 General considerations

This section introduces the way DTOC-WCMS is analyzing the provision of system services. They are presented in this section in the same way the services are aggregated in the previous section, by: frequency support, voltage support and congestion management.

On the other hand, the WPP are considered dispatchable units that can be committed to provide a service or to schedule active power to the power system either day-head or intraday. In this context, the forecasted power for the WPP are used to create schedules of power that can be used either as a reserve or allocated as active power scheduled day-head -both based on the day-head forecast- or as balancing power schedules, based on intraday forecasts. The differences between the addition of those schedules and the real active power production are considered as undispatchable and therefore considered as losses due to (forecast) uncertainty.

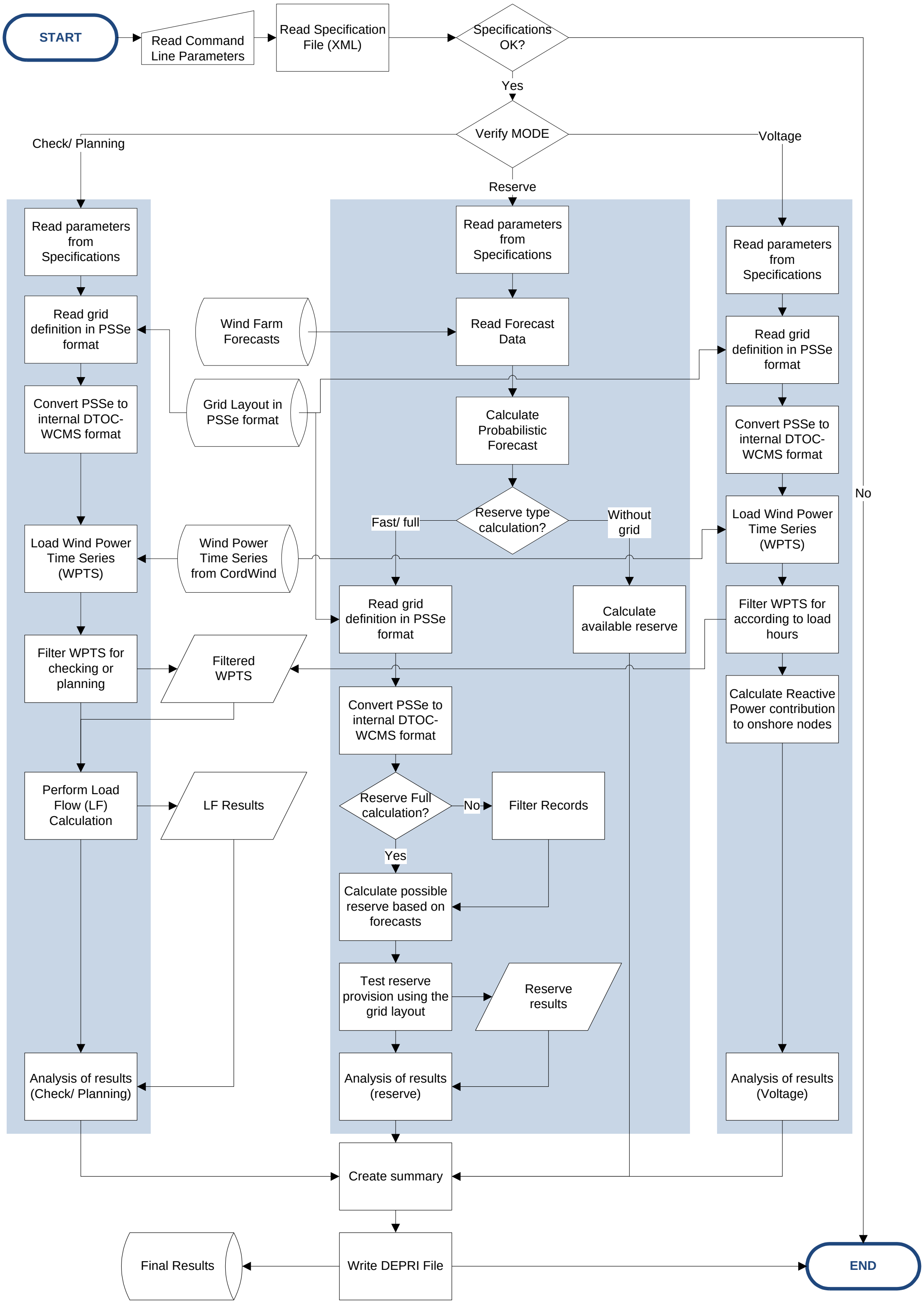


Figure 16. Outline of the run flow using DTCO-WCMS.

The run flow of the DTOC-WCMS is basically divided in three main blocks or modes:

1. Check/planning mode: the grid layout is investigated in order to detect its capability to manage the electrical flows using wind power production time series. The "check" mode calculates the load flows for maximum power output of the WPP (rated power) and in low wind conditions (minimum generation). This calculation allows knowing if the utilized grid layout is able to accommodate the power flows, detecting possible congestions and overloads.
2. Reserve mode: in this mode, the provision of reserve, balancing power and active power provision for the day-ahead market (based on schedules) is investigated. Two sub-modes exist: one (called "no grid") using the time series of available power and the forecasted power for the wind farms, without considering the grid layout or calculating the power flows, and another considering the grid layout. The first option investigates what it is possible to be delivered since the generator point of view, which acting on a market is able to offer and amount of power reserve at the POI, being the TSO or DSO the responsible of the grid operation. The last mode is in its turn divided again in two: considering all records in the loaded wind power/ forecast time series (called "reserve full") or filtering the time series to reduce the calculation time (called "reserve filter"). The last one is selecting three records per day out from the time series representing the generation and the system load values at peak, mean and low conditions. This calculations allows knowing how much power can be deliver as reserve (combined FRR and RR), how much power can be allocated as balancing power (for intraday trading) and how much can be dispatch (scheduled day-ahead) as power for the electricity market.
3. Voltage mode: using the grid layout and the wind power time series the maximum reactive power contribution of all WPP in a cluster to the onshore nodes is calculated. This calculation allows knowing how much reactive power can be provided to the onshore nodes by a cluster.

The congestion detection is automatically implemented for each calculation due to the fact, the best option in terms of electrical losses reduction and component utilization reduction is selected.

2.3.2 Frequency support

Recent studies [24] [25] have proposed new methods for proof of power reserve provision.

The first proposes an 8-hour procedure where economic variables are considered as well as the stability of the offered reserve is being monitored and evaluated according to TSO requirements, at wind farm level. The main idea of the procedure is that power reserves are tendered every hour, 8 hours before the “Power Reserve Activation Time”. During this period, the tenders are posted, economically evaluated and finally their availability and stability is validated. The validation process has as objective to evaluate the relation between “offered power” and “available power” during the last 4 hours before the power activation takes place. The “offer stability” validation process considers an offer to be unstable when the offered power volume is bigger than the one reported by a pre-defined lower interval from the wind power forecast for a given wind farm.

For frequency support (reserve and balancing power provision) the system uses the time series of forecasted power output[14]. For calculating the available reserve the 24 hours in advanced forecast (day ahead) is implemented. For balancing power provision, the 1 hour ahead forecast is implemented, representing the intraday.

The methodology used to calculate a secure forecast with given probability is described in [25] using the forecasts provided by the user with a time resolution of 1 hour. In operational conditions would be preferred to have 15 minutes interval forecast for intraday. Nevertheless, for planning purposes 1 hour resolution is enough to estimate the available power output at each wind farm.

[14] Time series could be those provided by the variability and predictability model described in D2.8 [7]

In [25] and [26] two different proof methods of control reserve are discussed. For operational purposes is definitively the so-called proof of control reserve under the available active power mechanism the most suitable. Nevertheless, for planning activities and for the hourly time series used, the proof of control reserve under the balance control mechanism is enough to estimate the rough available power for reserve and balancing purposes.

On Figure 17 and Figure 18 the mentioned proof mechanisms are depicted.

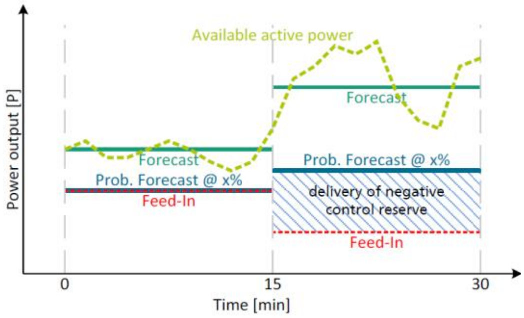


Figure 17. Proof of control reserve under the balance control mechanism, reproduced from [26]

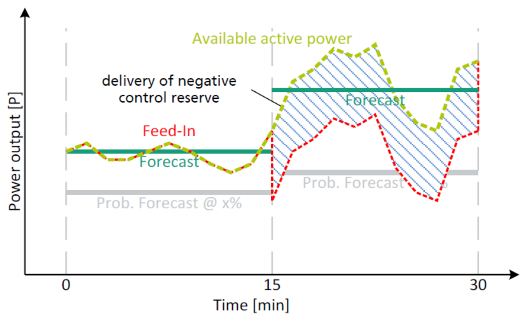
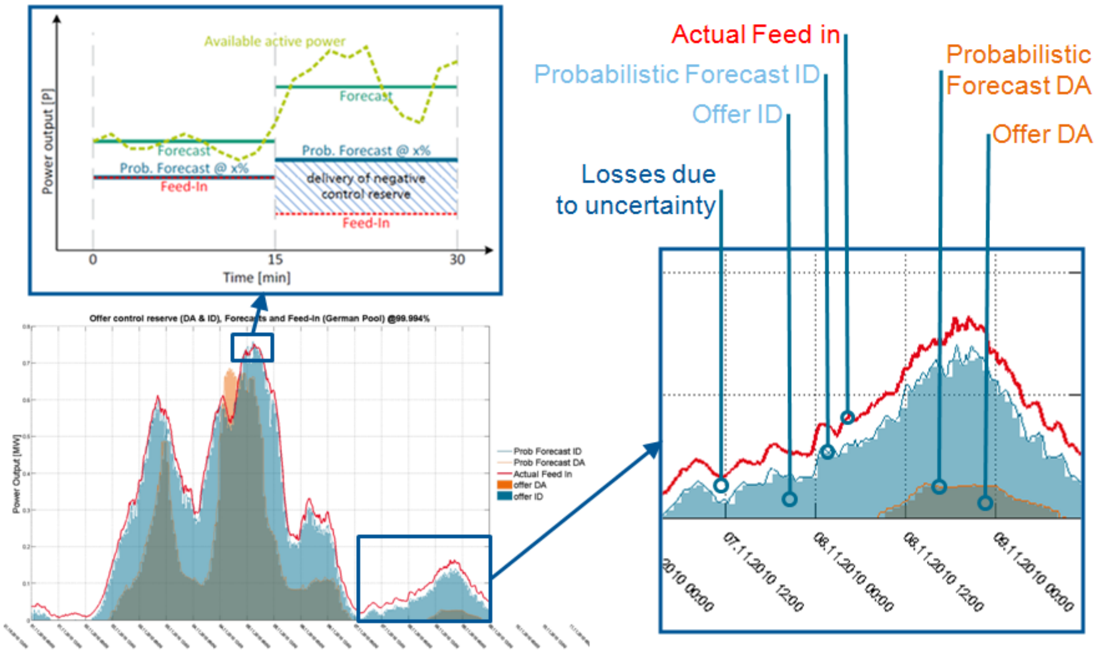


Figure 18. Proof of control reserve under the available active power mechanism, reproduced from [26]

The mechanism depicted in Figure 17 is the one selected on this report to calculate the secure forecast and -moreover- the interval values are of one complete hour.



Source: Malte Jansen – Fraunhofer IWES

Figure 19. Reserve and balancing power calculation (images source: Malte Jansen, Fraunhofer IWES)

The proof mechanism, the day ahead forecast and the hourly (intraday) forecast allow calculating the available reserve and balancing power, as it is depicted in Figure 19.

On the upper-left side of the picture the proof mechanism is depicted, based on a probabilistic forecast of a given percentage (in this report, typically 99.5%). On the right side of the picture a graphical example is provided:

The orange line represents the calculated probabilistic forecast and based on this forecast the offer for the day ahead (with a probability of 99.5%) can be traded day ahead as power reserve, represented by the orange bars below.

The blue line represents the probabilistic forecast intraday (with a probability of 99.5%). The blue bars below represent the possible offers intraday that can be sold as balancing power.

The red curve represents the real power output (based on the power output time series).

The white area between the red curve and the blue bars represents the untraded (undispatched) energy due to the forecast error and can be computed as energy lost due to the fact can be produced but it is not scheduled for dispatch.

2.3.3 Reserve and Balancing Power

The results of the available reserve calculation are depicted in Figure 20. The picture summarizes the complete approach to calculate frequency support based on wind farm possible power output and 1/ 24 hours forecasts.

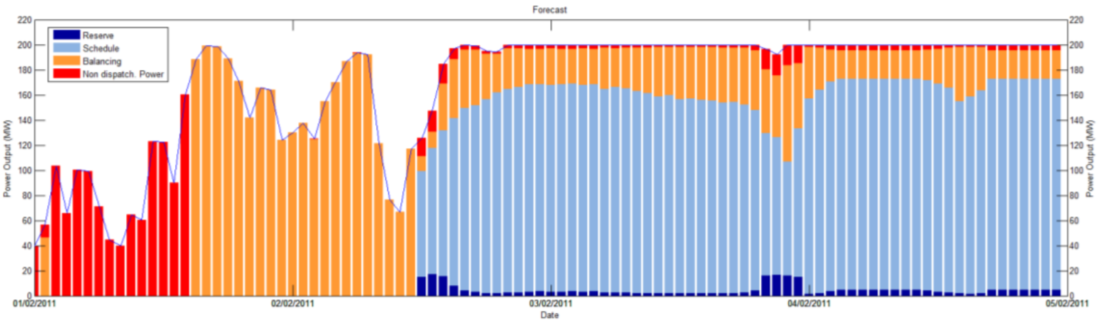


Figure 20. Calculation of power reserve, scheduled active power and balancing power for the wind farm (Kriegers Flak) KF_A_K1 of 200 MW of installed capacity between the 01/02/2011 and 05/02/2011.

The procedure to calculate the possible reserve (depicted in dark blue in Figure 20) and the possible active power schedule is as follows:

- For a given wind farm, the time span or calculation time window is defined: in this case between 01/02/2011 and 05/02/2011 was selected[15].
- The 24 hours (day ahead) and 1 hour (intraday) forecasts is loaded and the probabilistic (secure) forecast is calculated using the kernel density estimator (KDE) for a probability of 99.5%[16].
- For each calculated day, the KDE is estimating the probability based on the previous and following days contained in the time series.
- The 24 hours forecast with a probability of 99.5% is considered the available reserve power for the next day (in dark blue on Figure 20).
- Then, the 24 hours in advance forecast with a probability of 90% is calculated and considered a firm capacity for the next day. Subtracting the already calculated reserve to the firm capacity is possible to calculate the schedules for the next day (in light blue), considered as the active power dispatchable next day as regular active power.
- The 1 hour in advance secure forecast with a probability of 99.5% is calculated. These values are considered as the available power hour by hour intraday. So, subtracting the

[15] A small time window has been selected to enable a comfortable data representation.

[16] This probability is a parameter that can be modified by the final user using a configuration file.

already calculated reserve and schedules, the remaining power is considered the available balancing power (intraday), which is depicted in orange on Figure 20.

- Finally, the difference between the addition of reserve, schedules and balancing power with the available power depicted with the blue thin line represents the undispatchable energy. This energy could be produced but due to the forecast errors is not possible to dispatch it as reserve, active power (schedule) or balancing power so this portion is considered lost in a market-oriented energy trading environment[17].

This first calculation is the theoretical available power reserve and balancing power and would be the volumes that owners and traders could market.

In a separated and final step, the capability of the grid to transport the calculated volumes of power that the wind farms can generate is verified. With the calculated values a time series file is created and the DTOC-WCMS is using the information along with the grid description to compute the power flows on the grid and verifies those schedules. As part of the calculation, the HVDC links setpoints are estimated.

To enable the load flow calculation the loads onshore or the HVDC links setpoints should be previously computed, otherwise the Newton-Raphson algorithm would not be able to determine the proper results. For that reason, the loads at each single onshore (mainly matching with each connected country) node is estimated based on the maximum demand. This maximum demand per onshore node is provided to the DTOC-WCMS as a parameter described in the specification file; usually, the values estimated by the NETOP model as the onshore load[18] can be used here.

As mentioned, the resulting flows onshore are affected not only by the wind farm in-feeds and the resulting AC flows but for the HVDC set-points provided to the HVDC links. For that reason several alternative setpoints are automatically calculated, based on variations of 20%[19], starting at 20 up to 100%, and most suitable are used. The preferred setpoint selection process

Reserve

In Figure 20 is depicted that 279 MW can be procured as reserve power distributed in 60 hours between 02/02/20111 at noon and 05/02/2011 until 23 hr.

In Figure 21, for the Wikinger wind farm, with a rated power of 400 MW, only two days is possible to provide reserve up to 8 MW.

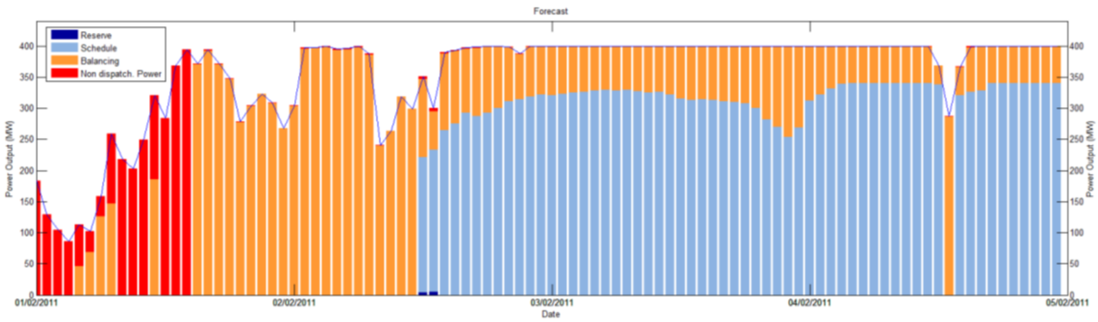


Figure 21. Calculation of power reserve, scheduled active power and balancing power for the wind farm (Kriegers Flak) Wikinger of 400 MW of installed capacity between the 01/02/2011 and 05/02/2011

[17] On an energy direct marketing scheme, like the German EEG (Erneuerbare-Energien-Gesetz), all produced energy can be directly sold to the energy system.

[18] See [9] , page

[19] Those variation steps or percentages are configurable.

Balancing Power

For KF_A_K1 (Figure 20) is possible to deliver 927.4 MW active power as schedule during 60 of 96 hours and the rest of the energy (524.8 MW distributed in 82 hours) is possible to be delivered as balancing power in the intraday market.

Wikinger wind farm (Figure 21) is able to deliver 1,860 MW of scheduled active power during 59 of 96 hours and can provide 1,265 MW balancing power in 86 hours.

The undispatched power due to forecast error is 148 MW distributed irregularly in 96 for KF_A_K1 and 270.7 MW for Wikinger in 96 hours, too.

2.3.4 Reactive power contribution to onshore nodes

The contribution of a cluster with reactive power to the onshore nodes is investigated only for some specific situations, selected by three parameters: peak, low load and mean load conditions.

The procedure to investigate the reactive power contribution is as follows:

- The user provides the grid layout and active power time series[20].
- Using the configuration file, the PQ diagrams of the wind turbines/ farms and the definition of peak, mean and low load times of the system are defined to the program (parameter *pqDiagram*).
- The DTOC-WCMS filter the time series (*timeseries* parameter on the specification file) for the mentioned conditions using three parameters: *dailyPeakTime*, *dailyValleyTime* and *dailyRestTime* for peak, mean and low load times respectively; the default values for those parameters are 0800 (8 AM), 1500 (3 PM) and 0400 (4 AM). Also the timestamps for the beginning and the end of the temporal windows to perform the calculation are given by the *VoltageControlStartTime* and *VoltageControlEndTime* parameters.
- With the selected conditions, several load flow calculations are performed based on the participation factors of all generators whose *cluster* parameter is equal to the parameter *ClusterId* to fulfill the active power schedules while simultaneously extracting as much reactive power as possible from the nearby generators without: reducing the active power outputs, violating the voltage limits and overloading any grid component.

  The algorithm only consider the generators whose *cluster* parameter is equal to *ClusterId* to perform the voltage control. The others generators are not modify. At the same time, the reactive power capabilities of the generators are described in a text file which name is stored in the *pqDiagram* parameter of each generator.
- The active as well as reactive power provision, voltages and losses are computed.

Example of the input file:

```
#version 1.3A
#datatype timeseries
#language en
#creator LMF
#user mariano
#channel TimeMeas      UTC      DateTime d      datetime:UTC
#channel KF_A_K2       Power    Power           MW       mean
#channel KF_A_K3       Power    Power           MW       mean
```

[20] The time series can be provided either by CorWind model, the variability and predictability model or directly by the user in DEPRI format.

```
#channel KF_A_K4         Power   Power           MW      mean
#channel KF_A_K1         Power   Power           MW      mean
#channel EnBW_Baltic_2   Power   Power           MW      mean
#channel EnBW_Baltic_1   Power   Power           MW      mean
#channel Baltic_Power    Power   Power           MW      mean
#channel Wikinger        Power   Power           MW      mean
#channel ArkonaBeckenSud Power   Power           MW      mean
#channel KriegersFlak    Power   Power           MW      mean
#begindata      2011-01-01T0000
2011-01-01T0000  0.9997169       0.999568 0.99975  0.9995946       0.9994894       0.9997494
        0.9996405       0.99975  0.9996257       0.9995748
2011-01-01T0005  0.9995874       0.999568 0.9994745       0.9997002       0.99975  0.99975
        0.9995433       0.9994659       0.9995582       0.99975
...
2011-12-31T2350  0.386957 0.5267488      0.2840666       0.3001174       0.3142345
        0.2098898       0.2511788       0.174196 0.1616631      0.2107469
2011-12-31T2355  0.3465076       0.4714049       0.2909253       0.304201 0.2325805
        0.2378421       0.2324941       0.1922949       0.1965168       0.1552681
#enddata 2011-12-31T2355
```

Example of the output file:

The output file contains 22 channels: the time stamp for which the calculation was performed and for each connected onshore node a reference calculation (a simple load flow calculation to establish the boundary conditions for the next calculations). After that column, the maximum inductive and capacitive reactive power flows at the considered node when the contribution of the reactive power is intended to all considered onshore nodes.

For example, channels 3 and 4 are the inductive and capacitive reactive power contribution to Sweden when the intention is to provide the contribution to Sweden, too. But channels 5 and 6 are the inductive and capacitive reactive power contribution to Sweden when the intention is to provide maximum contribution to Denmark.

```
#version DEPRI V1.3A
#creator DTOC-WCMS_depriwrite() v1.0
#channel Time     UTC                      DateTime        d               datetime:UTC
#channel Sweden   Reference                QPower          MVar            mean
#channel Sweden   MaxInductiveToSweden     QPower          MVar            max
#channel Sweden   MaxCapacitiveToSweden    QPower          MVar            max
#channel Sweden   MaxInductiveToDenmark    QPower          MVar            max
#channel Sweden   MaxCapacitiveToDenmark   QPower          MVar            max
#channel Sweden   MaxInductiveToGermany    QPower          MVar            max
#channel Sweden   MaxCapacitiveToGermany   QPower          MVar            max
#channel Denmark  Reference                QPower          MVar            mean
#channel Denmark  MaxInductiveToSweden     QPower          MVar            max
#channel Denmark  MaxCapacitiveToSweden    QPower          MVar            max
#channel Denmark  MaxInductiveToDenmark    QPower          MVar            max
#channel Denmark  MaxCapacitiveToDenmark   QPower          MVar            max
#channel Denmark  MaxInductiveToGermany    QPower          MVar            max
#channel Denmark  MaxCapacitiveToGermany   QPower          MVar            max
#channel Germany  Reference                QPower          MVar            mean
```

```
#channel Germany  MaxInductiveToSweden      QPower           MVar            max
#channel Germany  MaxCapacitiveToSweden     QPower           MVar            max
#channel Germany  MaxInductiveToDenmark     QPower           MVar            max
#channel Germany  MaxCapacitiveToDenmark    QPower           MVar            max
#channel Germany  MaxInductiveToGermany     QPower           MVar            max
#channel Germany  MaxCapacitiveToGermany    QPower           MVar            max
#begindata 2011-07-09T000000
2011-07-09T000000        367.566300               347.157900               394.757900
        367.566300               367.566300               367.566300               367.566300
                -0.000000                -0.000000                -0.000000               -
359.048200               359.048200       0.000000         0.000000         36.788030
                36.788030                36.788030                36.788030
        36.788030                -2263.680500             2336.737300

2011-07-05T010000        370.893900               304.044100               459.746200
        370.893900               370.893900               370.893900               370.893900
                0.000000         0.000000         0.000000         -359.715900
        359.715900               0.000000         0.000000         36.769800
        36.769800                36.769800                36.769800                36.769800
                -2266.618300             2339.637000
```

…

This information is useful to analyze how the power flow is influenced by the grid and the onshore nodes when different provision objectives are defined.

2.3.5 Congestion Detection/ Management

The congestion detection is performed by the DTOC-WCMS as part of the load flow calculation. Considering the actual power output of each wind turbine/ farm and the given grid layout, the WCMS is calculating several grid operation modes and all computed possible operational modes of wind turbines/ farms and setpoints for HVDC links is selecting from those that provide a valid solution the one avoiding voltage problems and minimizing losses.

Due to the fact DTOC-WCMS is a planning tool congestions are only detected and the related components are depicted, but no remedy action is taken besides choosing the best calculation solution in case of multiple solutions are available.

3 CASE STUDY: KRIEGERS FLAK

3.1 Case study description

The selected case study is defined in [9] and was adopted for all validations in WP2. The Kriegers Flak area wind farms have a combined capacity of 2,276 MW. Export cables to shore have a combined capacity of 3,166 MW, so there is an over-capacity that is used to exploit the price differences in the three power markets. The solution includes a link between the two Kriegers Flak clusters with a capacity of 515 MW, and a mean power flow of 92.1 MW in the direction towards Denmark, and a mean flow of 184.2 MW from Denmark[21].

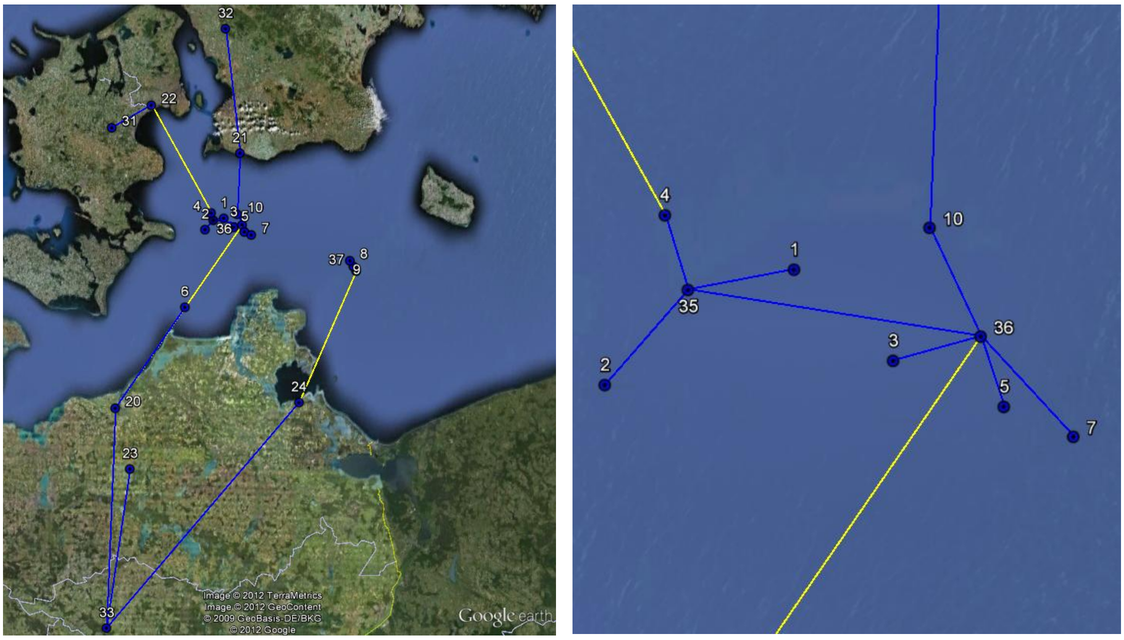


Figure 22. Resulting optimal grid according to [9]

3.2 Case study definition

For the perspective of the system services, the DTOC-WCMS is used to investigate how different wind farm cluster configuration can affect or improve the provision of those services. In order to assess this impact, several scenarios were developed for the study case.

First of all, a baseline case study is established in order to perform a sensitivity analysis modifying the cluster composition and varying some operational parameters of wind turbines/ farms.

In the baseline scenario all wind turbines/ farms remain uncontrolled and the only possibility for the software is to manage the HVDC links in order to control and balance the grid. This is considered the worst case and current scenario.

Then, the full cluster or (assumed) best case scenario is investigated, in which all wind farms are controllable and they are part of a big cluster connected to different countries.

Finally, the additional case studies aggregate in clusters the wind farms belonging to the same country (Denmark, Germany and Sweden). In those scenarios three different clusters are controlled separately and one cluster at a time, aggregated by country as suggested in Table 2.

[21] See [9]

Table 2. Wind farms investigated on the Kriegers Flak case study.

#	Country	Wind farm	Capacity	Latitude	Longitude	Connection point
1	DK	Kriegers Flak A K2	200	55.05	12.98	DK Ishøj
2	DK	Kriegers Flak A K3	200	54.99	12.82	DK Ishøj
3	DK	Kriegers Flak A K4	200	55.01	13.07	DK Ishøj
4	DK	Kriegers Flak B K1	200	55.08	12.87	DK Ishøj
5	DE	EnBW Baltic 2	288	54.98	13.16	DE Bentwisch
6	DE	EnBW Baltic 1	48	54.61	12.65	DE Bentwisch
7	DE	Baltic Power	500	54.97	13.22	DE Bentwisch
8	DE	Wikinger	400	54.83	14.07	DE Lubmin
9	DE	Arkona Becken Südost	480	54.78	14.12	DE Lubmin
10	SE	Kriegers Flak	640	55.07	13.10	SE Trelleborg

3.2.1 Case Studies and investigated services

Investigated services and processes:

- **Checking the grid**: the checking algorithm takes either 2 samples (maximum power output of the WF and lowest wind condition, but not lowest than the value of the *lowWindConditions* parameter) or a set of records filtered by hour. In this last option basically representing times during the day are selected, using the parameters: *dailyRestTime*, *dailyValleyTime* and *dailyPeakTime*.

With this last option the grid layout was checked and there were no convergence problem on the algorithm, meaning that the flows can be solved. But in this case there have been detected several overload problems that could lead to congestion problems.

The problematic components were:

- Cable_10-13: overloaded by 140.5%
- Cable_10-19: overloaded by 244% (impossible to be implemented!)
- Cable_4-15: overloaded by 103.4%
- Trafo_19-17: overloaded by 190.3%

Having this situation, the user should come back to the grid layout to analyze possible changes in order to avoid those overloads and possible congestions. It is recommended to provide the needed changes on the components and the grid layout to proceed with the next steps.

The module then is useful to check the integrity and the grid design.

- **Voltage**: due to the problems found on the grid layout, the voltage calculation wasn't performed.

- **Provision of reserve with wind farm and cluster:** with the options *-reserve-nogrid* and *-reserve-fast* the possibility of providing active power as power schedule (for participating in the energy market, with a 90% of probability), reserve power (either FRR or RR) assuming the day ahead scheduling with a probability of 99.5% and the possibility of provide balancing power as schedules organized 1 hour previous to the delivery (implementing the hour ahead forecast with a 99.5% of security) was investigated.

In order to simplify the analysis of the data provided by the software, only the reserve between 15/01/2011 and 17/01/2011 (3 days) is presented.

Following, the forecast for the 10 wind farms located in the area of Kriegers Flak are presented:

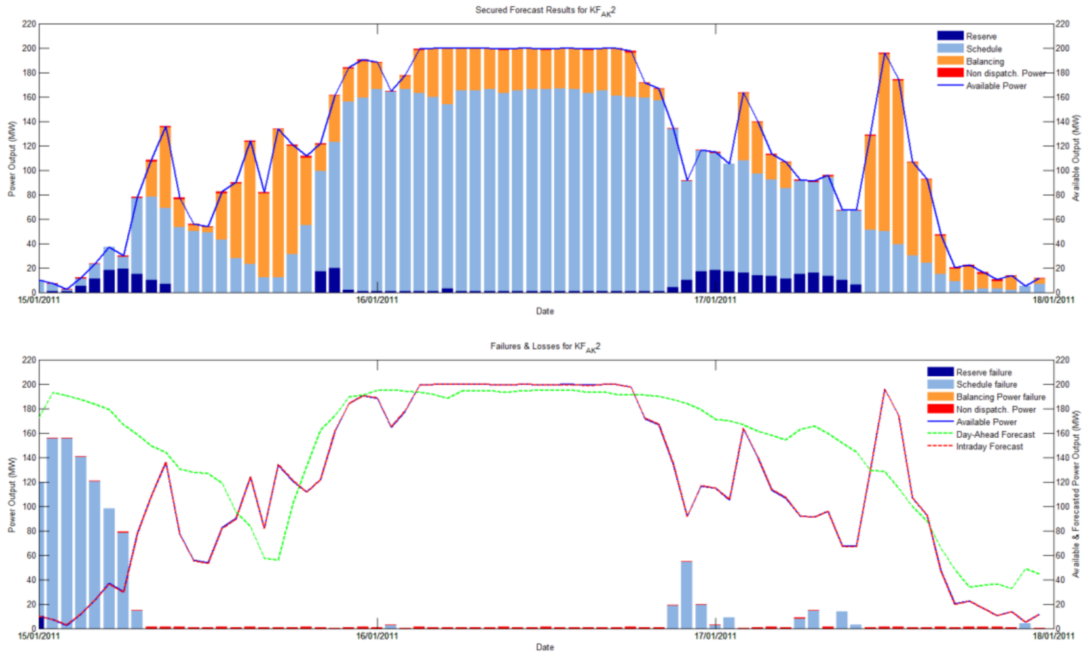


Figure 23. Forecast of KF_A_K2 WF.

For each WF two graphics are presented, like in Figure 24: the first one showing the possible reserve calculated with the 99.5% of security using the day ahead forecast; the schedule, representing the portion of the energy that is traded in the energy market; in orange the balancing energy, calculated based on the hourly forecast, for the hour ahead and a probability of 99.5%, too. Finally, what has not been forecasted (difference between schedules and possible power) is the undispatchable power.

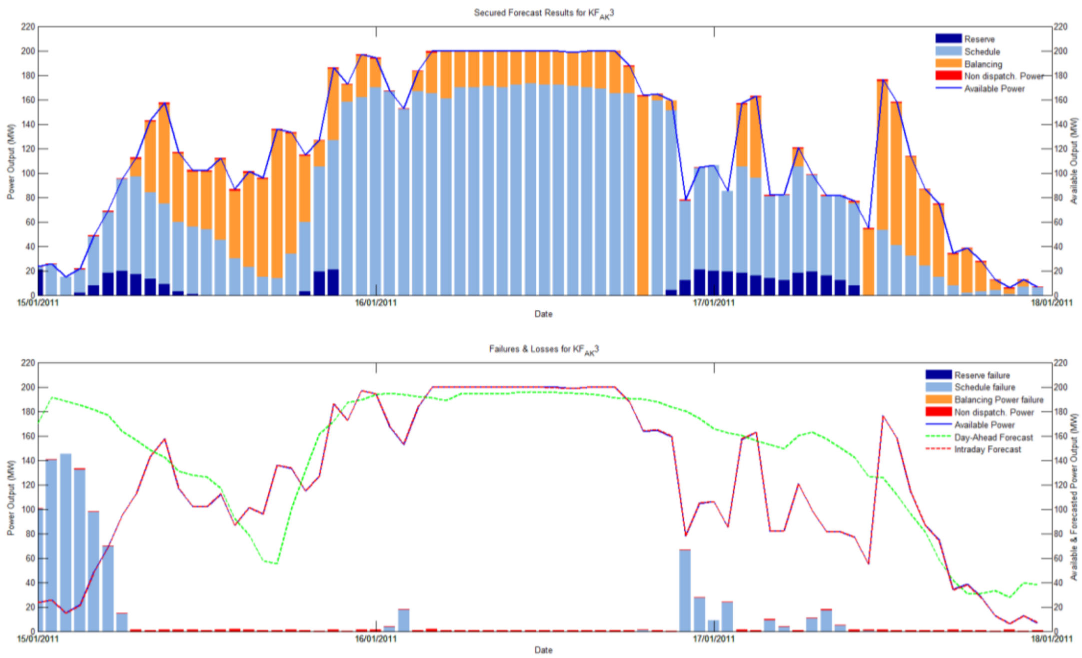


Figure 24. Forecast of KF_A_K3 WF.

The same information as for Figure 24 is presented for all WF until Figure 32.

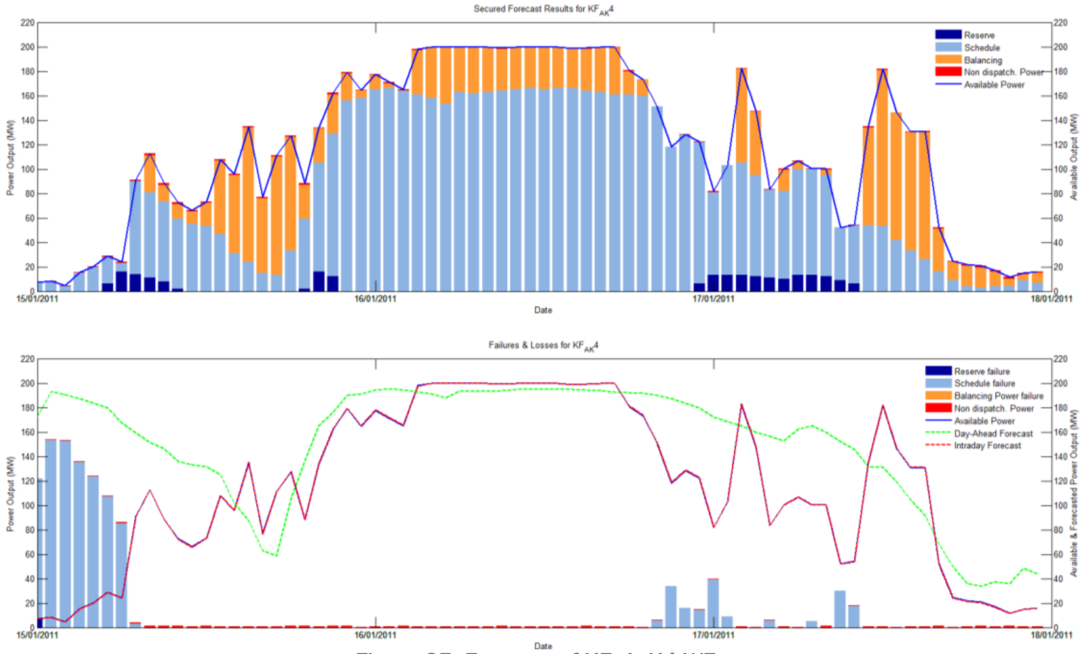


Figure 25. Forecast of KF_A_K4 WF.

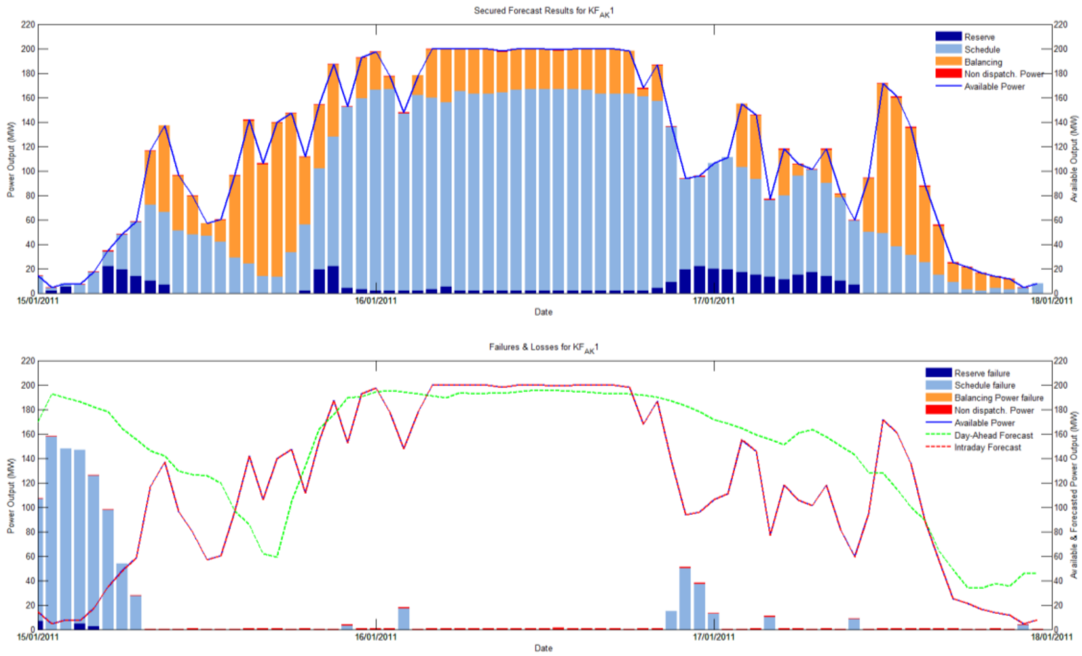


Figure 26. Forecast of KF_A_K1 WF.

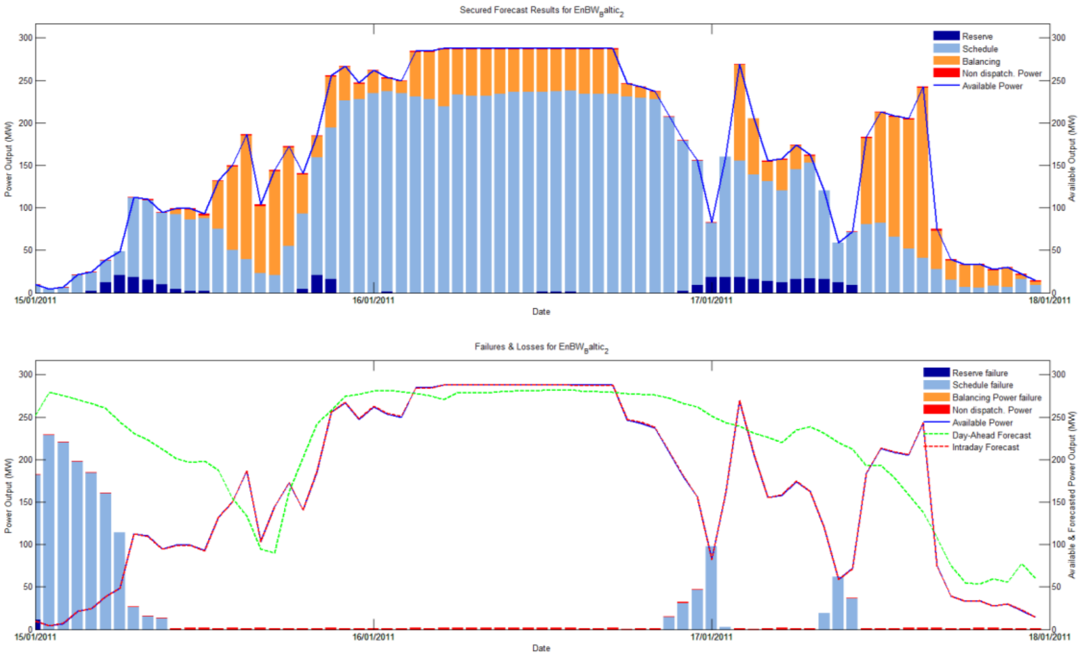


Figure 27. Forecast of EnBW_Baltic_2 WF.

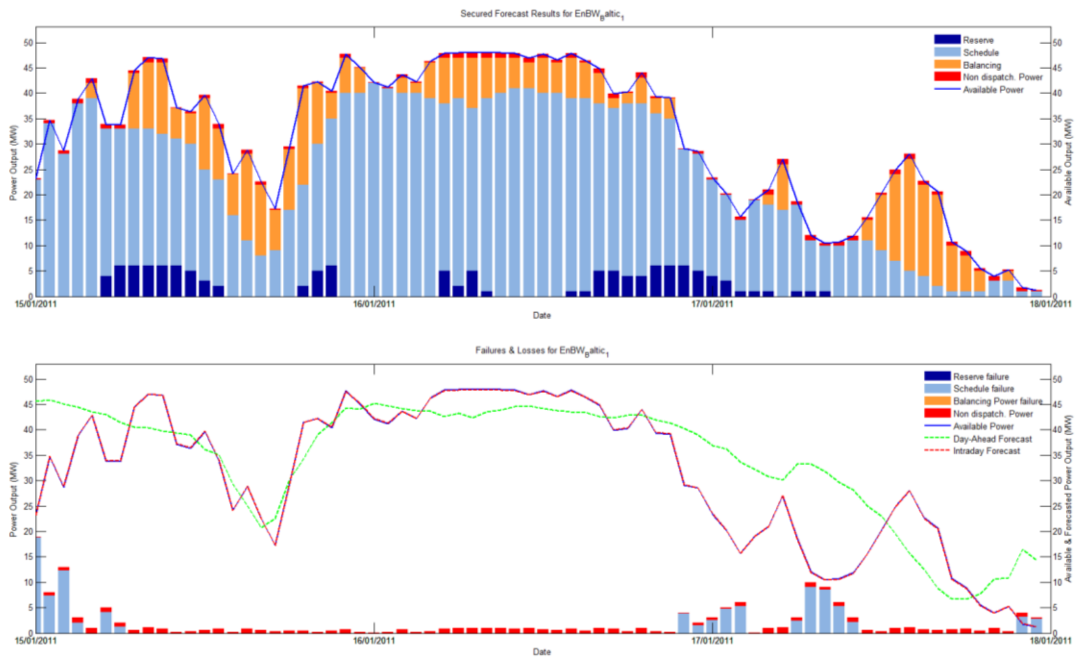


Figure 28. Forecast of EnBW_Baltic_1 WF.

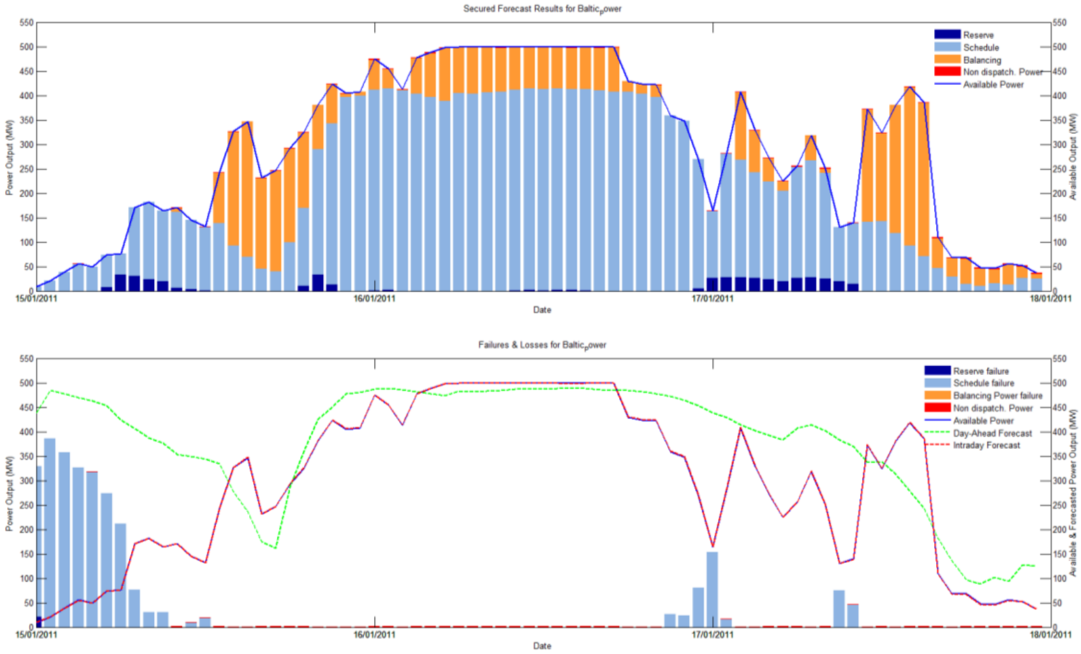


Figure 29. Forecast of Baltic_Power WF.

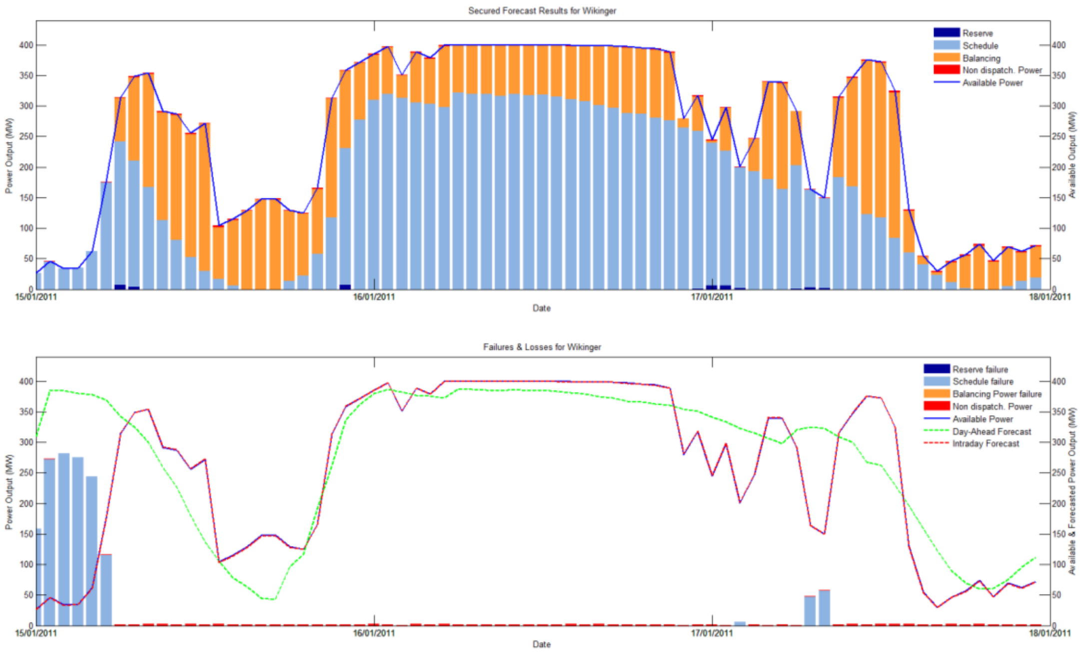


Figure 30. Forecast of Wikinger WF.

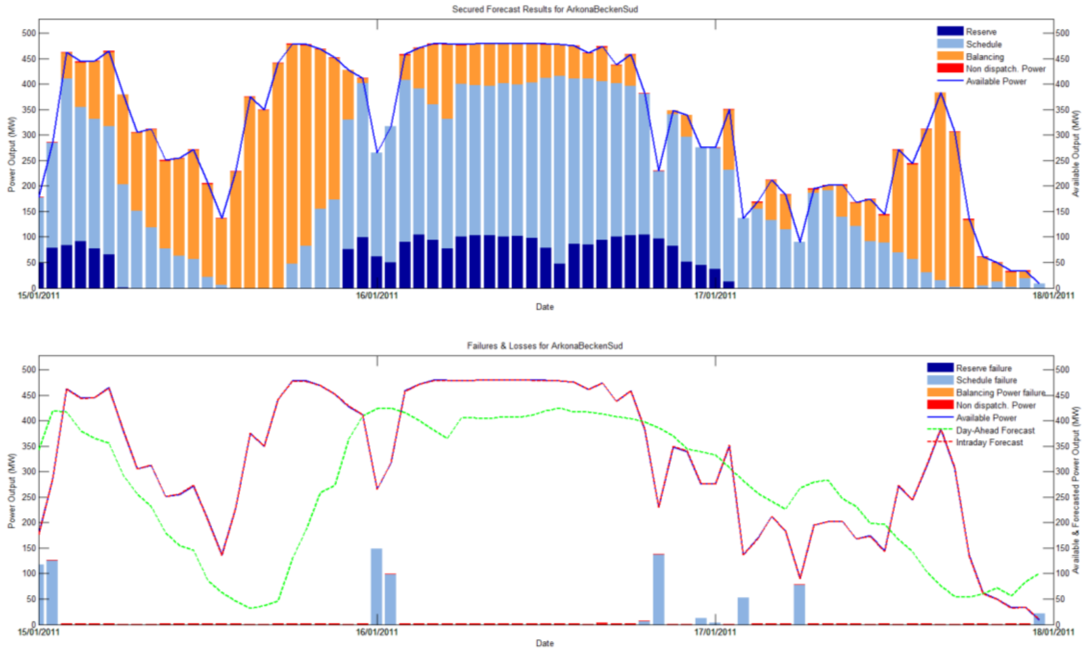


Figure 31. Forecast of ArkonaBeckenSud WF.

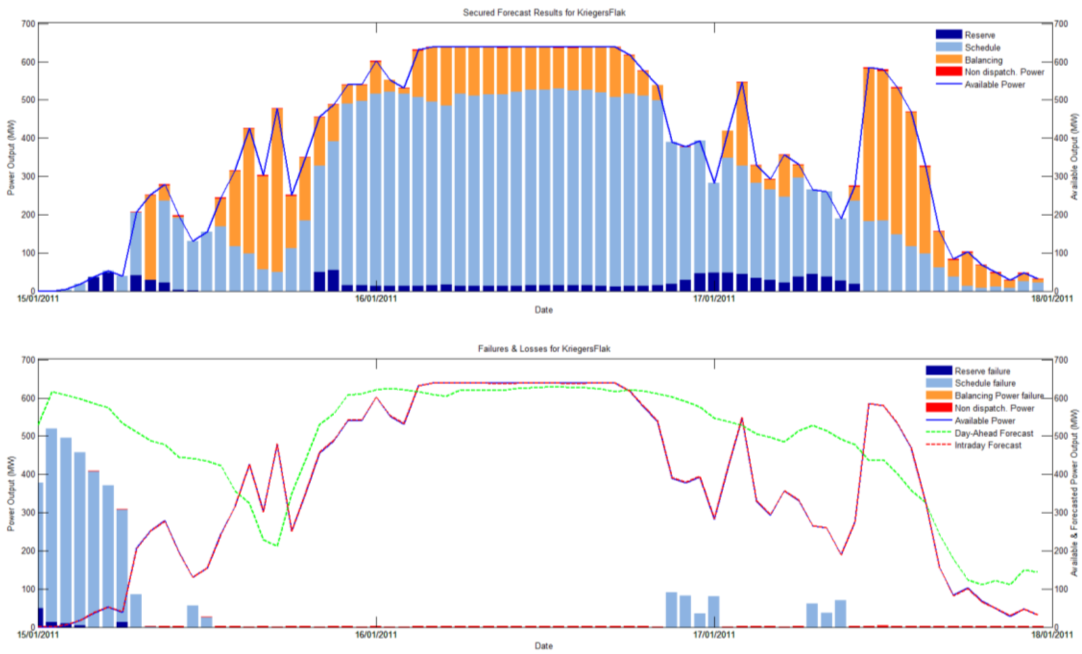


Figure 32. Forecast of KriegersFlak WF.

Finally, the capabilities for all wind farms belonging to a specific country are depicted in Figure 33 to Figure 35.

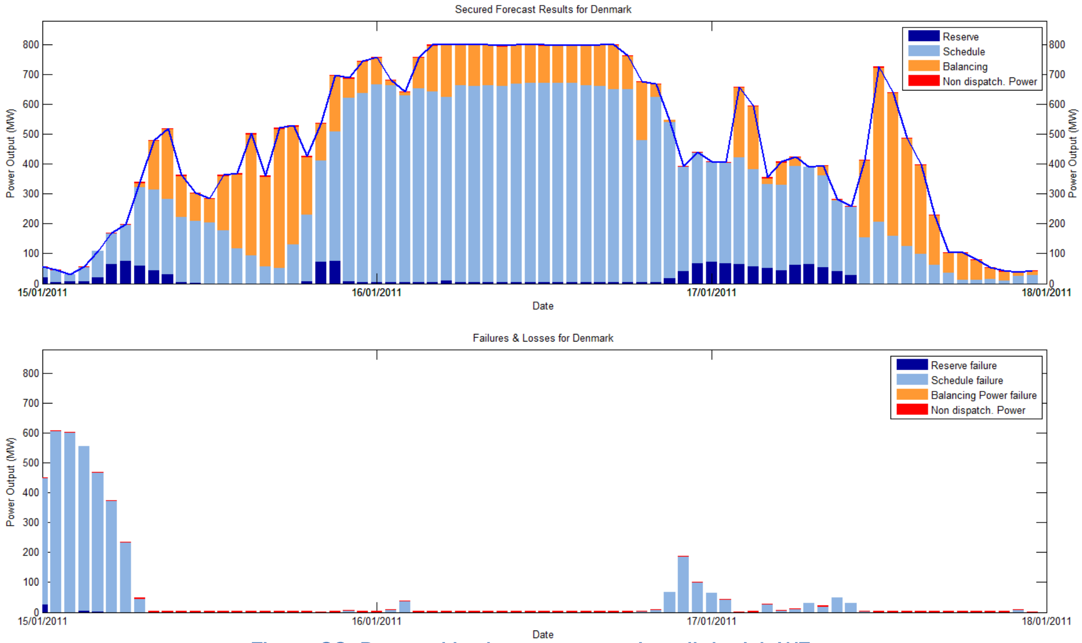


Figure 33. Denmark's cluster aggregating all danish WFs.

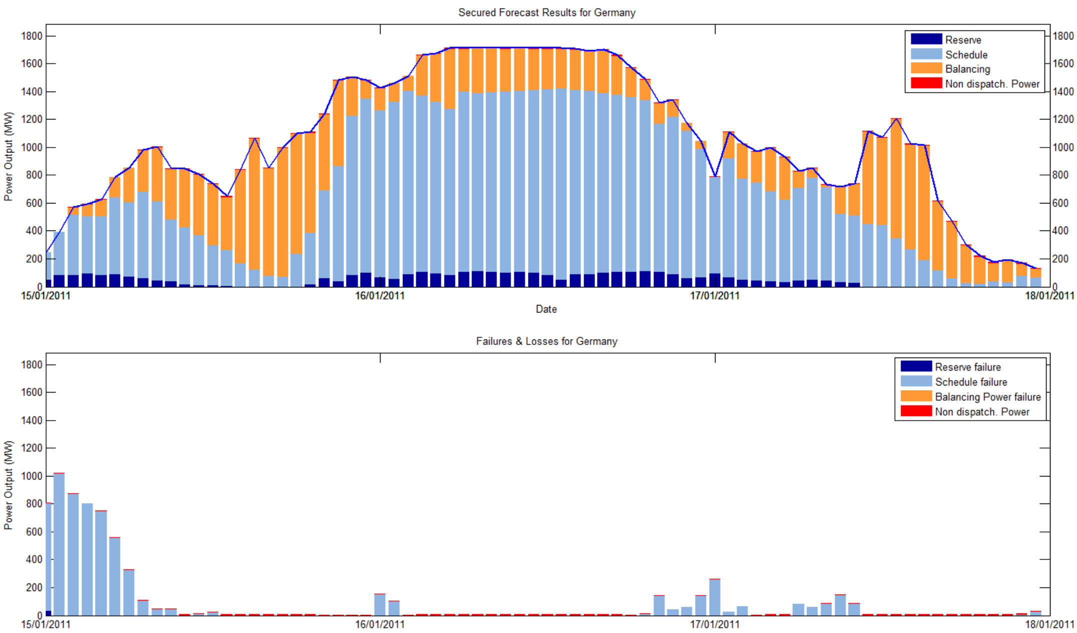


Figure 34. German cluster, constitute by all WF in Germany.

The aggregation on the clusters allows the possibility of enlarging the contribution of reserve during the days. Never the less, there is a minimum amount of power that can be provided for each wind farm. This minimum power in-feed is described by the *minimumBid* parameter in the specification file. This minimum is defined per WF meaning that the aggregation is not influencing this value.

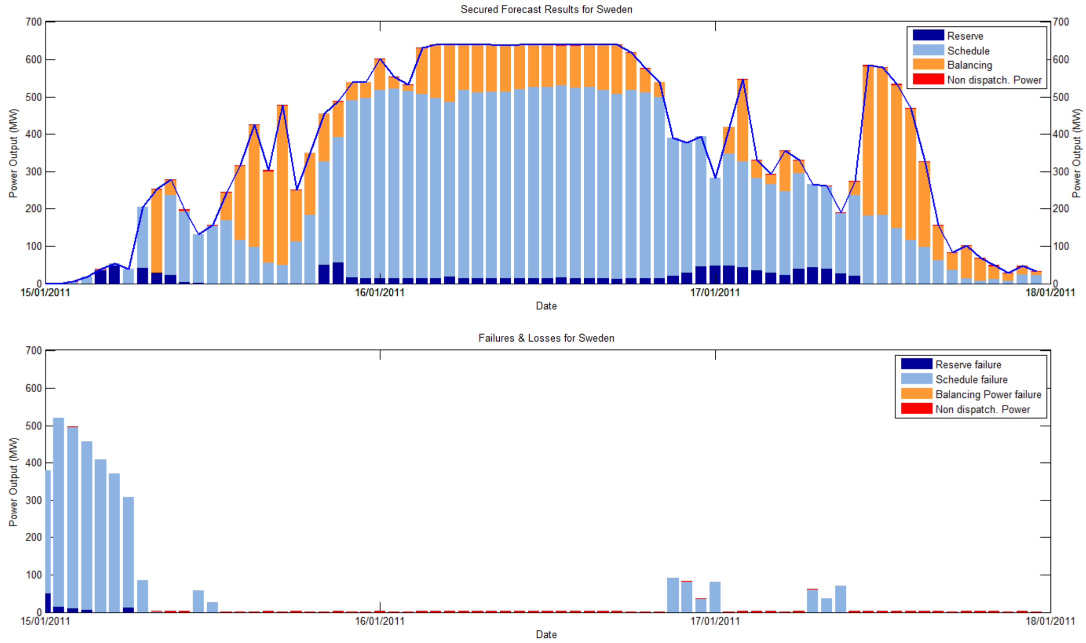


Figure 35. Cluster constitute by the only WF belonging to Sweden.

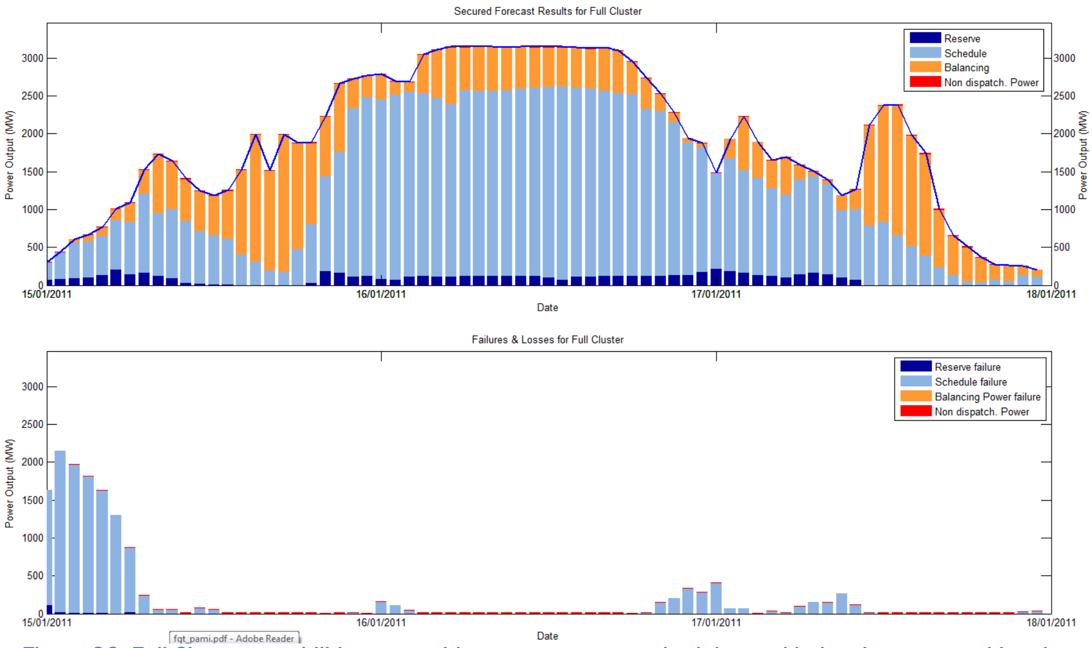


Figure 36. Full Cluster capabilities to provide reserve, energy schedules and balancing power taking the advantage of the smoothing effect.

The best results are presented on the Full Cluster (Figure 36) where the smoothing effect can be appreciated. One of the most important impacts is regarding the provision of reserve: an almost constant reserve can be provided during most of the time. At the same time, the balancing power can be used internally for the cluster to balance the forecast deviations.

- **Voltage support based on the cluster configuration**: the final scenario is modifying the amount of wind farms providing voltage control as well as the WT capabilities.

The basic Q capabilities of the wind farms and their effect on the Q requirements on the onshore nodes are presented in the Figure 37. The graphic shows more than 200 samples of the considered time series.

There, the samples are ordered taking into account the power output level of the wind farms: 10%, 20%, 30%, until 100%, represented in the graphic with the red dotted line.

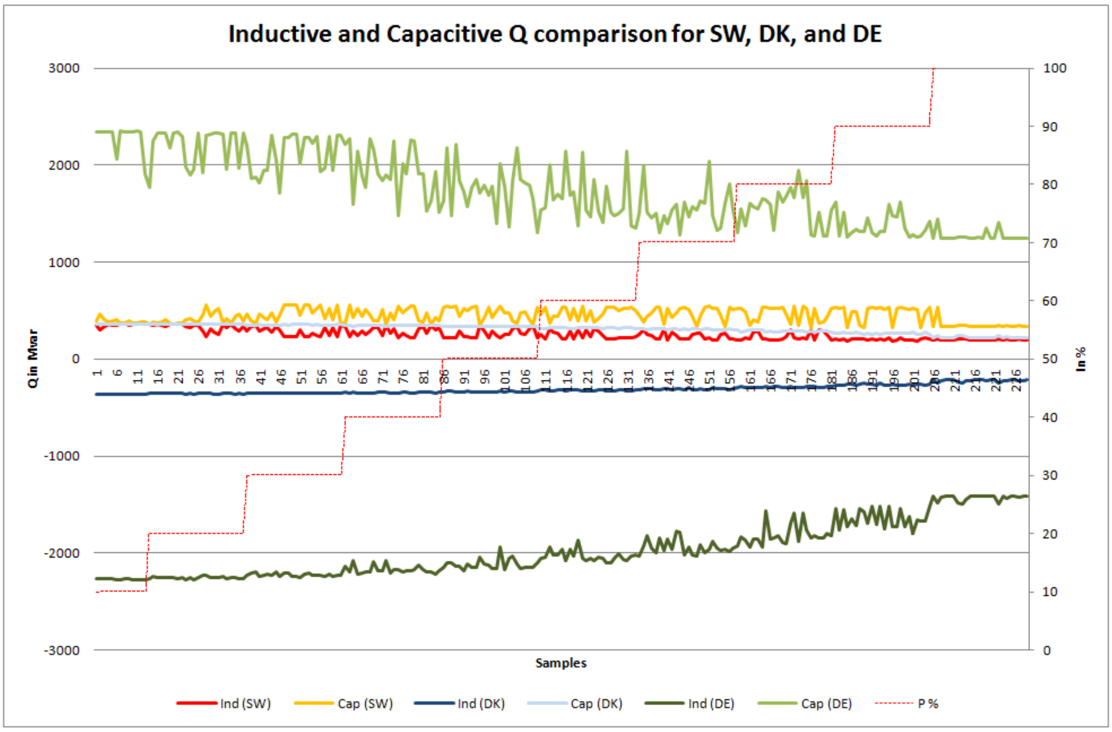


Figure 37. Onshore Q requirements vs. WF capabilities at different power infeed levels.

The considered wind farms are the ones located in German territory, near to the country. It can be appreciated that, as long as the power output is increased the reactive power requirements onshore are reduced.

Three different capabilities for all turbines belonging to Germany (EnBW_Baltic_2, EnBW_Baltic_1, Baltic_Power, Wikinger and ArkonaBeckenSud) were investigated:

a. Normal capabilities (baseline scenario)

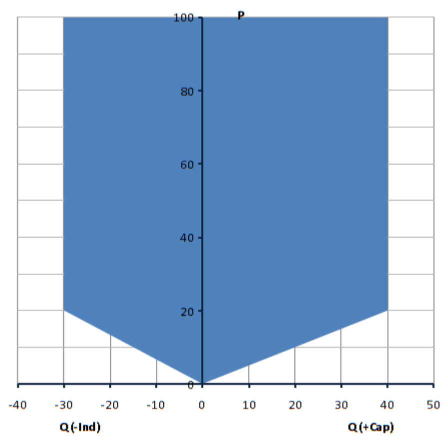


Figure 38. Basic Q capabilities.

b. Extended Q capabilities to provide reactive power at 0 power output:

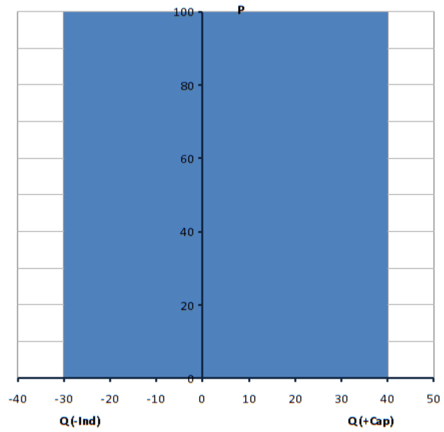


Figure 39. Q provided at P=0.

c. Extended capabilities, providing Q at P=0 and 10% larger inductive and capacitive possibilities.

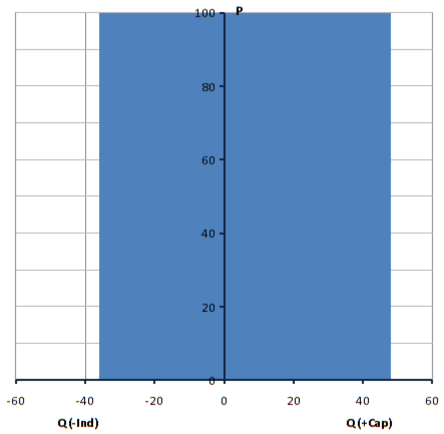


Figure 40. 10% increased Q capabilities.

The utilization of different types of WF can be assessed in order to compare the influence of their Q capabilities on the onshore connection. In Figure 41 the impact on the capacitive capabilities when WT with 10% more reactive power output are used is depicted.

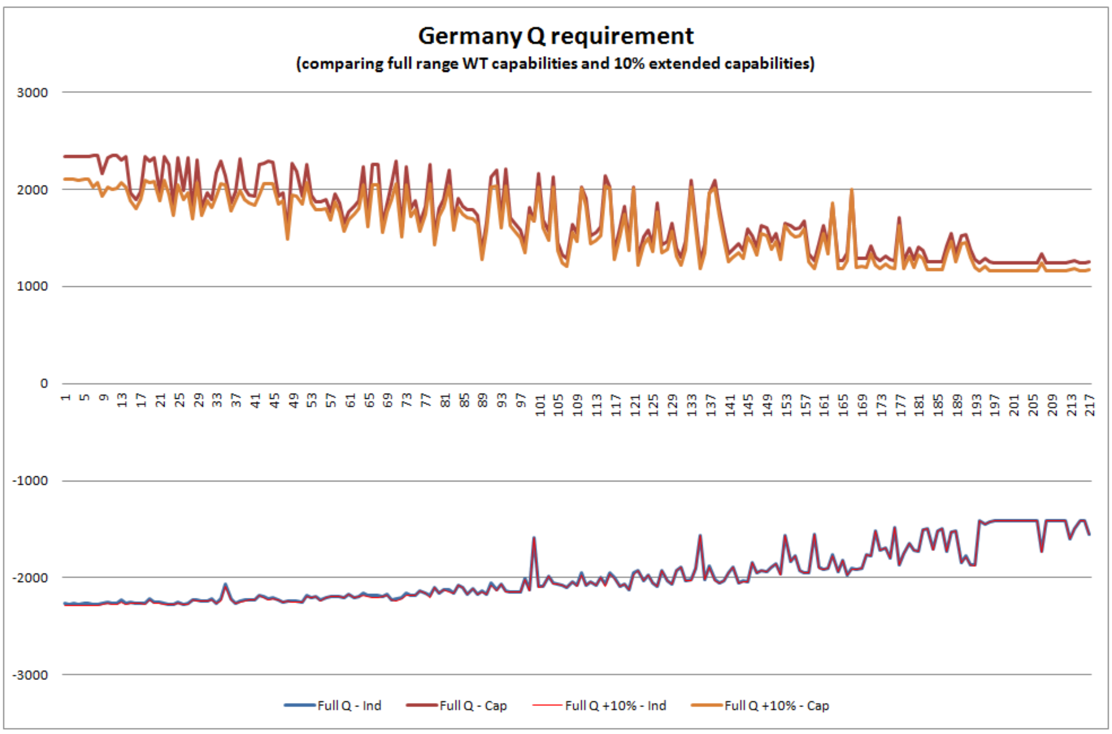


Figure 41. Inpact of the increase of 10% in the WF Q capabilities on the onshore nodes (Germany)

3.3 Problems found during the grid conversion

Before running the scenarios, some problems were found using the NET-OP grid description. Due to that a modified version of the grid were used during the simulations. This version was created manually by an electrical engineer in order to overcome some difficulties, as:

- Generators must be depicted in the generators section instead of loads (as negative loads)
- The voltage levels are not provided by NET-OP: they were assumed based on the capacity of the branches and reducing the amount of different voltages to reduce the costs on transformers.
- NET-OP does not provide information about needed transformers.
- The rated power of generators is not provided in PG field.
- PSSE format is not providing the length of DC lines in VSC-HVDC links.
- In VSC-HVDC section describe in DCSET="Nominal Power" in record where TYPE=2.
- PSSE doesn't support geo coordinates cannot be represented in PSSE.
- PSSE cannot represent PQ diagrams.

Those difficulties should be analyzed when the modules (NET-OP and DTOC-WCMS) would be connected.

4 CONCLUSION

The tool has proved to be useful to analyze the grid layout looking for possible overloads and design problems. When using the tool to check the grid the components overloaded and the rating is provided. With this information the user is able to find design problems and solve them.

Regarding the calculation of possible reserve the included calculations provide an idea based on time series about the amount of power reserve that can be provided between two specific dates, computing or not the capability of the grid. When the grid is not used, only the generator capabilities based on probabilistic forecasts is investigated. When the grid is used, can be tested if the grid is capable of allocate the required power.

Regarding the balancing power, it is computed as the difference between the reserve plus the energy schedules calculated using the day ahead forecast and the forecasted power 1 hour in advance. Then, the difference of the aggregation of all schedules and the real available power are the losses due to the impossibility of dispatching this energy. These losses are not electrical, which are computed in all calculations, but they are losses due to market issues.

Finally, when estimating the voltage support the contribution to all or different onshore nodes can be calculated. Even, the software is calculating internally the setpoints to each WT/WF to achieve the depicted values. It is also possible to modify the WT Q capabilities in order to perform a sensitivity analysis modifying the PQ diagrams of the turbines.

All results are store in DEPRI (text) files and the information can be processed in different tools like Excel, Matlab, etc for a convenient graphical representation.

5 TOOL DESIGN

The DTOC-WCMS is provided as a standalone, command-line executable (Windows 64-bits or Linux 64-bits). In order to run the software module, it requires the free MATLAB Compiler Runtime environment. The tool has been compiled using MATLAB 2013a 64-bits.

5.1 Obtaining the tool

The DTOC-WCMS tool is available upon request from Fraunhofer IWES. The contact person is: Dipl.-Ing. Mariano Faiella (mariano.faiella@iwes.fraunhofer.de).

The software is distributed as a ZIP file which includes the executable (dtoc-wcms.exe).

5.2 Computer requirements

The main system requirements are to use the DTOC-WCMS module are:

- 64-bits Windows (or 64-bits Linux)
- MATLAB Compiler Runtime version 2013a

The MATLAB Compiler Runtime is included in a MATLAB installation, or can be obtained freely at Mathworks webpage: http://www.mathworks.com/products/compiler/mcr/index.html

5.3 Installation

The installation of the module is really simple. It requires the previous installation of the MATLAB Compiler Runtime as a pre-requirement for running the software.

Then, simply unzip the ZIP file to a chosen location. No further installation is necessary – the command-line executable (dtoc-wcms.exe) requires no particular installation process and can be put anywhere on the computer. Adding the installation folder into the PATH environment variable is recommended.

The command-line syntax for running the different pre-defined analysis are:

```
dtoc-wcms <commands> <specification file>
```

Where `<commands>` are:

```
dtoc-wcms -check -specifications=<file.xml>
dtoc-wcms -planning -specifications=<file.xml>
dtoc-wcms -reserve-no-grid -specifications=<file.xml>
dtoc-wcms -reserve-fast -specifications=<file.xml>
dtoc-wcms -reserve-full -specifications=<file.xml>
dtoc-wcms -voltage -specifications=<file.xml>
dtoc-wcms -voltage-full -specifications=<file.xml>
```

5.4 Configuration file

The following is an example (Figure 42) of the configuration file for all modes. The specification file is a configuration file containing the parameters of a simulation for checking the grid, the calculation of available reserve and balancing power and for voltage support/ reactive power contribution simulation.


```xml
<specifications>
    <generators>
        <generator name="KF_A_K2" country="DK" ratedPower="200.0" connectedNode="1" cluster="1" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="KF_A_K3" country="DK" ratedPower="200.0" connectedNode="2" cluster="1" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="KF_A_K4" country="DK" ratedPower="200.0" connectedNode="3" cluster="1" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="KF_A_K1" country="DK" ratedPower="200.0" connectedNode="4" cluster="1" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="EnBW_Baltic_2" country="DE" ratedPower="288.0" connectedNode="5" cluster="2" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="EnBW_Baltic_1" country="DE" ratedPower="48.0" connectedNode="6" cluster="2" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="Baltic_Power" country="DE" ratedPower="500.0" connectedNode="7" cluster="2" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="Wikinger" country="DE" ratedPower="400.0" connectedNode="8" cluster="2" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="ArkonaBeckenSud" country="DE" ratedPower="480.0" connectedNode="9" cluster="2" type="4" pqDiagram="pq_type4.pqt"/>
        <generator name="KriegersFlak" country="SE" ratedPower="640.0" connectedNode="10" cluster="3" type="4" pqDiagram="pq_type4.pqt"/>
    </generators>
    <onShoreNodes>
        <node name="Sweden" country="SE" maxDemand="800" connectedNode="21" hourlyDemandShape="[0.45 0.4 0.37 0.6 1.0 0.9 0.8 0.75 0.8 0.87 0.83 0.6]"/>
        <node name="Denmark" country="DK" maxDemand="360" connectedNode="22" hourlyDemandShape="[0.45 0.4 0.37 0.6 1.0 0.9 0.8 0.75 0.8 0.87 0.83 0.6]"/>
        <node name="Germany" country="DE" maxDemand="2200" connectedNode="20" hourlyDemandShape="[0.45 0.4 0.37 0.6 1.0 0.9 0.8 0.75 0.8 0.87 0.83 0.6]"/>
    </onShoreNodes>
    <parameters>
        <parameter name="verbose" value="true"/>
        <parameter name="debug" value="true"/>
        <parameter name="generateProbabilisticForecast" value="false"/>
        <parameter name="grid" value="D:\Projects\EERA-DTOC\Arbeitsordner\WP2\Task 2.4\DTOC\data\result_psse31_v3.raw"/>
        <parameter name="timeseries" value="D:\Projects\EERA-DTOC\Arbeitsordner\WP2\Task 2.4\DTOC\data\KriegersFlakPowerTS_2011.dep"/>
        <parameter name="forecastDA" value="d:\tmp\forecasts-24hr.dep"/>
        <parameter name="forecastID" value="d:\tmp\forecasts-1hr.dep"/>
        <parameter name="ProbabilisticForecast" value="d:\tmp\probForecast_full.dep"/>
        <parameter name="forecastProbabilityService" value="99.5" unit="%"/>
        <parameter name="forecastProbabilitySchedule" value="90.0" unit="%"/>
        <parameter name="output" value="d:\tmp\dtoc"/>
        <parameter name="cosPhi" value="0.95"/>
        <parameter name="AC_Compensation_Factor" value="0.8"/>
        <parameter name="defaultVoltage" value="275" unit="kV"/>
        <parameter name="Sk_factor" value="50"/>
        <parameter name="Parallel_System_Factor" value="0.81"/>
        <parameter name="ClusterId" value="2"/>
        <parameter name="ForecastStartTime" value="2011-01-15T0000"/>
        <parameter name="ForecastEndTime" value="2011-01-16T2359"/>
        <parameter name="minimumBid" value="1" unit="MW"/>
        <parameter name="minimumDownRegulation" value="0.2"/>
        <parameter name="lowWindConditions" value="0.05"/>
        <parameter name="dailyRestValue" value="0.4"/>
        <parameter name="dailyRestTime" value="1500"/>
        <parameter name="dailyValleyValue" value="0.7"/>
        <parameter name="dailyValleyTime" value="0800"/>
        <parameter name="dailyPeakValue" value="1.0"/>
        <parameter name="dailyPeakTime" value="1900"/>
        <parameter name="VoltageControlStartTime" value="2011-01-01T0000"/>
        <parameter name="VoltageControlEndTime" value="2011-12-31T2355"/>
    </parameters>
</specifications>
```


Figure 42. Example of a DTOC-WCMS specification file in XML format (specification.xml).

The specification file (enclosed by the *specifications* tag) has three main child containers or sections:

- **generators**: important parameters describing generators. The required information cannot be represented on PSSe raw format, and then this information is hosted in the specification file. The main parameters are:
    - *name*: the same name of the generator given in the PSSe raw file. It is used to bind the generator's information contained in the raw file [String].
    - *country*: country code in ISO format. Example: DE, DK, etc. This information is useful to link the generators with a specific country [String].
    - *ratedPower*: rated power or maximum power output of the generator [Float].
    - *connectedNode*: id of the node to which the generator is connected. The id should be the same value as the *"I"* value in the *Bus Data* section of the PSSe raw file [Integer].
    - *cluster*: id used to aggregate several generators in a cluster. The *cluster* value binds of group different generator together and the parameter *ClusterId* in the parameter section defines to DTOC_WCMS which group of generators will be investigated [Integer].
    - *type*: defines the wind generator type according to the conversion technologies described before in this document. Most of the generators will be type 3 or 4 [Integer].

- *pqDiagram*: name and path on disk of a text-based file containing the PQ characteristics of the generators expressed as XY points, where X is active power output (P) and Y is the correspondent reactive power value (Q), both given in MW [String].

- onShoreNodes: for each onshore node (not country) a node should be described. This information is useful to know which node of the PSSe raw file is connecting the grid infrastructure to the land. Those nodes are important due to the fact at those points some system services (like voltage support) should be delivered. The main parameters are:
  - *name*: name of the node [String].
  - *country*: connected country, described in ISO format [String].
  - *maxDemand*: the maximum demand or power flow expressed in MW that can be admitted at this node. This is a dimensioning parameter and represents the addition of all maximum flows in case of connecting several links, lines or generators [Float].
  - *connectedNode*: the id should be the same value as the *"I"* value in the *Bus Data* section of the PSSe raw file [Integer].
  - *hourlyDemandShape*: vector of values containing the distribution of the power demand onshore, expressed as percentage of the maximum demand (*maxDemand* parameter). The number of values into the vector is arbitrary and will be uniformly distributed between 0 and 23 Hr and then the intermediate values interpolated [Vector of Floats].
- parameters: this container gather into a section diverse parameters in the form *name=value* and -eventually- providing a unit. The parameters are:
  - *verbose*: a boolean value indicating if the program should be verbose and more information show on the screen [True|False].
  - *debug*: boolean value requesting some routines to provide extra feedback during program execution [True|False].
  - *generateProbabilisticForecast*: boolean value indicating when the model should use the files indicated in *forecastDA* and *forecastID* to create before calculating the available reserve the probabilistic forecasts for all generators. If *generateProbabilisticForecast* is True the model will use the file mentioned in forecast files and will create the probabilistic forecast for all generator based on the information described in *forecastDA* (forecast day ahead) and *forecastID* (forecast intraday) files. The results will be stored in the file mentioned in *probabilisticForecast*. If *generateProbabilisticForecast* is False, then the 1 hr and 24 hrs in advanced forecasts are not calculated and the program assumes that those forecasts are already calculated in the file described in the *probabilisticForecast* parameter. [True|False]
  - *grid*: filename of the PSSe raw file containing the grid description [String/ filename]
  - *timeseries*: filename of a DEPRI file containing the generation time series (normalized power output) of all generators. Those time series are provided by CorWind and the data frequency could be arbitrary; nevertheless, only hourly values are taken into account [String/ filename].
  - *forecastDA*: filename of a DEPRI file containing the hourly values of the day ahead forecast (24 hours in advance forecast) calculated by the Predictability module[22]. This time series is used to calculate the probabilistic forecast. [String/ filename].
  - *forecastID*: filename of a DEPRI file containing the hourly values of the hourly forecast (1 hour in advance forecast) calculated by the Predictability module[23]. This time series is used to calculate the probabilistic forecast. [String/ filename]
  - *ProbabilisticForecast*: filename of a DEPRI file containing the calculated probabilistic forecast (if *generateProbabilisticForecast* is True) or where the result of the calculation will be stored (in case *generateProbabilisticForecast* would be False) [String/filename].

[22] Refer to D2.8

[23] Refer to D2.8

- *forecastProbabilityService*: the probability of the forecast calculated for services. For day ahead forecasts, this value is used to calculate the reserve and for the 1 hour in advanced forecast this is the probability used for balancing power calculation [Float].
- *forecastProbabilitySchedule*: probability of the forecast calculated to create the power schedules, based on day-ahead forecasts.
- *output*: folder name where all resulting files of running the program will be created.
- *cosPhi*: default cos(φ) used for the program during grid calculations [Float, between 0.0 and 1.0]
- *AC_Compensation_Factor*: default AC line compensation factor [Float, between 0.0 and 1.0] (Not used)
- *defaultVoltage*: value of the default voltage lines [Float] (not used)
- *Sk_factor*: short circuit factor given in percentage [Float] (not used)
- *Parallel_System_Factor*: factor applied to the capability of parallel systems when two or more parallel systems are implemented in a branch [Float, between 0.0 and 1.0].
- *ClusterId*: id of the cluster that will be investigated during the utilization of the program. The program look for all generators in the *generators* section where *cluster = ClusterID* [Integer].
- *ForecastStartTime*,
- *ForecastEndTime*: when calculating the probabilistic forecast, the program uses only those records from the time series in *forecastDA* and *forecastID* located between these two timestamps.
- *minimumBid*: when calculating power reserve, this is the minimum amount of reserve (in MW) that can be offer. If the calculated reserve for a given timestamp is lower than *minimumBid*, the reserve will be zero [Float].
- *minimumDownRegulation*: minimum power output expressed in p.u. when the generators are down-regulated. As part of the congestion management and voltage support strategies the power output of the generators belonging to a cluster can be modified. If this modification in the power output implies the reduction of the power in-feed the algorithms will reduce the power output up to this given value. Usually this value can be set to 0.2 (20% of the rated power), but this means the flexibility of the generators could be reduced in some cases [Float between 0.0 and 1.0].
- *lowWindConditions*: when the program, during the filtering of time series, wants to consider (or choose) time series representing low wind conditions, this value given in p.u. indicates the minimum power of all generators. E.g.: if 0.05 p.u. is setup, this means that all record in a time series containing power outputs below 5% of the rated power are not taken into account. This limit is only apply during the checking of the grid, when the algorithm looks for a row into the power time series representing low wind conditions. It is clear that the intention of this parameter is to avoid neither selecting records where one or more generators are nor producing power at all [Float, between 0.0 and 1.0].
- *dailyRestValue*: value expressed in p.u. (not used).
- *dailyRestTime*: time at which the minimum power demand occurs on onshore nodes (countries, e.g. 1500 / 3PM). This value is used to filter time series; then, only values of records at rest, valley and peak hours are considered as representative of the onshore load conditions. The filtering of the time series is useful to speed up the calculation due to the selection of only representative record [Integer].
- *dailyValleyValue*: value expressed in p.u. (not used).
- *dailyValleyTime*: time at which the average power demand occurs on onshore nodes (countries, e.g. 0800 / 8AM). This value is used to filter time series; then, only values of records at rest, valley and peak hours are considered as representative of the onshore load conditions. The filtering of the time series is useful to speed up the calculation due to the selection of only representative record [Integer].
- *dailyPeakValue*: value expressed in p.u. (not used).

- *dailyPeakTime*: time at which the maximum power demand occurs on onshore nodes (countries, e.g. 1900 / 7PM). This value is used to filter time series; then, only values of records at rest, valley and peak hours are considered as representative of the onshore load conditions. The filtering of the time series is useful to speed up the calculation due to the selection of only representative record [Integer].
- *VoltageControlStartTime*,
- *VoltageControlEndTime*: timestamps used to filter the time series. Only records included within those two timestamps will be used [datetime].

5.5 PQ Diagrams

The PQ diagrams of different generators can be stored in simple text files describing three columns: active power output in percentage, inductive reactive power capability in percentage and capacitive reactive power capability in percentage.
For example:

file name: pq_type4.pqt

```
0       0       0
20      -30     40
100     -35     45
```

The text before means:

- For 0% active power output, the inductive and capacitive capabilities are 0% .
- For 20% active power output, the inductive capability is 30% and the capacitive capability is 40%.
- For 100% active power output, the inductive capability is 35% and the capacitive capability is 45%.

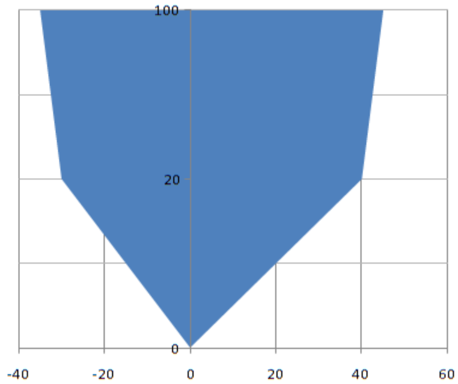


Figure 43. Graphical representation of the PQ diagram corresponding to pq_type4.pqt.

Another possible example could be:

file name: pq_example2.pqt

```
0       -35     45
50      -35     45
100     -35     45
```

The text before means:

- For 0% inductive and capacitive capabilities are -20 and 20%, respectively.
- For 50 and 100% active power output, the inductive and capacitive capabilities are 35% and 45% respectively.

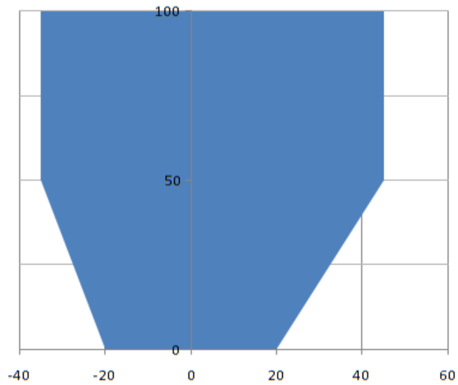


Figure 44. Graphical representation of the PQ diagram corresponding to pq_example2.pqt

6 REFERENCES

[1] EERA-DTOC project. www.eera-dtoc.eu (accessed 2013-05-15).

[2] EWEA. "Wind in our Sails – The coming of Europe's offshore wind energy industry", November 2011. Available on www.ewea.org/publications/reports (accessed 2013-05-15).

[3] Holttinen, H. et al. "Design and operation of power systems with large amounts of wind power". Final summary report, IEA WIND Task 25, Phase two 2009–2011, VTT Technology 75, VTT.

[4] EURELECTRIC, Ancillary Services. Unbundling Electricity Products – an Emerging Market. EURELECTRIC Thermal Working Group, Ref: 2003-150-0007, Feb. 2004.

[5] REServices Project. "Capabilities and costs for ancillary services provision by wind power plants". REServices Project Deliverable D3.1. April 2013. Available on www.reservices-project.eu/publications-results (accessed 2013-06-15).

[6] REServices Project. "Ancillary services: technical specifications, system needs and costs". REServices Project Deliverable D2.2. November 2012. Available on www.reservices-project.eu/publications-results (accessed 2013-06-15).

[7] Cutululis, N. et al. "Report on design tool on variability and predictability". EERA-DTOC Project Deliverable D2.8. July 2013. DTU.

[8] Svendsen, H. et al. "Design tool module and procedure for optimized grid connection of wind farm clusters". EERA-DTOC Project Deliverable D2.1. January, 2013. SINTEF Energy Research.

[9] Svendsen, H. et al. "Report on tools and results from a case study". EERA-DTOC Project Deliverable D2.3. February, 2013. SINTEF Energy Research.

[10] NOAA. "Global Forecast System". National Weather Service, National Centers for Environmental Prediction. Environmental Modeling Center. Available on www.emc.ncep.noaa.gov/index.php?branch=GFS (accessed 2013-06-15).

[11] WINDGRID Project. "Wind on the grid: an integrated approach". November 2009. Available on http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=10049766 (accessed 2013-06-15).

[12] ENTSO-E. "Network Code for Requirements for Grid Connection Applicable to all Generators". Final Version. March, 8th 2013. Available online: https://www.entsoe.eu/fileadmin/user_upload/_library/resources/RfG/130308_Final_Version_NC_RfG.pdf (accessed 2013-04-03).

[13] ENTSO-E. "Draft Network Code on Load-Frequency Control and Reserves". June, 28th 2013. Available online: http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/130628-NC_LFCR-Issue1.pdf (accessed 2013-11-15).

[14] ENTSO-E. "Draft Network Code on Electricity Balancing". Version 1.22. May, 29th 2013. Available online: https://www.entsoe.eu/fileadmin/user_upload/_library/resources/BAL/130529_NC_EB_draft_V1_22.pdf (accessed 2013-06-15).

[15] ENTSO-E. "Network Code on Operational Security". February, 27th 2013. Available on: https://www.entsoe.eu/fileadmin/user_upload/_library/resources/OS_NC/130227-AS-NC_OS_final_.pdf (accessed 2013-06-15)

[16] Margaris, I. D., Hansen, A. D., Bech, J., Andresen, B., & Sørensen, P. (2012). Implementation of IEC Standard Models for Power System Stability Studies. Proceedings of 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems. Lisbon, Portugal.

[17] Hansen, L. H., Helle, L., Blaabjerg, F., Ritchie, E., Munk-Nielsen, S., Bindner, H., et al. (2001). Conceptual survey of Generators and Power Electronics for Wind Turbines. Roskilde, Denmark: Risø National Laboratory.

[18] Polinder, H., Bang, D., Li, H., & Chen, Z. (2007). Concept Report on Generator Topologies, Mechanical & Electromagnetic Optimization (Deliverable No.: D 1B2.b.1). Project UpWind.

[19] European Wind Energy Association - EWEA. (2013). Wind Energy Facts. Abgerufen am 01. 03 2013 von EWEA-European Wind Energy Association: http://www.ewea.org/fileadmin/files/library/publications/statistics/Factsheets.pdf#page=1&zoom=237,0,402.

[20] WECC-Western Electricity Coordinating Council. (2010). WECC Wind Power Plant Dynamic Modeling Guide. WECC Renewable Energy Modeling Task Force.

[21] Rohrig, K., Schlögl, F., Jursa, R., Wolff, M., Fischer, F., Hartge, S., et al. (01. 05 2005). Advanced Control Strategies to Integrate German Offshore Wind Potential into Electrical Energy Supply. Abgerufen am 01. 03 2013 von http://renknownet2.iwes.fraunhofer.de/pages/wind_energy/data/Advanced_Control_Strategies_to_Integrate_German_Offshore_Wind_Potential_into_Electrical_Energy_SupplyNo27.pdf

[22] ENTSO-E. "Network Code on Capacity Allocation and Congestion Management". September, 27th 2012. Available online: http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/120927_CACM_Network_Code_FINAL.pdf (accessed: 2013-11-15)

[23] Dobschinski, J., & Lange, B. (2012). Forecastability of Wind Farm Power Production - Main Drivers of Forecast Quality. DEWEK 2012 - 11th German Wind Energy Conference. Bremen: DEWI.

[24] Gesino, A. J. (2011). Power reserve provision with wind farms. Kassel: Kassel University Press GmbH.

[25] Jansen, M., Speckmann, M., & al, e. (2012). Impact of Control reserve Provision of Wind Farms on Regulating Power Costs and Balancing Energy Prices. EWEA Event 2012. Copenhagen.

[26] Jansen, M., & Speckmann, M. (2013). Wind turbine participation on Control Reserve Markets. EWEA Conference 2013. Vienna: EWEA.

[27] ENTSO-E Working Group. Survey on Ancillary Services. Procurement & Balancing market design, September 2012.

[28] ENTSO-E Meta Repository (EMR). ENTSO-E Definitions and Acronyms. https://emr.entsoe.eu/glossary/bin/view/GlossaryCode/GlossaryIndex