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Ancillary Services Analysis of an Offshore Wind Farm Cluster – Technical Integration Steps of a Simulation Tool

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Abstract

In this publication, the authors present methodology and example results for the analysis of ancillary services of an offshore wind farm cluster and its electrical power system. Thereby the operation tool Wind Cluster Management System (WCMS) is used as simulation tool to evaluate certain planning scenarios. Emphasis is made on two topics: 1) the integration of high voltage direct current (HVDC) technology to the WCMS, 2) the ancillary service analysis. As examples, voltage source converter based HVDC (VSC-HVDC) and the provision of reserve respectively balancing power are discussed in detail. The analyzed study case considers the Kriegers Flak area while the associated power system connects wind farms to Sweden, Denmark and Germany.

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Keywords: Offshore Wind Farms; Ancillary Services; HVDC Technology; EERA-DTOC; Cluster Control, Reserve, Balancing Power

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1. Introduction – The EERA-DTOC Project

This publication describes a planning tool that is used for ancillary service analysis of an offshore wind farm cluster. The project *Design Tool for Offshore Wind Farm Clusters (DTOC)*[1] by the *European Energy Research Alliance (EERA)* combines several state-of-the-art wake, yield and electrical models available in the consortium. In

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this context, the operational tool Wind Cluster Management System (WCMS) [1,2] is expanded to be applied as simulation software analyzing the ancillary service provision by wind farm clusters during planning stages of offshore developing areas. In the framework of the EERA-DTOC some adaptations have been made to the WCMS module to create a simulation platform from the operational tool. The new version is referred to as DTOC-WCMS (DTOC-Wind Farm Cluster Modeling & Simulation). The paper consists of two integral parts namely the integration of direct current (DC) technology into the WCMS, making it suitable for hybrid networks consisting of alternating current (AC) and DC equipment, and the methodology for analyzing the ancillary services itself. Due to the transformation process of the electrical power system based on centralized mainly thermal power production to a system fed by decentralized renewable energy sources, those renewable power plants need to take over functionalities of conventional power plants like ancillary services. Amongst others, voltage support, frequency control, fault-ride through capabilities and congestion management can be treated as ancillary service.

Nomenclature

Symbols:		Subscripts:	
f	general function	AC	alternating current
I	current	DC	direct current
$\mathbf{J}$	Jacobian Matrix	d,q	Park components (VSC control)
P	active power	i,j	connection node
Q	reactive power	iter	iteration step
R	resistance	q	source quantity (load flow model)
V	voltage	ref	reference value
X	reactance	T	transformer quantity
Z	impedance	VSC	voltage source converter
δ	voltage angle		

1.1. Study Case

The study case for EERA-DTOC software development is the offshore region Kriegers Flak. In the framework of this project, the power system layout is done by an optimization tool (Net-Op), which is described in [3] with further details. The offshore structure in fig. 1 consists of two areas, which are marked in green respectively red. HVDC connections are in yellow while AC branches are in blue color.

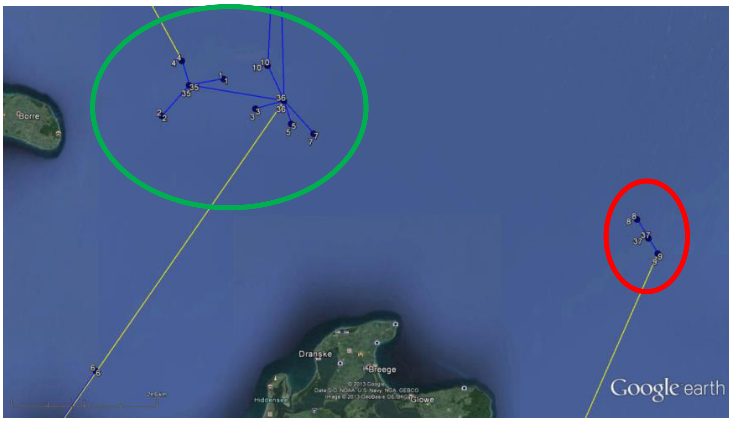


Fig. 1. offshore study case Kriegers Flak (encircled areas are discussed in section 3.3)

The output of the Net-Op tool includes, connection points, cable length, applied technology (AC/DC) and transmission capacity in active power. The information is provided by output file compatible to PSS/E Raw Data Format description [4]. All information is considered as input data for the DTOC-WCMS.

1.2. Electrical Power System Data

Since the provided data mentioned above is mainly aimed to be used at strategic planning level, it cannot include many technical details. However, enabling ancillary service analysis needs a complete electrical description of the system. Therefore, additional data was used using free accessible sources. Electrical cable data for subsea AC systems can be found in [5]. Data for DC cables and converters were taken from [6]. Empirical transformer data could be taken from [7]. Moreover, voltage levels for the offshore system had to be defined since they were not integrated in the optimization of system design so far. Due to the fact that selection of voltage levels normally takes place under economic considerations, the influence cannot be neglected for offshore power systems as well. Disadvantageous decisions could lead to additional transformers and higher voltage levels also imply more dielectric material for cable insulation. Furthermore, higher voltage levels also increase insulation distances in gas or air insulated platform installation which would lead to higher space requirements, which is a crucial aspect for offshore building sites. Therefore, manually selection of voltage levels was performed in such a way that desired active power transmission capacity is achieved with a minimal amount of transformers.

2. Wind Farm Cluster Management System

The geographically distributed wind farms are aggregated to clusters with several points of common coupling which can span over two or more voltage levels and can differ in size depending on which ancillary service or coordinated functionality is under consideration. These clusters provide grid supporting functions help in the optimization of the grid operation. This is carried out under consideration of the grid between the wind farms and by using wind forecast data with different temporal resolutions [8]. The system itself is developed since a couple of years [9]. Field test were already conducted in Portugal [10]. Simple offshore structures were already under the scope where the WCMS took over the stationary park controller functionality but additionally applied wind forecast data to improve performance [11]. At the newest applications, WCMS uses forecast data and power system analysis to optimize reactive power behavior of meshed distribution grids with multiple transmission grid feeders due to system needs. This will be done via direct communication link to several accessible wind farms and transformer tap-changer control. Set-points will be generated by optimization functionality applied not only on points in time but considering time periods with evolving wind conditions. For the latter application fields, load flow calculation routines are necessary for the set-point generation.

The Newton-Raphson load flow calculation is a 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, topology and impedance of all passive grid components are given, the system state is fully described. Therefore, complex AC node voltages can be interpreted as state-variables for the classic Newton-Raphson algorithm. Furthermore, AC nodes can be of different types which have 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. (1).

$$\begin{pmatrix} \Delta\vec{V}_{\mathrm{AC}} \\ \Delta\vec{\delta}_{\mathrm{AC}} \end{pmatrix} = \mathbf{J}_{\mathrm{AC}}^{-1} \cdot \begin{pmatrix} -\Delta\vec{P}_{\mathrm{AC}} \\ -\Delta\vec{Q}_{\mathrm{AC}} \end{pmatrix} \tag{1}$$

At each iteration step, complex node voltages are corrected by the solution of eq. (1). However, certain simplifications can be made since arbitrary per-unit systems can be used. This results in fast building up of the matrix since all terms are functions of node voltages [12]. Due to the fact that the Jacobian Matrix already represents the linearization of the system, it can be reused in sensitivity analysis. For operation purpose it is applied to overcome critical or undesired system conditions in an efficient way. In static stability analysis sensitivities provide also estimation and valuation on power system stability. Even linear approaches in optimization can make use of the Jacobian. However, the DTOC-WCMS uses sensitivity analysis to find matching and beneficial steady-state system conditions in terms of set-points for controllable devices during time series simulation for planning purposes.

3. Integration of Offshore Transmission Technology

Since the primary application fields of the WCMS were onshore building sites or simple offshore system topologies so far, offshore transmission aspects need to be respected within the system. Thereby, one major impact is evoked by representing and respecting HVDC technology during the calculation process. The necessary steps as well as background information are given in this section.

Even though the VSC-HVDC systems are the preferred technology for offshore grids due to their capabilities in voltage control and islanding operation, current source converter based HVDC (CSC-HVDC) systems are manageable if the grid is strong enough e.g. due to meshed AC connections to an onshore grid. 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 (still) better efficiency of CSC-HVDC systems at this aspect could gain importance. Hence, classical (CSC) and VSC based HVDC systems were implemented to the system. However, due to lack of space only the integration VSC-HVDC technology is described in this publication.

3.1. Voltage Source Converter HVDC

The VSC-HVDC transmission link is based on self-commutated converter technology. Fig. 2 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 are 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 e.g. by phase locked loop. By means of the same angle, the set voltage of the converter is transformed back, before the pulse-width modulation (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. Limiting the magnitude of the source voltage components set values permits overmodulation, which could lead to undesired harmonics, depending on applied PWM technique, and is able to respect current heating limits of converter [13].

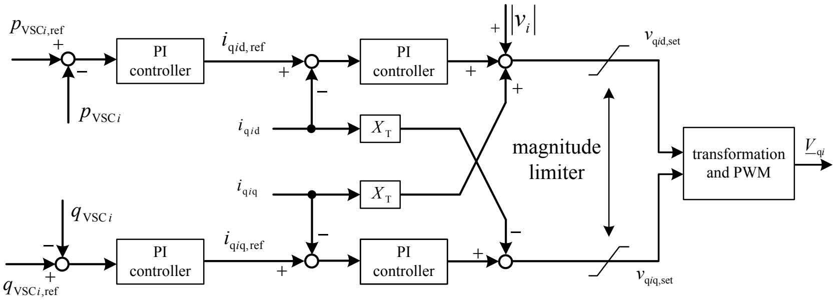


Fig. 2. Outer (power) and inner (current) control loop of VSC-HVDC.

However, for steady-state calculations after all dynamic/transient processes are decayed, only the source voltage of the converter is necessary to calculate the power flow in a hybrid AC/DC 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. Fig. 3 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. Using circuit analysis, active and reactive power can be calculated by means of source voltages at both nodes, details to this topic can be found in [14].

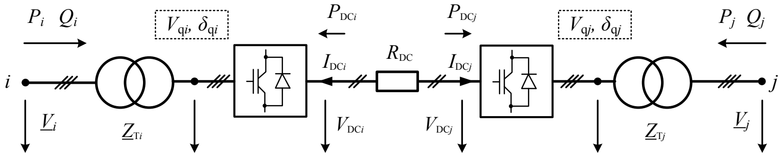


Fig. 3. Power flow of VSC-HVDC systems with all quantities (consumer oriented sign convention), state-variables are encircled.

3.2. Modified Newton-Raphson 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. In contrast to sequential approaches where the DC and the AC is calculated independently of one another, the parallel approach guarantees a nearly similar degree of convergence [15,16].

The principle is illustrated in eq. (2) for the example of one VSC-HVDC transmission link with the associated state variables [14,16].

$$\begin{pmatrix} \Delta\vec{V}_{\mathrm{AC}} \\ \Delta\vec{\delta}_{\mathrm{AC}} \\ \Delta\vec{V}_{\mathrm{q}} \\ \Delta\vec{\delta}_{\mathrm{q}} \end{pmatrix} = \begin{bmatrix} \mathbf{J}_{\mathrm{AC}} + \mathbf{J}_{\mathrm{UL}} & \mathbf{J}_{\mathrm{UR}} \\ \mathbf{J}_{\mathrm{LL}} & \mathbf{J}_{\mathrm{LR}} \end{bmatrix}^{-1} \cdot \begin{pmatrix} -\Delta\vec{P}_{\mathrm{AC}} \\ -\Delta\vec{Q}_{\mathrm{AC}} \\ -\Delta\vec{f}_{\mathrm{VSC}} \end{pmatrix} \tag{2}$$

As already denoted, to make sure the system remains solvable after the HVDC state-varariables 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. Thereby, several modes of VSC-HVDC can be distinguished for active and reactive power. Due to the point-to-point topology, active power set-points can only be reached for the converter of one connection point (master converter), while the other has to perform a balancing operation (slave converter). Furthermore, VSC-HVDC system can provide reactive power or even voltage control to their connection node, which has to be considered within the mismatch equations. Consequences for mismatch equations and constructing the Jacobian are shown in the appendix A.

3.3. Selection of Control Modes and Set-Points of Wind Farms and Controllable Transmission Equipment

For the matter of simplicity, only VSC-HVDC systems are considered in the study case. Considering the red part of fig. 1, 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 of fig. 1, 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 systems are set to reactive power provision by fixed values. Here, the converter capabilities are the only limit for reactive power provision to onshore nodes. In any way, this section has pointed out that the coordination between certain functionalities of wind farms enabling ancillary service provision and controllable transmission devices is necessary during system simulation and will also be an important aspect of operating an offshore power system

4. Ancillary Service Analysis

The impact of wind power variability [17] on the provision of system services can be significant, especially at individual wind farms level. In order to mitigate this phenomenon, it is possible to take advantage of the smoothening effect that geographical spreading of wind farms has on the wind power production. It is shown that there is an almost linear relation between variability and predictability or forecast quality. 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 adapted pre-qualification methods to the particular 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 [18]. There, a comprehensive study of the correlation between the variability (wind power fluctuations) and predictability (forecast quality) for a single wind farm and for clusters of wind farms is given. The results show that in both cases, the correlation between the Mean Absolute Gradients of the measured 1hour-power time series, defined as the absolute difference between the power in each time step, and the Root Mean Square Error, normalized with the installed capacity, is very high. Therefore, minimizing the wind power variability will result in better predictability. These notions are the basis behind the aggregation of wind farms to clusters and have consequences on how ancillary services can be provided.

4.1. Overview of Considered Services

Table 1. Analyzed Power Plant System Services.

Category	Service	Description
Frequency Support	Reserve	Frequency Restoration Reserve (Secondary Reserve) as defined in [17]
		Replacement Reserve (Minute Reserve) as defined in [17]
	Balancing Power	Balancing power supply [19]
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 [20]
System Management	Congestion Management	Maximum load flow into the grid due to congestions on land [20]

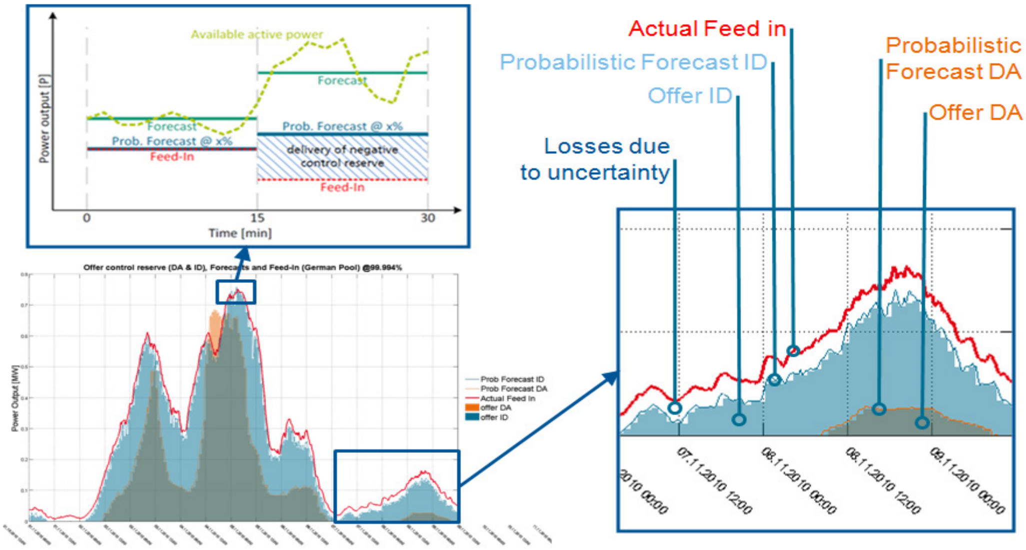
The power plant system services are different supporting actions provided by a power plant (in this case specifically wind power plants) to maintain the grid operation in correct (or even optimum) level. Some of those services are the so-called ancillary services, as well as congestion management support and balancing power supply. The considered power plant system services are organized as they are depicted in Table 1.

4.2. Frequency Support

Recent studies [9,21,22] have proposed new methods for proof of power reserve provision. For frequency support (reserve and balancing power provision) the system uses the time series of forecasted power output provided by [17]. By default, the system uses a probability of 99.5% for the reserve calculation and 90% for power provision (day ahead market schedules); nevertheless, those probabilities can be modified by the end user. For calculating the available reserve, the 24 hours in advanced forecast (day ahead) is implemented. For balancing power provision, the 1 hour forecast is implemented, representing the intraday.

The methodology used to calculate a secure forecast with given probability is described in [21] using the forecasts provided by the user with a time resolution of 1 hour. In operational conditions it would be beneficial 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.

In [21,22] two different proof methods of control reserve are discussed. For operational purposes, definitively the so-called proof of control reserve under the available active power mechanism is 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.



Source: Malte Jansen – Fraunhofer IWES

Fig. 4. Reserve and balancing power calculation.

The proof mechanism, the day ahead forecast and the hourly (intraday) forecast allow calculating the available reserve and balancing power are depicted in Fig. 4. On the upper-left side of the picture the proof mechanism is depicted, based on a probabilistic forecast of a given percentage (here typically 99.5%). On the right side of the picture 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 offered as day ahead 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 it can be produced but it is not scheduled for dispatch.

4.3. Reserve and Balancing Power

The results of the available reserve calculation are depicted in Fig. 5. The picture summarizes the complete approach to calculate frequency support based on wind farm possible power output and 1/ 24 hours forecasts.

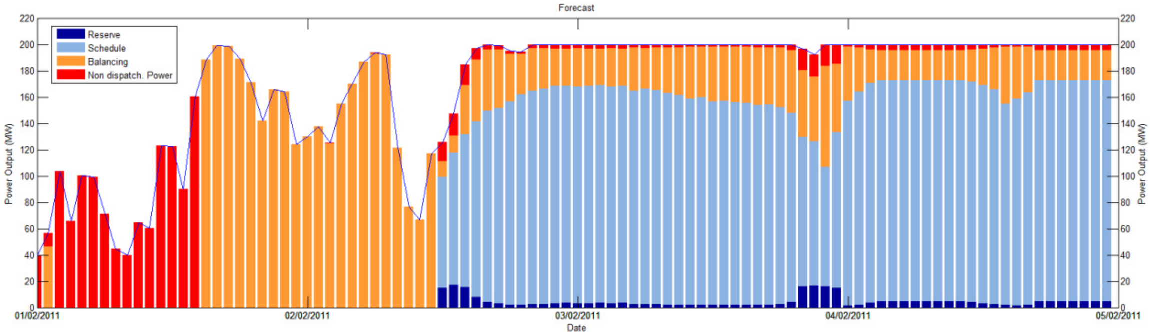


Fig. 5. Calculation of power reserve, scheduled active power and balancing power for the wind farm (Kriegers Flak) Wikinger of 400 MW of installed capacity between the 01/02/2011 and 05/02/2011

The procedure to calculate the possible reserve (depicted in dark blue) and the possible active power schedule is as follows. For a given wind farm, the time span is defined, in this case between 01/02/2011 and 05/02/. The 24 hours (day ahead) and 1 hour (intraday) forecasts are loaded and the probabilistic (secure) forecast is calculated using kernel density estimator (KDE) for a probability of 99.5 %. 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 as available reserve power for the next day (in dark blue on Fig. 5). Then, the 24 hours in advance forecast with a probability of 90% is calculated and considered as firm capacity for the next day. Subtracting the already calculated reserve to the firm capacity, it is possible to calculate the schedules for the next day (in light blue), considered as the active power dispatchable next day. After that, 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 already calculated reserve and schedules, the remaining power is considered as the available balancing power (intraday), which is depicted in orange on Fig. 5. 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 it is not possible to dispatch as reserve, active power (schedule) or balancing power. As a consequence, this portion is considered lost. 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 verify those schedules.

4.4. 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 user provides the grid layout and active power time series. Using the configuration file, the active/reactive power diagrams of the wind turbines/ farms and the definition of peak, mean and low load times of the system are defined to the program. The DTOC-WCMS filter the time series for the mentioned conditions using three parameters: for peak, mean and low load times respectively (default values are implemented). With the selected conditions, several load flow calculations are performed based on the sensitivity analysis with respect to all generators 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 or overloading any grid component. The active as well as reactive power provision, voltages and losses are computed.

4.5. Congestion Management

The congestion management 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 DTOC-WCMS is calculating several grid operation modes and all computed possible operational modes of wind turbines/ farms and set-points for HVDC links. The process is guided by load flow sensitivities. From valid solutions the one avoiding voltage problems and minimizing losses is selected.

5. Remarks and Outlook

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 its rules. Moreover, sometimes procurement rules for services are different in different European countries. Those rules are simplified and some basic assumptions are made. The coupling between market rules respectively their design and the supervisory operation and control of offshore structures should be topic of further analysis.

From a technical perspective, voltage level selection and transformer placement, which was done manually for the analysis, should be included in optimization of topology and technology. Thereby, the focus should be on modular expansion stages that are ready for operation by their own at certain phases of system construction. In this context, evolving technologies like different DC circuit breaker technologies with their estimated market release and the expansion from point-to-point to meshed multi-terminal HVDC structures can be analyzed and optimized on time axis. For planning purposes, reliability studies can be conducted to evaluate the influence of different topologies or even alternative technologies like reduced frequency systems. For operation purposes, sophisticated modeling of losses for different converter types should be developed to evaluate the influence of evolving semiconductor and power electronic technology on a system level and - important for operation - to help management systems including hybrid AC/DC optimal power flow approaches gain suitability for a developing offshore area.

Appendix A. Control modes of VSC-HVDC and sub-matrices of Jacobian

Table 2. Example VSC-HVDC control modes with associated mismatch equations [14].

	Converter at node *i*	Converter at node *j*
Active power	Master (set-point compliance) $\Delta f_{\mathrm{VSC1}} = P_{\mathrm{VSC}i,\mathrm{iter}} - P_{\mathrm{VSC}i,\mathrm{ref}}$	Slave (balancing mode) $\Delta f_{\mathrm{VSC2}} = P_{\mathrm{VSC}i,\mathrm{iter}} + P_{\mathrm{VSC}j,\mathrm{iter}} - R_{\mathrm{DC}} I_{\mathrm{DC}}^2$
Reactive Power	Specified reactive power provision $\Delta f_{\mathrm{VSC3}} = Q_{\mathrm{VSC}i,\mathrm{iter}} - Q_{\mathrm{VSC}i,\mathrm{ref}}$	Voltage control $\Delta f_{\mathrm{VSC4}} = V_{j,\mathrm{iter}} - V_{j,\mathrm{ref}}$
$\mathbf{J}_{\mathrm{UL}}$	$\partial P_{\mathrm{VSC}i}/\partial V_i, \partial P_{\mathrm{VSC}i}/\partial \delta_i, \partial Q_{\mathrm{VSC}i}/\partial V_i, \partial Q_{\mathrm{VSC}i}/\partial \delta_i$	$\partial P_{\mathrm{VSC}j}/\partial V_j, \partial P_{\mathrm{VSC}j}/\partial \delta_j, \partial Q_{\mathrm{VSC}j}/\partial V_j, \partial Q_{\mathrm{VSC}j}/\partial \delta_j$
$\mathbf{J}_{\mathrm{UR}}$	$\partial P_{\mathrm{VSC}i}/\partial V_{\mathrm{q}i}, \partial P_{\mathrm{VSC}i}/\partial \delta_{\mathrm{q}i}, \partial Q_{\mathrm{VSC}i}/\partial V_{\mathrm{q}i}, \partial Q_{\mathrm{VSC}i}/\partial \delta_{\mathrm{q}i}$	$\partial P_{\mathrm{VSC}j}/\partial V_{\mathrm{q}j}, \partial P_{\mathrm{VSC}j}/\partial \delta_{\mathrm{q}j}, \partial Q_{\mathrm{VSC}j}/\partial V_{\mathrm{q}j}, \partial Q_{\mathrm{VSC}j}/\partial \delta_{\mathrm{q}j}$
$\mathbf{J}_{\mathrm{LL}}$	$\partial \Delta f_{\mathrm{VSC1}}/\partial V_i, \partial \Delta f_{\mathrm{VSC1}}/\partial \delta_i, \partial \Delta f_{\mathrm{VSC3}}/\partial V_i, \partial \Delta f_{\mathrm{VSC3}}/\partial \delta_i$	$\partial \Delta f_{\mathrm{VSC2}}/\partial V_i, \partial \Delta f_{\mathrm{VSC2}}/\partial \delta_i, \partial \Delta f_{\mathrm{VSC2}}/\partial V_j, \partial \Delta f_{\mathrm{VSC2}}/\partial \delta_j, \partial \Delta f_{\mathrm{VSC4}}/\partial V_j$
$\mathbf{J}_{\mathrm{LR}}$	$\partial \Delta f_{\mathrm{VSC1}}/\partial V_{\mathrm{q}i}, \partial \Delta f_{\mathrm{VSC1}}/\partial \delta_{\mathrm{q}i}, \partial \Delta f_{\mathrm{VSC3}}/\partial V_{\mathrm{q}i}, \partial \Delta f_{\mathrm{VSC3}}/\partial \delta_{\mathrm{q}i}$	$\partial \Delta f_{\mathrm{VSC2}}/\partial V_{\mathrm{q}i}, \partial \Delta f_{\mathrm{VSC2}}/\partial \delta_{\mathrm{q}i}, \partial \Delta f_{\mathrm{VSC2}}/\partial V_{\mathrm{q}j}, \partial \Delta f_{\mathrm{VSC2}}/\partial \delta_{\mathrm{q}j}, \partial \Delta f_{\mathrm{VSC4}}/\partial V_{\mathrm{q}j}$

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