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Secondary Model Predictive Control Architecture for VSC-HVDC Networks Interfacing Wind Power

J. Carmona S., O. Marjanovic, *Member, IEEE*, M. Barnes, *Senior Member, IEEE* and P. R. Green *Member, IEEE*

Abstract-- This paper proposes a secondary Model Predictive Control (MPC) based architecture to provide DC voltage and DC power control to MT VSC-HVDC networks interfacing wind power generation. The proposed architecture places the controller at a supervisory level, thus providing coordination amongst existing converters' local droop controllers. Droop control is a type of decentralized DC voltage/power control. Hence, in case of secondary controller failure, droop control acts as a contingency control scheme. A simplified linear dynamic model of the MT VSC-HVDC network is utilised for the MPC's design, thus minimizing computational effort needed to compute secondary control action. Updates of droop gains and offshore and onshore "AC" variables, in the dq domain, are explicitly considered as measured input disturbances within the formulation of the MPC controller, thus ensuring appropriate control response in order to minimise adverse impact of their variation on the overall system's performance, particularly under wind power variations. Simulation results show that MPC, whose design is based on the system's simplified linear model, is capable of delivering satisfactory performance when applied to the high fidelity non-linear full order model of a six-terminal VSC-HVDC network simulated in PSCAD.

Index Terms — HVDC, Multi-terminal Network, MPC, Secondary Control, Wind Power.

I. INTRODUCTION

IN electrical power networks, voltage source converter high-voltage direct current (VSC-HVDC) transmission has been used extensively because of its ability to flexibly control power flows and to connect to AC weak grids [1]. For the interconnection of offshore wind power generation far from shore to AC systems, VSC-HVDC is the preferred technology due to its smaller footprint and more advanced/flexible control compared to the LCC-HVDC technology. The interconnection of three or more VSC-HVDC stations forms a multi-terminal (MT) network. MT VSC-HVDC systems are beginning to emerge in China (Nan'ao, Zhoushan and Zhangbei) [2] as well as in Germany (Ultranet) [3].

Due to their relatively low overall stored energy (in capacitance, equivalent to energy stored in inertia in conventional AC systems), power imbalances in MT VSC-HVDC networks result in fast and large DC voltage fluctuations. Therefore, the main problem in such networks is to maintain the DC voltage within acceptable levels whilst achieving the desired power exchange amongst stations [4].

Fig. 1: Hierarchical control of MT VSC-HVDC networks (with information from [6]-[7]).

This is of particular importance when interfacing with wind power generation due to its variability and intermittent nature.

The converters are the key components of the MT VSC-HVDC network, similar to the synchronous generators in AC systems. Hence, a robust and optimal grid control which takes into account converter dynamics and operational constraints, namely converter power and DC voltage, is highly desirable in order to avoid unexpected converter failures and the damage to other key components such as transformers or protection systems.

The simplest way to operate a MT VSC-HVDC network is to use one converter to control the DC voltage, which would represent a slack DC bus. However, this presents many inconveniences such as reaching voltage or current limits of the converter or the transmission line interconnecting the converter to the network, especially during contingencies. Further, in case of loss of the converter controlling the DC voltage, very fast inter-station communication and coordinated control is necessary to bypass the slack DC bus to another station and thus to take control over the DC voltage [5]. Hence, this has led to the emergence of a sort of decentralized DC voltage/power (or DC voltage/current) control, commonly referred to in the literature as "droop control" as outlined in Fig. 1 [6]-[7]. By using a droop control approach many converters can participate in the control of the DC voltage, hence making the network more robust to contingencies.

However, the operating points, defined in terms of voltages and currents, achieved by a droop control strategy alone (for a desired transmitted power) might not be the optimal ones, since droop control is a type of proportional open loop control as seen from the system level control perspective. Additionally, droop control, acting on its own, lacks the ability to bring the MT VSC-HVDC network back to

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its pre-disturbance state of operation, as is shown later in Section IV of this paper. Hence, a more elaborate control architecture is necessary in wind power transmission applications that includes multiple converter stations as well as multitude of DC nodes and DC lines. This could be addressed by implementing a Multiple Input Multiple Output (MIMO) system level controller, as outlined in Fig. 1. Such a system level controller, also known in the literature as secondary controller, can be based on a Power Flow Solver (PFS), as in [8], or on a Model Predictive Control (MPC) technique as outlined in this paper.

Pioneering work regarding the application of MPC in HVDC networks, interconnecting AC systems and wind power generation, was reported in [9] and [10]. However, the MPC design in [9] and [10] ignores converters' and DC cables' dynamics. Thus, the MPC design relies on the HVDC network model that captures only steady state conditions. This led to MPC being executed in the order of seconds (5s) in [10] and in the order of minutes (15mins) in [9]. Executing the secondary controller in the order of seconds to minutes is justifiable from the transmission system operator (TSO)'s point of view, where control actions are delivered in a matter of seconds to minutes. However, for stochastic, large and relatively fast power fluctuations, such as those occurring in wind power generation, a faster control action is essential to mitigate system disturbances and hence reduce the stress on the MT VSC-HVDC system components and avoid large deviations of the system from nominal-safe operating conditions. In order to address this need for rapid response, in the approach proposed by [11], MPC is executed in the order of milliseconds, with the MT HVDC network providing AC frequency support. However, although the work in [11] considers key system states such as DC voltages, it does not explicitly account for key system input disturbances in the MPC design, such as offshore and onshore AC voltage magnitude variations and changes in droop gains.

Leading HVDC technology manufacturers, such as ABB have also shown interest in implementing MPC for multi-terminal HVDC control as outlined by one of ABB's patents on master control for VSC-HVDC systems [12]. Although, they do not provide detailed explanation on the MPC architecture itself.

The objective of this paper is to further develop and verify the secondary MT VSC-HVDC grid control design, based on MPC, by investigating the system's performance under different scenarios such as wind power fluctuations, unmeasured system disturbances and system model inaccuracies.

The general methodology and underpinning theory for the application of MPC to MT VSC-HVDC networks is presented in Section II. Section III describes the MT VSC-HVDC test system and its linear model used for the MPC design in this paper. Section IV compares MPC and PFS system control architectures when applied to the MT VSC-HVDC network and presents comparative results among MPC, PFS and droop control. Section V presents conclusions.

II. MPC ARCHITECTURE – THE UNDERPINNING THEORY

The MPC architecture, outlined in Fig. 2, is based around the idea of utilizing a system model in order to forecast the impact of a given control strategy, hence the name “Model Predictive Control”, on future system behavior as exemplified

Fig. 2: MPC architecture.

Fig. 3: MPC evolution diagram example.

in Fig. 3 [13]–[14]. An MPC controller can be designed using both linear and non-linear models for single-input single-output (SISO) and MIMO systems. In the MPC implementation presented in this paper, the prediction system model is formulated in its discrete time state space form, with sampling period t_{sp} , as given by (1), thus, resulting in a linear-discrete-time MPC implementation as shown in Fig. 2. In (1) and (2), $\mathbf{x}(k)$ denotes the state variables vector, $\mathbf{v}(k)$ denotes the vector composed of control moves calculated by MPC, $\mathbf{w}(k)$ denotes the vector composed of measured disturbances affecting the system, $\mathbf{y}(k)$ denotes the vector composed of measured system outputs and k denotes the sampling instant. The control objective (i.e. tracking of a given reference, $\mathbf{r}(k)$) is attained by implementing the best (i.e. optimal) control strategy $\mathbf{v}(k)$ obtained by solving an appropriately structured optimization problem which in this paper is of a convex quadratic form as described in Subsection II.B.3 of this paper.

$$\left. \begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}_d \mathbf{x}(k) + \mathbf{B}_d \mathbf{u}(k) \\ \mathbf{y}(k) &= \mathbf{C}_d \mathbf{x}(k) + \mathbf{D}_d \mathbf{u}(k) \end{aligned} \right\} \quad (1)$$

Where:

$$\mathbf{u}(k) = \begin{pmatrix} \mathbf{v}(k) \\ \mathbf{w}(k) \end{pmatrix} \quad (2)$$

As exemplified in Figs. 2-3, the controller measures plant outputs $\mathbf{y}(k)$ and disturbance inputs $\mathbf{w}(k)$ as well as control inputs $\mathbf{v}(k)$, to calculate the next control actions $\mathbf{v}(k+1)$. Therefore, the control implementation based on MPC follows other types of closed-loop feedback controllers in the sense that it measures plant outputs to calculate the corresponding control actions to achieve a stable operation of the system. This feedback capability also allows MPC to mitigate

uncertainties associated with both model inaccuracies and unmeasured disturbances affecting the system. The design of the controller can be mainly divided in two parts:

- i) State estimation using observer such as Kalman Filter
- ii) Solution to an optimisation problem which produces a sequence of the future control moves. However, only the first control move, i.e. $\mathbf{v}(k+1)$, is actually implemented at each sampling time and the rest of the future control sequence is discarded. This is referred to as the receding horizon implementation and is exemplified in Fig. 3. Thus, $\mathbf{v}(k+1)$ becomes $\mathbf{v}(k)$ in the next sampling instant.

Fig. 4 offers a more comprehensive outlook for the steps to be followed for the MPC design. Detailed explanation of the observer and formulation of the optimization problem are given in the following subsections.

A. State Estimation – Kalman Filter

In order to forecast future system behaviour, knowledge of the system states is necessary. States can be estimated by using an observer, which in this paper is chosen to be the well-known Kalman Filter. Hence, based on (1), optimal estimates of plant states and outputs, differentiated from their measured counterparts by including “ $\hat{\cdot}$ ”, are obtained by implementing the Kalman filter, which is given in (3). Gain matrix $\mathbf{L}$ is chosen such that optimal state estimates are obtained under certain general assumptions regarding probability distributions of various disturbances affecting system and measurement noise as well as regarding their mutual correlation [15]. The discrete time Kalman filter predicts the state values at the next sample time, i.e. $k+1$ (one-step-ahead predictor), based on the current state estimate $\hat{\mathbf{x}}(k)$, current inputs and measurements of outputs.

$$\left. \begin{aligned} \hat{\mathbf{x}}(k+1) &= \mathbf{A}_d \hat{\mathbf{x}}(k) + \mathbf{B}_d \mathbf{u}(k) + \mathbf{L}(\mathbf{y}(k) - \hat{\mathbf{y}}(k)) \\ \hat{\mathbf{y}}(k) &= \mathbf{C}_d \hat{\mathbf{x}}(k) + \mathbf{D}_d \mathbf{u}(k) \end{aligned} \right\} \quad (3)$$

B. Optimization Problem

1) Separation of Inputs: Disturbance and Control Inputs

Inputs to the plant model in (1) are composed of control inputs (CIs), $\mathbf{v}(k)$, as well as disturbance inputs (DIs), $\mathbf{w}(k)$. The MPC cost function, described in Subsection II-B-3, is minimised by determining optimal CIs for fixed and given values of DIs. In order to account for the fact that DIs and CIs are treated separately by the MPC optimisation problem, the plant model given by (1) is restated as follows:

- i. Matrix $\mathbf{B}_d$ is restated as given by (4), where $\mathbf{B}_{d,v}$ and $\mathbf{B}_{d,w}$ are sub-matrixes of $\mathbf{B}_d$ that correspond to CIs and DIs respectively.
- ii. Similarly, matrix $\mathbf{D}_d$ is restated as given by (5), where $\mathbf{D}_{d,v}$ and $\mathbf{D}_{d,w}$ are sub-matrixes of $\mathbf{D}_d$ that correspond to CIs and DIs respectively.
- iii. From the aforementioned, the state space model given by (1) can be re-stated as given by (6), where the space vector $\mathbf{x}_{xw}(k)$ is an augmented state space vector composed of original states $\mathbf{x}(k)$ and DIs $\mathbf{w}(k)$ as given by (7).

$$\mathbf{B}_d = [\mathbf{B}_{d,v} \quad \mathbf{B}_{d,w}] \quad (4)$$

$$\mathbf{D}_d = [\mathbf{D}_{d,v} \quad \mathbf{D}_{d,w}] \quad (5)$$

$$\left. \begin{aligned} \mathbf{x}_{xw}(k+1) &= \mathbf{A}_{xw} \mathbf{x}_{xw}(k) + \mathbf{B}_{xw} \mathbf{v}(k) \\ \mathbf{y}(k) &= \mathbf{C}_{xw} \mathbf{x}_{xw}(k) + \mathbf{D}_{d,v} \mathbf{v}(k) \end{aligned} \right\} \quad (6)$$

Fig. 4: Flowchart-steps for the MPC design.

Where:

$$\mathbf{x}_{xw}(k) = \begin{pmatrix} \mathbf{x}(k) \\ \mathbf{w}(k) \end{pmatrix} \quad (7)$$

$$\mathbf{A}_{xw} = \begin{pmatrix} \mathbf{A}_d & \mathbf{B}_{d,w} \\ 0 & \mathbf{I} \end{pmatrix} \quad (8)$$

$$\mathbf{B}_{xw} = \begin{pmatrix} \mathbf{B}_{d,v} \\ 0 \end{pmatrix} \quad (9)$$

$$\mathbf{C}_{xw} = (\mathbf{C}_d \quad \mathbf{D}_{d,w}) \quad (10)$$

The aforementioned procedure allows the MPC controller to implicitly account for key system disturbance inputs, as will be explained later. In a MT HVDC network, these disturbances could be variations of the offshore and onshore AC voltage magnitudes as well as updates on droop gains. This is further discussed in Sections III and IV of this paper.

2) Forecast of Future Outputs

In order to predict future plant outputs, from $\hat{\mathbf{y}}(k+1)$ to $\hat{\mathbf{y}}(k+N)$ over the so-called *prediction horizon* (N), the state space plant model given by (6) is utilized with initial (one-step-ahead) optimal state estimation $\hat{\mathbf{x}}(k+1)$ provided by (3). Thus, predictions of future plant outputs can be obtained as given by (11) [13]. For more detailed explanation of future plant outputs based on the initial plant state estimation, $\hat{\mathbf{x}}(k+1)$, please refer to [13].

$$\begin{pmatrix} \hat{\mathbf{y}}(k+1) \\ \vdots \\ \hat{\mathbf{y}}(k+N) \end{pmatrix} = \mathbf{\Lambda} \cdot \hat{\mathbf{x}}_{xw}(k+1) + \mathbf{\Phi} \begin{pmatrix} \mathbf{v}(k+1) \\ \vdots \\ \mathbf{v}(k+N) \end{pmatrix} \quad (11)$$

Where:

$$\hat{\mathbf{x}}_{xw}(k+1) = \begin{pmatrix} \hat{\mathbf{x}}(k+1) \\ \hat{\mathbf{w}}(k+1) \end{pmatrix} = \begin{pmatrix} \hat{\mathbf{x}}(k+1) \\ \mathbf{I} \mathbf{w}(k) \end{pmatrix} \quad (12)$$

$$\mathbf{\Lambda} = \begin{pmatrix} \mathbf{C}_{xw} \\ \mathbf{C}_{xw} \cdot \mathbf{A}_{xw} \\ \vdots \\ \mathbf{C}_{xw} \cdot \mathbf{A}_{xw}^N \end{pmatrix} \quad (13)$$

$$\Phi = \begin{pmatrix} \mathbf{D}_{d,v} & 0 & \cdots & 0 \\ \mathbf{C}_{xw} \cdot \mathbf{B}_{xw} & \mathbf{D}_{d,v} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C}_{xw} \cdot \mathbf{A}_{xw}^{N-2} \cdot \mathbf{B}_{xw} & \mathbf{C}_{xw} \cdot \mathbf{A}_{xw}^{N-3} \cdot \mathbf{B}_{xw} & \cdots & \mathbf{D}_{d,v} \end{pmatrix} \quad (14)$$

Equation (13) is obtained by employing (10), where $\mathbf{D}_{d,w}$ is a sub-matrix of $\mathbf{D}_d$ that corresponds to DIs, and (8), where $\mathbf{B}_{d,w}$ is a sub-matrix of $\mathbf{B}_d$ that corresponds DIs, see subsection II-B-1. Equation (14) also makes use of (8) and (10) as well as (9) with $\mathbf{B}_{d,v}$ being a sub-matrix of $\mathbf{B}_d$ that corresponds to CIs. $\mathbf{D}_{d,v}$, a sub-matrix of $\mathbf{D}_d$ that corresponds to CIs, is also needed to compute (14).

3) Formulation of the Optimization Problem

With predicted outputs as given by (11), the MPC optimisation problem in Fig. 2, which is solved at every sampling instant in time, can be stated as given by (15). The cost function J (also known as the optimisation problem or control objective function) is essentially composed of two terms. The first term quantifies tracking error of the system's outputs $\hat{\mathbf{y}}(k+j)$ from their respective set-points over the future *prediction horizon* N whilst the second term quantifies the control effort $\mathbf{v}(k+i)$ over the so called *control horizon* M . Matrices $\mathbf{Q}$ and $\mathbf{R}$ denote the user-specified parameters that assign priorities (weights) to either tracking error of system outputs or control effort, respectively. The optimal control strategy, $\mathbf{v}(k+i)^*$, is obtained by minimising (15), as stated by (16), subjected to (17)-(18), such that both the control effort and deviation of system's outputs from their respective set-points $\mathbf{r}(k+j)$ are minimised whilst also ensuring that various constraints (i.e. $v_{\min}$, $v_{\max}$, $y_{\min}$ and $y_{\max}$) imposed on system controllable inputs and/or outputs are respected.

$$J = \left. \begin{aligned} & \frac{1}{2} \sum_{j=1}^N [\mathbf{r}(k+j) - \hat{\mathbf{y}}(k+j)]^2 \mathbf{Q} \\ & + \frac{1}{2} \sum_{i=1}^M [\mathbf{v}(k+i) - \mathbf{v}(k+i-1)]^2 \mathbf{R} \end{aligned} \right\} \quad (15)$$

$$\mathbf{v}(k+i)^* = \arg \min J \quad (16)$$

$$v_{\min} \leq \mathbf{v}(k+i) \leq v_{\max} \quad (17)$$

$$y_{\min} \leq \hat{\mathbf{y}}(k+j) \leq y_{\max} \quad (18)$$

The control horizon is always set to be equal to or less than the prediction horizon ($M \leq N$) since it would be nonsensical to calculate future control moves whose impact on the plant states and/or outputs is not considered in the control algorithm.

Solution of (16) produces a sequence of future control moves. However, only the first control move is actually implemented at each sampling time, i.e. $\mathbf{v}(k+1)$, as exemplified in Fig. 3. The remainder of the computed control strategy is discarded since it is very likely to become obsolete at the next sampling instant when unanticipated disturbances as well as the inevitable model inaccuracies cause the system to deviate from its predicted behaviour. This procedure is typically referred to as the receding horizon and is exemplified in Fig. 3.

III. TEST SYSTEM: PLANT MODEL

The six-terminal VSC-HVDC network shown in Fig. 5 is considered in this paper to demonstrate the benefit of deploying secondary model predictive control architecture. This MT VSC-HVDC network is based on the DC configuration of the New Jersey Energy link section of the Atlantic Wind Connection (NAWC) system. It has been built on publicly available information as given in [16] and [8] [17]. Offshore wind turbines generate medium-voltage AC power, which is collected and transformed to higher-voltage AC power. The AC power is converted to DC power and transmitted by means of a low-loss DC current transmission system. Finally, the transmitted DC power is converted back to AC and fed to the onshore AC grid.

The offshore converters operate in an AC voltage-frequency control mode, based on vector control as described in [18], thus providing the required AC voltage magnitude and frequency for the interconnection of the wind power plants to the HVDC network. The offshore converters with their associated controls appear at the DC side as uncontrollable DC voltage sources injecting the power produced by the wind farms. The onshore converters operate in a droop control mode, shown in Fig. 6, based on the Autonomous Converter Control (ACC) given in [5]. This allows the onshore converters to participate, in a decentralized fashion, in the DC voltage/power balance of the network. The ACC is cascaded with the converter's DC voltage control which in turn is cascaded with the converter's current vector control. The droop gain, k_{droop} , affects how much a converter participates in the regulation of the DC voltage. The smaller the droop gain, the higher its participation.

A detailed electromagnetic transient model of the system, shown in Fig. 5, is given in [19], where VSCs are considered to be of the Modular Multilevel Converter (MMC) type based on half-bridge sub-modules technology. Such a model is highly nonlinear and of high order. The nonlinearity of this MT VSC-HVDC network is due to the fact that in order to compute DC current one must divide power by voltage, similarly the AC active and reactive powers are given as the products of dq -axes voltage and current components. A simplified DC linear state space model of this system, that accurately represents the key dynamics of the MT VSC-

Fig. 5: Six-Terminal VSC-HVDC network - NAWC New Jersey Energy link section.

Fig. 6: Implementation of ACC, cascaded with DC voltage control, on onshore converters. Control design for a converter working in inverter mode (adapted from [19]).

HVDC network (corresponding to DC current, voltage and power), is also presented in [19]. In such a model, the continuous time state vector, $\mathbf{x}$, is composed of converters' DC positive and negative pole voltages, cables' DC currents and the integral action of the onshore converters' DC voltage PI controllers. Refer to [19] for more details on the composition of the state vector. Likewise, the control inputs, $\mathbf{v}$, are composed of onshore converters' droop set-points (v_{dcd}^* and P_{dcd}^*), outlined in Fig. 6) as stated by (19). The vector of disturbance inputs, $\mathbf{w}$, is composed of droop gains (k_{droop}), onshore and offshore d -axis components of AC voltages (v_d) and offshore d -axis current components (i_d) as given in (20).

$$\mathbf{v} = [v_{dcd1}^* \ v_{dcd2}^* \ v_{dcd3}^* \ P_{dcd1}^* \ P_{dcd2}^* \ P_{dcd3}^*]^T \quad (19)$$

$$\mathbf{w} = \begin{pmatrix} k_{droop1} \\ k_{droop2} \\ k_{droop3} \\ v_{d1} \\ v_{d2} \\ v_{d3} \\ v_{d4} \\ i_{d4}^* \\ v_{d5} \\ i_{d5}^* \\ v_{d6} \\ i_{d6}^* \end{pmatrix} \quad (20)$$

$\left. \begin{matrix} k_{droop1} \\ k_{droop2} \\ k_{droop3} \end{matrix} \right\} \text{Droop gains}$
 $\left. \begin{matrix} v_{d1} \\ v_{d2} \\ v_{d3} \end{matrix} \right\} \text{Onshore converter's PCC voltages}$
 $\left. \begin{matrix} v_{d4} \\ i_{d4}^* \end{matrix} \right\} \text{Offshore converter's PCC voltages}$
 $\left. \begin{matrix} v_{d5} \\ i_{d5}^* \end{matrix} \right\} \text{Offshore wind current}$
 $\left. \begin{matrix} v_{d6} \\ i_{d6}^* \end{matrix} \right\} \text{disturbances}$

The vector of measured outputs, $\mathbf{y}$, is composed of the DC terminal voltage corresponding to VSC Station 1 and DC input powers corresponding to Stations 2 and 3 respectively as shown in (21). Such a model can be straightforwardly converted to its discrete time form, which ultimately leads to the form given by (1).

$$\mathbf{y} = [v_{dc1} \ P_{dc2} \ P_{dc3}]^T \quad (21)$$

IV. CASE STUDY

This section describes the implementation and control architecture of two different system level controllers, namely MPC and PFS, as applied to the MT VSC-HVDC network shown in Fig. 5. These two control architectures are compared with each other as well as with droop control and the results are also provided at the end of this section.

A. Controller Set-Points

Control of the MT VSC-HVDC network shown in Fig. 5 can be achieved by manipulating the droop set-points ($\mathbf{v}$) of onshore VSCs. Hence, from the system level control perspective, onshore VSCs are seen as controllable stations, whilst offshore VSCs are seen as disturbance stations injecting power to the MT VSC-HVDC network. Consequently, the system level control set-points ($\mathbf{r}$), for either MPC or PFS, have been defined with the objective to maintain the DC voltage at Station 1 (v_{dc1}) and DC powers at Stations 2 and 3 (P_{dc2} and P_{dc3}) at their pre-disturbance reference values (*), as defined by (22). This is achieved by the controller generating the appropriated onshore converters' droop set-points ($\mathbf{v}$), given in (19), as exemplified in Fig. 7 for either MPC or PFS. Thus, the proposed control architectures provide coordination amongst existing converters' local droop controllers. Therefore, in case of secondary controller failure, droop control acts as a decentralized contingency control scheme.

$$\mathbf{r} = [v_{dc1}^* \ P_{dc2}^* \ P_{dc3}^*]^T \quad (22)$$

Fig. 7: Coordination between the system level (secondary) controller, implemented in MATLAB/Simulink, and the Six-Terminal VSC-HVDC network simulated in PSCAD. a) MPC control architecture layout and b) PFS control architecture layout.

Both MPC and PFS were implemented in MATLAB/Simulink. Conversely, the detailed non-linear model of the MT VSC-HVDC network was simulated in PSCAD. For such a co-simulation, it was necessary to develop the interface between PSCAD and MATLAB/Simulink. The detailed explanation of the implementation of this interface is out of the scope of this paper. However, the necessary information for the creation of such interface can be found in [20] and [21].

The following sections describe in more detail the MPC and PFS control architectures.

B. MPC Control Architecture

The block diagram shown in Fig. 7a exemplifies the MPC implementation. The simplified DC linear dynamic model of the MT VSC-HVDC network presented in [19] and further restated in its discrete time form as given by (1), with inputs and outputs as stated by (19)-(21), was employed for the MPC design. Detailed representation of the six-terminal VSC-HVDC system was achieved by employing its detailed non-linear model also described in [19].

Since MPC was implemented in discrete time form, being executed at a rate defined by $f_{sp} = 1/t_{sp}$, a pulse generator was implemented in PSCAD/EMTDC to generate the appropriate trigger command for the subroutine interfacing Matlab/Simulink (controller) and PSCAD (system).

The MPC optimization problem, stated (15), was designed with the objective to control the DC voltage at Station 1 (v_{dc1}) and DC powers at Stations 2 and 3 (P_{dc2} and P_{dc3}) at their pre-disturbance reference values $\mathbf{r}$, i.e. (22), whilst also accounting for the effect of measured system disturbances $\mathbf{w}$ given in (20).

Since a small-signal linear state space model was used for the design of the MPC controller, it was necessary to supplement the controller inputs/outputs by subtracting/adding their nominal values before interfacing them with the MPC controller as shown in Fig. 7a. Consequently, in Fig. 7a, $\mathbf{r}(0)$ denotes a vector containing nominal condition (values) corresponding to $\mathbf{r}$ and $\mathbf{r}(k)$ is the corresponding discrete-time vector containing deviations (i.e. Δ) from nominal conditions as stated in (23). The same convention applies to the output vectors $\mathbf{y}$, $\mathbf{y}(0)$ and $\mathbf{y}(k)$; disturbance input vectors $\mathbf{w}$, $\mathbf{w}(0)$ and $\mathbf{w}(k)$; and control input vectors $\mathbf{v}$, $\mathbf{v}(0)$ and $\mathbf{v}(k)$.

$$\mathbf{r}(k) = \Delta \mathbf{r} = \mathbf{r} - \mathbf{r}(0) = [\Delta v_{dc1}^* \quad \Delta P_{dc2}^* \quad \Delta P_{dc3}^*]^T \quad (23)$$

System variables v_{dc1} , P_{dc2} and P_{dc3} are measured and fed back to the controller, represented by output vector $\mathbf{y}$ in Fig. 7a. The desired values of the onshore converters' DC voltage and power v_{dc1}^* , P_{dc2}^* and P_{dc3}^* respectively, represented by vector $\mathbf{r}$ in Fig. 7a, are also fed into MPC, which then solves the optimisation problem in order to compute the optimal control moves, which are v_{dcd1}^* , v_{dcd2}^* , v_{dcd3}^* , P_{dcd1}^* , P_{dcd2}^* and P_{dcd3}^* . These control moves are then applied as reference values to the local droop controllers. Note that control moves produced by MPC are filtered by first order transfer functions, with time constant τ_{ref} , before being

applied to the MT HVDC network. The purpose of this post-processing of manipulated variables is to smooth the impact of the typical staircase shaped MPC output (exemplified in Fig. 3) and minimise spikes in voltages and currents, which would result from such abrupt changes.

C. PFS Control Architecture

The PFS implementation, outlined in Fig. 7b, is based on the steady state calculation of the DC network's node powers ($\mathbf{P}_i$) as given by (24), where the operator $\circ$ denotes point-wise multiplication [22] [8]. Such an implementation has been adapted from [8]. The vectors of DC node voltages $\mathbf{E}_i$ and $\mathbf{E}_j$, node powers, shunt admittances $\mathbf{Y}_{shunt_i}$ and series admittance matrix $\mathbf{Y}_{ij}$ are defined according to [8], where the individual elements in $\mathbf{Y}_{ij}$ and $\mathbf{Y}_{shunt_i}$ are solely dependant on the DC network resistivity.

$$\mathbf{P}_i = \mathbf{E}_i \circ (\mathbf{Y}_{ij} \mathbf{E}_j + \mathbf{E}_i \circ \mathbf{Y}_{shunt_i}) \quad (24)$$

Equation (24) represents a set of non-linear equations (due to the quadratic relationship amongst node voltages and the corresponding powers). Hence, this equation is typically solved by making use of the iterative Newton Raphson algorithm to calculate the corresponding DC node voltages and powers. To find either $\mathbf{P}_i$ or $\mathbf{E}_i$, one of them must be first specified. Hence, a VSC-HVDC network composed of "n" nodes will have "n" known variables and "n" unknown variables. Typically, one DC node voltage is specified (v_{dc1}^* in this case as set by (22)), and an initial guess for the remaining DC node voltages is given, which for an HVDC network, is relatively close to the specified voltage (i.e. v_{dc1}^* for the PFS implementation in this paper). Then, (24) is solved to obtain the corresponding DC powers that satisfy the network for such given initial voltages. If the estimated node powers are not close enough to the desired powers given by (22) and to the measured offshore disturbance powers given by (25), the vector of DC node voltages ($\mathbf{E}_i$) is updated with an improved estimation by solving the Jacobian of the system. The process is repeated until a specified tolerance is satisfied, resulting in the solution of the system that satisfies the balance between generation and demand with $\mathbf{v}$ as the control input, as defined by (19), for the MT VSC-HVDC network. More detailed description on how this process is done is out of the scope of this paper. However, all the required information can be found in [8].

$$\mathbf{w}_{pfs} = [P_{dc4} \quad P_{dc5} \quad P_{dc6}]^T \quad (25)$$

However, as observed in Fig. 7b, the actual system output $\mathbf{y}$, which corresponds to command vector $\mathbf{r}$ is not fed back to PFS, thus reflecting controller's open loop structure.

D. Results and Discussion

In this section a comparative analysis of the performance obtained using decentralized droop control as well as secondary PFS and MPC control architectures is presented. Five cases are presented, including steps up and down of wind power, variation of cables' resistance, turbulent wind power,

telecommunications delay and converter outage. For comparison purposes the analysis of the system without a system level controller is shown: results for the system with local constant DC voltage (for VSC1) and power control (for VSC2 and VSC3), i.e. without droop and secondary control, are presented for cases 1 and 5. The relevant parameters for this study are shown in Table I. Table II presents the converters rated parameters and limits. Table III presents the system pre-disturbance state.

The controllers and system were tested under the following five scenarios:

1) *Case 1: Step Up and Down in Wind Power Generation*

At $t=1s$, a step in mechanical power, represented by wind power P_{inwf2} , is applied to the Wind Farm 2, connected to VSC Station 5, as shown in Fig. 8a. This corresponds to a 100% generation increase by Wind Farm 2 (i.e. it doubles its generation). Such a step results in the corresponding first-order response, with time constant τ_w , for the output electric active power (P_{outwf2}), of the wind farm, which is injected and transmitted through the HVDC network. Although, such a rapid power change may not be considered realistic, it imposes a more critical scenario for the benchmarking of the system and its controls. In reality, large wind turbines are expected to have a time constant of about 6s [23], which implies a less challenging, i.e. lower control bandwidth, disturbance scenario to be dealt with by the converters' controls. Fig. 8b shows the resulting impact of the power disturbance on the DC terminal voltage corresponding to VSC Station 1 and Figs. 8c-d shows the resulting DC power at VSC Station 2 and VSC Station 3. Fig. 8e shows the DC voltage response of VSC Station 5. Fig. 8f shows the corresponding DC power response at VSC Station 1. Impact on the onshore PCC AC voltage magnitude and frequency are presented in Figs.8g-l. Similarly, Figs.8m-n present the impact on the offshore PCC AC voltage magnitude and frequency for offshore VSC Station 5.

Results obtained with droop control alone correspond to the open loop system response (i.e. without secondary control). Based on this and recommendations from [14], the sampling period t_{sp} for both MPC and PFS has been set to be 0.1s.

For comparative purposes, results for the system with local constant DC voltage (Vdc1-Const) and power control (Pdc2-Const and Pdc3-Const), i.e. without droop and secondary control, are presented as well. As can be observed, this type of local control offers a faster response compared to PFS and MPC. However, results presented for Case 5 (converter outage), demonstrate the inconvenience of having one converter dealing fully with the control of the DC voltage (as opposed to MPC or PFS which are coordinated with droop control) since loss of such a converter leads to a total loss of DC voltage control. Therefore, for the rest of the results (with exception of Case 5), this type of control is not considered.

Unlike droop control, with the proposed MPC and PFS, all power variation is reflected on VSC1, which might be undesirable. However, if the power at Station VSC1 were to reach its limit, the dynamic braking system [4] located at the terminals of the converter can be used to dissipate the excess

of energy for a short period of time. However, if the excess of energy were to be sustained for long, new power set-points would be necessary for the remaining stations to drive the system to a new operating state.

Similarly, at $t=1s$, Wind Farm 1 is subjected to a significant decrease in wind power generation, from 250 MW to 0 MW as shown in Fig. 9a. Fig. 9b shows the resulting impact of the power disturbance on the DC voltage at VSC Station 1 and Figs. 9c-d shows the resulting DC power at VSC Station 2 and VSC Station 3.

In all the cases, it can be observed that PFS and MPC are able to keep the system at its pre-disturbance reference values.

TABLE I: SIMULATION PARAMETERS

Variable	Value	Description
τ_w	0.45s	Wind farm power's equivalent time constant
t_{sp}	0.1s	MPC and PFS sampling period. State space model discretization time.
τ_r	0.5s	Resistance time constant
τ_{ref}	0.03s	Droop set-points' smoothing time constant
t_{tele}	0.9s	Time delay between VSC Station 5 and PFS/MPC
N	2	MPC prediction horizon
M	1	MPC control horizon

TABLE II: CONVERTERS RATED PARAMETERS AND LIMITS

Variable	Value	Description
P_{dc}	1010 MW	Rated power for all converters
P_{dc_max}	1040 MW	Maximum power for all converters at nominal voltage
v_{dc_nom}	594 kV	Nominal DC Grid voltage
v_{dc_max}	610 kV	Maximum DC Grid voltage
v_{dc_min}	576 kV	Minimum DC Grid voltage
i_{dc_max}	1.75 kA	Maximum DC Cable and Converter current

TABLE III: SYSTEM PRE-DISTURBANCE STATE

Variable	Value	Variable	Value
Droop set-points			
v_{dcd1}^*	594.00 kV	P_{dcd1}^*	228.21 MW
v_{dcd2}^*	594.40 kV	P_{dcd2}^*	600.00 MW
v_{dcd3}^*	594.70 kV	P_{dcd3}^*	500.00 MW
DC Powers			
P_{dc1}	228.43 MW	P_{dc4}	495.62 MW
P_{dc2}	600.00 MW	P_{dc5}	247.41 MW
P_{dc3}	500.00 MW	P_{dc6}	594.31 MW
DC Voltages			
v_{dc1}	594.00 kV	v_{dc4}	595.74 kV
v_{dc2}	594.39 kV	v_{dc5}	595.54 kV
v_{dc3}	594.69 kV	v_{dc6}	595.65 kV
Point of common coupling (PCC) AC Voltage Magnitudes			
V_1^{pcc}	327.00 kV	V_4^{pcc}	178.378 kV
V_2^{pcc}	324.51 kV	V_5^{pcc}	178.378 kV
V_3^{pcc}	325.60 kV	V_6^{pcc}	178.378 kV

Fig. 8: System response to an increase in wind power generation. a) Increase in wind power corresponding to the wind farm connected to VSC Station 5, b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e) DC voltage response at VSC Station 5, f) DC power response at VSC Station 1 and g-n) impact on the onshore and offshore PCC AC voltage magnitude and frequency.

Fig. 9: System response to a significant decrease in generation. a) Decrease in wind power corresponding to the wind farm connected to VSC Station 6, b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e) DC voltage response at VSC Station 5, f) DC power response at VSC Station 1 and g-n) impact on the onshore and offshore PCC AC voltage magnitude and frequency.

2) Case 2 – HVDC network resistance variation

The combination of the cable resistance and DC current produces heat losses. Therefore, as the load varies, the DC current varies and so does the cable temperature. Under load conditions both thermal expansion and pressure stress the cable. This leads to a change of the cable's electrical properties [24]. Cable parameters are calculated according to IEC 60287 series of standards at a temperature in sea bed of 20°C and laying depth of 1.0 m [25]. However, submarine XLPE cables can reach a temperature of 90°C under normal operating conditions [25]. As the conductor temperature changes, a correction factor can be used to estimate the conductor resistance with respect to that corresponding to 20°C [26]. The correction factor to estimate the copper conductor resistance at 90°C is 1.28 [26], meaning an increase in resistance of 28% from that corresponding to 20°C.

Based on the aforementioned, in this paper the change in resistance due to temperature has been emulated by increasing the resistance of the cables that interconnect VSC Stations 1 and 4 by 28% from 1s onwards, with time constant $t_r=0.5s$, as shown in Fig. 10a. Results presented in Fig. 10b-n show the impact of the variability of the cables resistance on the performance of the overall controlled system. None of the controllers were made aware of the change in resistance in the HVDC network. As can be observed, droop control and PFS provide a satisfactory control of the system during the period when the resistance of the network remains at its nominal value. However, they are unable to adequately control the DC voltage and power when the resistance of the HVDC network deviates from its nominal value. Although PFS can deal with disturbances that are implicitly considered in its architecture design, such a controller is essentially an open loop feed-forward control and, therefore, incapable of adequately reacting to unmeasured system disturbances. Conversely, inherent closed loop feedback capability enables MPC to better mitigate uncertainties related to model inaccuracies and unmeasured disturbances affecting the system, as demonstrated by the results shown in Figs. 10b-n.

3) Case 3 – Turbulent wind-power conditions

At $t=1s$, a turbulent wind power input (P_{inwf2}) is applied to wind farm 2, connected to VSC Station 5, lasting 3s, as shown in Fig. 11a. This power profile corresponds to turbulent wind conditions reported in [23] and results in a corresponding turbulent electric active power output (P_{outwf2}), by Wind Farm 2, which is injected and transmitted through the HVDC network. All of the three considered control strategies struggle to deal with the power transfer across the network with the poorest performance obtained when deploying droop control as observed in Figs. 11b-n. PFS and MPC behave similarly under this scenario.

4) Case 4 – Effect of Telecommunications: Signal Delay

Submarine HVDC cables are usually integrated with optical fibre. Hence, the six-terminal HVDC system is likely to have, under normal operation, a dedicated fibre-optic network to allow communication between the secondary controller and VSC Stations with negligible time delay. However, submarine HVDC cables could suffer damage due to different factors such as tidal currents, fishing and ships

Fig. 10: System response to variation of the HVDC network resistance. a) 28% increase in resistance for cables interconnecting VSC Stations 4 and 1, b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e) DC voltage response at VSC Station 5, f) DC power response at VSC Station 1 and g-n) impact on the onshore and offshore PCC AC voltage magnitude and frequency.

Fig.11: System response to turbulent wind-power conditions. a) Turbulent mechanical power applied to the wind farm 2 connected to VSC Station 5, b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e) DC voltage response at VSC Station 5, f) DC power response at VSC Station 1 and g-n) impact on the onshore and offshore PCC AC voltage magnitude and frequency.

dragging their anchor. This, in turn, could also adversely affect their internal optical fibres, causing degradation or complete loss of the communication channel. Hence, from the reliability and availability point of view, it is highly desirable to have a backup communication system in place. Based on the aforementioned, the system with turbulent wind-power conditions, as described in Subsection IV-D-3, was further tested considering a time delay t_{tele} between VSC Station 5 and secondary controllers PFS and MPC. This time delay corresponds to Satellite back-up communications reported in [27]. The corresponding results for this scenario are shown in Figs.12d-n. As can be observed, droop and PFS deliver a poor control performance compared to MPC. The reason for such a difference in results is due to the fact that even if MPC is not provided with the actual information, e.g. wind-power disturbance, from VSC Station 5, such a power disturbance is still propagating throughout the network and its impact is being reflected on the onshore VSC Stations, which ultimately the MPC takes into account due to its inherent feedback capability (i.e. through y). This feedback capability combined with MPC's observer (Kalman filter) provides MPC with a "virtual" communication capability similar to that of a Power Line Communication (PLC) system. For more on PLCs refer to [28].

5) Case 5 – Converter Outage

At 1s, the VSC Station 1 is lost (the converter is blocked). Hence, its DC current and power are reduced to zero as can be appreciated in results presented in Fig. 13g. Under normal operating conditions, the control of the DC voltage at VSC Station 1 is achieved by indirectly controlling its DC power. MPC and PFS accomplish this by manipulating the converter's droop references. Losing VSC1 implies losing control over two DC variables (DC voltage and DC power for converter 1) by MPC and PFS. Even with the right information from the offshore converters, Stations 2 and 3 can no longer follow their references and have to deviate from their corresponding power references to satisfy the energy balance in the network. Thus MPC and PFS lose controllability of the system. However, the system still remains in operation due to the participation of the lower level droop controllers, keeping the system under safe conditions at the price of not fulfilling the target values. This exemplifies the importance of the droop control in the voltage and power balance in the HVDC network when coordinated with a system level controller such as PFS or MPC.

The PFS's response in this scenario is similar to the system response when droop control alone is used to operate the system. This reflects PFS open loop nature, it is only aware of the injected power by the offshore VSC stations. Conversely, the inherent closed loop feedback capability of MPC is reflected as spikes in the DC power and as a stepping up DC voltage.

Blocking the converter implies a topology change for the MT HVDC network. For MPC and PFS to be able to deal with the "new system", they would need to be fed with the updated state space model of the MT HVDC network and updated set-points to drive the system to new operating conditions. However, this case is out of the scope of this paper.

Comparative results for the system with local constant DC

Fig.12: System response to turbulent wind-power conditions with signal delay. a) Turbulent mechanical power applied to the wind farm 2 connected to VSC Station 5, b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e) DC voltage response at VSC Station 5, f) DC power response at VSC Station 1 and g-n) impact on the onshore and offshore PCC AC voltage magnitude and frequency.

Fig.13 System response to converter outage. a)-b) DC voltage response at VSC Station 1, c) DC power response at VSC Station 2, d) DC power response at VSC Station 3, e)-f) DC voltage response at VSC Station 5, g) DC power response at VSC Station 1 and h-n) impact on the onshore PCC AC active powers.

voltage (Vdc1-Const) and power control (Pdc2-Const and Pdc3-Const), i.e. without droop and secondary control, are also provided in Figs. 13. In this case, losing VSC Station 1 implies full loss of the DC network voltage. The energy that is not transmitted to the onshore AC side is being absorbed by the HVDC network capacitance which causes a continuously increase of the DC voltage. This demonstrates the

inconvenience of having one converter dealing fully with the control of the DC voltage (as opposite to MPC or PFS which are coordinated with droop control). Under this scenario, very fast inter-station communication and coordinated control is necessary to bypass the slack DC bus to another station and thus to take control over the DC voltage. However, this is out of the scope of this paper.

The DC power entering the converters is composed of the power injected to the AC network plus the power absorbed by the converter capacitance as can be concluded from results presented in Figs. 13c-d and g-j.

V. CONCLUSIONS

Results presented in this paper demonstrate that designing MPC based on a simplified linear model of the MT VSC-HVDC network renders satisfactory results when implementing MPC as the secondary DC grid controller to the high fidelity non-linear MT HVDC network model. Droop control, PFS and MPC were tested under different scenarios such as: significant increase and decrease in wind power generation, turbulent wind conditions and substantial variability of system parameters such as cable resistance. The superiority of MPC to provide satisfactory control performance under such scenarios was shown. The methodology detailed in this paper, for MPC implementation, can be readily applied to other types of MT VSC-HVDC network topologies by making use of the state space model of the system.

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VII. BIOGRAPHIES

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