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Coordinated direct current matching control strategy for multi-terminal DC transmission systems with integrated wind farms

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A B S T R A C T

A new direct current matching control (DCMC) scheme is proposed in this paper. The scheme is ideally suited for the integration of a large number of wind farms with AC grid systems via a multi-terminal HVDC (MTDC) network incorporating several grid-side converters. The proposed DCMC, which matches, in a near-instantaneous fashion, the cumulative injected DC currents from all wind farms with the total of the output DC currents to the AC grids (via inverters) by communicating real-time data between all terminals, is an improvement upon and potential replacement for conventional DC voltage droop and master–slave control strategies. Through the utilization of a wide-area supervisory control and data acquisition (WA-SCADA) system, the proposed DCMC aims to enhance MTDC network voltage stability and facilitate flexible power dispatch to the supplied AC grids, while maximizing the total amount of generated wind power and offering more flexibility in terms of the ability for wind farms to independently control and maximize their outputs without any requirement for output to be constrained. A six-terminal MTDC system connecting three wind farms to three independent mainland AC grids is used to validate the proposed DCMC and compare its performance with conventional control strategies, three simulation studies are carried out to test and verify the DCMC.

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1. Introduction

Offshore wind power is a major contributor toward meeting global targets of reduced CO2 and greenhouse gas emissions. 35 GW of offshore wind power is proposed to be sourced in Europe by 2020 and 120 GW by 2030 [1]. These targets require large investments in more efficient and reliable transmission networks. The remote locations of offshore (and many onshore) wind farms (WF) render conventional high-voltage AC transmission systems technically and economically unattractive [2]. A single multi-terminal HVDC (MTDC) transmission system may be favored over multiple point-to-point HVDC transmission systems, as it provides benefits such as: improved security of supply through diversity and redundancy in supply paths; a reduction in the impact of wind power variability as energy collection and delivery can be made across large geographic areas incorporating multiple wind farms; reduced capital investment due to a requirement for less converter stations; and opportunities to transfer power from one AC system to another, which offers economic and technical benefits.

From a technical perspective, voltage source converter-based HVDC (VSC-HVDC) systems are attractive for offshore connections for a number of reasons: VSC systems offer black-start and voltage support capabilities for wind farms; power reversal can be achieved without changing the DC voltage polarity; VSC has a smaller physical footprint than alternative converter types such as line-commutated converters (LCC) [3].

MTDC-HVDC networks have been proposed by several authors as an effective means of integrating wind power with AC grids [4–13]. One of the major advantages relating to integration using MTDC networks and converters is that connected groups of wind turbines may operate at independent frequencies. Therefore, groups of wind turbines can operate at optimal speeds to maximize power production. However, the main limitations of the approaches outlined in [4,5] are that only one VSC inverter delivers power to the grid and regulates the DC link voltage. The present trend for DC network architectures is to increase the number of grid-side inverters to improve the flexibility of power dispatch and between the mainland AC grids [6]. Further research into the dynamic behavior, control strategies and protection of MTDC systems with increased numbers of terminals is required.

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Operation of an MTDC system requires at least one converter terminal to act to maintain a constant DC voltage (typically known as the master or DC voltage regulating converter) and maintain the power balance within the DC network. Other converters (typically known as slaves [13]) can be controlled using various other modes (e.g. power reference mode [13], frequency reference mode [7]) in conjunction with AC voltage/reactive power regulation. Two major MTDC control strategies have been proposed in the literature: “DC voltage margin control” [11–13] and “DC voltage droop control” [15–17]. When operating in accordance with the voltage margin control strategy, if the power capability of the DC voltage regulating converter is exceeded, it will continue to operate at its power limit and another converter will be designated as the new master to regulate DC voltage at a different level. The drawback of this approach is that it exposes the DC voltage-regulating converter and associated AC-side equipment to increased power variations and the risk of DC over-voltages. This arises from the fact that a single converter is assigned the function of balancing the power for the entire network with other converters passively operated at constant power input/output mode, which is disadvantageous from a security perspective [11] that losing this single DC regulating converter can result in instability of DC network voltage. Conversely, the DC voltage droop control strategy dictates that all grid-side inverters operate in DC voltage regulation mode to permit power sharing; this can effectively limit the magnitudes of DC voltage variations. The power sharing between inverters is based upon a DC voltage/active power droop, which is computed according to the MTDC network parameters (primarily the resistances of the interconnectors between the DC nodes of each of the inverters which can be used to compute the power transferred between terminals according to a known voltage difference between the terminals). However, as shown in [16], the droop characteristic may be required to be highly complex in order to achieve multiple control objectives (e.g. converter power dispatch & power reversal) and must be designed for specific sets of line parameters. This means that during scheduled or forced outage of one of the lines, the droop characteristics must be modified; otherwise, they become invalid and the network may become unstable.

Wide-area (WA) control systems, and supervisory control and data acquisition (SCADA) systems, have been used for enhanced monitoring and operation of power systems in many applications [10,20,22,24,25,27]. Ref. [20] describes the use of WA control systems to facilitate and optimize HVDC damping control systems. However, advanced communication-based control technologies have not been proposed extensively for new MTDC system applications. To address the aforementioned issues associated with DC voltage variations and inflexibility of power dispatch to the supplied AC systems, this paper contains a proposal for a new communication-based coordinated control strategy, known as direct current matching control (DCMC), which is underpinned by a WA-SCADA system. The proposed control strategy accurately matches the DC output currents from all grid-side VSCs (GVSC) with the cumulative current inputs of all wind-side VSCs (WVSC). It is shown that this offers improved power dispatch and DC voltage stability compared to other strategies proposed in the literature.

Sections 2 and 3 of this paper present and analyze the MTDC system and control strategy, analyze DC voltage stability and outline practical issues, including dealing with communications failure. Section 4 defines and investigates communications latency and analyses its impact on DCMC performance. Section 5 presents simulation studies to validate the DCMC strategy and demonstrate the advantages of the scheme according to three categories: (1) flexibility and security of power dispatch to onshore AC grids; (2) improvement of DC voltage stability under variable levels of wind power generation; (3) ride-through capability when AC-side faults are experienced and in response to loss of a wind farm. Section 6 concludes by summarizing the properties and applicability of the DCMC, and makes a number of recommendations for the future.

2. Test MTDC network with connected wind farms

2.1. Configuration

Fig. 1 presents a candidate MTDC configuration which is used as the basis for the studies of the control strategy performance. In this case, there are independent wind farms inject power into a ring DC network via converters WVSC1, WVSC2 and WVSC3. The converters GVSC1, GVSC2 and GVSC3 deliver power to AC power systems 1, 2 and 3. While the DC system is of a ring configuration, other DC network configurations, such as radial or meshed systems, are possible.

2.2. Control of GVSCs

The control systems applied to the MTDC network in this study are illustrated in Fig. 2. The GVSC control strategy has the objectives of dispatching power (originating from the wind farms) to the connected AC grids, while simultaneously ensuring satisfactory DC voltage stability within the MTDC network. The control system for the GVSCs consists of an inner current controller and outer controllers which perform the functions of DC voltage regulation, real power regulation, AC voltage regulation and reactive power regulation.

The AC-side electrical dynamics of the converter can be expressed as shown below:

\[
\dot{v}_{a/b/c} - v_{a/b/c} = L \frac{d}{dt} \frac{d_{a/b/c}}{R_{a/b/c}} + \frac{L}{R_{a/b/c}} \frac{d_{a/b/c}}{dt} + \frac{d_{a/b/c}}{\omega L_{a/b/c}} + v_{a/b/c}
\]  

In Eq. (1), \(v_{a/b/c}\) and \(L_{a/b/c}\) refer to the converter’s switch- and grid-side voltages respectively. \(L_{a/b/c}\) refers to the three-phase currents passing through the reactor and the converter transformer at the grid interface, and \(L_{a/b/c}\) and \(R_{a/b/c}\) are the equivalent combined inductance and resistance of the reactor and transformer. A conventional synchronous d–q–r reference approach is employed to facilitate VSC–HVDC control [5,7]. The three-phase voltages \(v_{a/b/c}\) and currents \(i_{a/b/c}\) are measured at the point of common coupling (PCC) as illustrated in Fig. 2. They are transformed to d–q–r components \(v_{dq}\) and \(i_{dq}\) via the Park transformation [9]:

\[
v_{dq} = v_d + j v_q = \frac{2}{3} j e^{-j\frac{2\pi}{3}} (v_a + e^{j\frac{2\pi}{3}} v_b + e^{-j\frac{2\pi}{3}} v_c)
\]

\[
i_{dq} = i_d + j i_q = \frac{2}{3} j e^{-j\frac{2\pi}{3}} (i_a + e^{j\frac{2\pi}{3}} i_b + e^{-j\frac{2\pi}{3}} i_c)
\]

A phase-locked-loop (PLL) block is used to synchronize the VSC to the grid voltage at the PCC and to align the voltage vector of the grid with the d-axis (when the network voltage at the PCC remains constant and balanced, \(v_q = 0\)). In the synchronous d–q reference frame, the dynamics of the VSC in (1) can be expressed as:

\[
v_{d} = \frac{L}{T_{d} L_{d}} \frac{d}{dt} i_{d} + R_{d} i_{d} - \omega L_{q} i_{q} + v_{d}
\]

\[
v_{q} = \frac{L}{T_{q} L_{q}} \frac{d}{dt} i_{q} + R_{q} i_{q} + \omega L_{d} i_{d}
\]

where \(v_{d/q}\) and \(i_{d/q}\) are the d-axis and q-axis converter-side voltage and current vectors.

In order to track the reference currents \(i_{d/q}\), the inner current control loop uses proportional–integral (PI) controllers with feedback to regulate the current vectors \(i_{d/q}\) as shown in Fig. 2. Therefore, the VSC voltage vector references \(v_{d/q}\) for the VSC are computed as follows:

\[
v_{d/q} = \left( k_p + \frac{k_i}{s} \right) (i_{d/q} - i_{d/q}) + R_{d/q} i_{d/q} - \omega L_{d/q} i_{d/q} + v_{d/q}
\]
where \( k_p \) and \( k_i \) are the PI controllers’ gains that are selected and tuned by analyzing the VSC’s electrical characteristics.

The voltage vector references \( v^*_{dq1} \) and \( v^*_{dq2} \) are transformed to a three-phase value \( v^*_{abc1} \) for pulse width modulation (PWM) or for use within a cellular multilevel HVDC modulation scheme [17].

The outer controllers, as illustrated on the right hand side of Fig. 2, are used to compute the reference current \( i^*_{dq} \) based on an active power reference or DC voltage reference, and to compute \( i^*_{d} \) based on reactive power grid reference or AC voltage amplitude reference for the inner current control function.

\[
v^*_{dq1} = \left(k_p + \frac{k_i}{s}\right)(i^*_d - i_d) + Ri_q + \omega L_i_q + v_q
\]  

\( (7) \)

2.3. Control of WVSCs

Wind turbine control systems are typically applied to individual wind turbine generators independently to extract maximum power under varying wind speed conditions [4,5,7,8], using the wind-power versus turbine-speed characteristics for specific turbine types as a reference within the control scheme. The coordinated control strategy reported in this paper is applied to the MTDC WVSC converter station to collect all power generated by many turbines in the “wind power park module” (PPM) and exports this to the MTDC network. The WVSC regulates constant offshore network frequency and voltage by modulating the output three-phase voltage to maintain a relatively constant phase angle and magnitude.

As illustrated in Fig. 2, through regulating the AC voltage amplitude component \( v_d \) with a target of 1 pu, and controlling the phase angle voltage component \( v_q \) with a target of 0, the reference currents \( i^*_{dq} \) for the inner current control scheme are produced. A virtual phase angle \( \hat{\omega}_p \) (normally set to 0) with constant cycle period of \( \hat{\omega}_p = 2\pi f_p \) is provided for the Park and inverse Park transformations. In a similar fashion to an infinite bus, the WVSC automatically “absorbs” the power generated by the PPM and transfers this power to the MTDC grid.

2.4. Representative MTDC network

To facilitate analysis using a number of case studies, the relatively complex MTDC network has been simplified to produce the network shown in Fig. 3. At the DC network interface, each VSC can be regarded as a DC current sink [18]. Converters WVSC1, WVSC2 and WVSC3 act as input DC current sources \( i^*_{DC1}, i^*_{DC2} \) and \( i^*_{DC3} \), whereas converters GVSC1 and GVSC2 act as output DC current sinks \( i_{DC4} \) and \( i_{DC5} \). In this paper, GVSC2 is selected as the DC voltage regulator to balance the difference between input and output currents via current \( i_{DC5} \).
2.5. Rate of change of DC voltage levels

For a typical AC power system, frequency is a dynamic indicator of the power balance between generation and load, whereas for an MTDC system, the indicator is the instantaneous DC network voltage levels with respect to a target level [16]. To securely operate an MTDC network, it is important that DC voltage levels across capacitors at all nodes in the MTDC system are maintained within limits, as transient DC over-voltage may damage the converter equipment and cables, while under-voltage may affect converter controllability [15].

During any dynamic change in DC voltage, the overall trends of the DC voltage changes at all converters are generally aligned with the voltage level of the DC voltage regulating terminal GVSC2, due to the relatively small DC cable impedances that interconnect the converters [19]. Neglecting the network impedance, the dynamics of the DC circuit can be approximated as expressed in (8):

$$ N C \cdot \frac{dU_{DC}}{dt} = \sum l_{DCin} - \sum l_{DCout} $$

where $N$ is the total number of capacitors and $U_{DC}$ is the average DC voltage level in the MTDC network, $\sum l_{DCin}$ and $\sum l_{DCout}$ are the total input and output DC currents respectively.

Eq. (8) reflects the main hypothesis that is investigated in this paper and is the essence of the reported method: the function of the DC voltage regulating terminal GVSC2 in catering for power mismatches in MTDC systems can be assisted and compensated through the instantaneous matching of the input DC currents of the WVSCs with the output DC currents of the other two converter GVSC1 and GVSC3. This matching action reduces the total DC current mismatch in (8) using communication facilities to command the other two GVSCs to respond in the correct fashion. Using this technique, higher DC voltage stability can be obtained. Furthermore, the matching action can be used to facilitate dispatch of individual GVSC power levels.

3. The supervisory control and data acquisition (SCADA) system

A SCADA system is a combined computer and communications-based system that monitors and controls industrial processes. It typically consists of several data interface devices (e.g. remote terminal unit (RTU), programmable logic controllers), a central computer server (e.g. master terminal unit (MTU)), a communications system to transfer data between RTUs and the MTU, and a human machine interface [20]. The data transmission media is classified into two categories, dependent media (e.g. power line carriers, optical fibers) and independent media (e.g. satellites, microwave radio) [22,24]. Fig. 5 illustrates a suitable WA-SCADA system that may be used within the DCMC system; it consists of one master terminal unit (MTU) and six remote terminal units (RTUs).

4. Design of the direct current matching control (DCMC) strategy

The DCMC has the objective of estimating/computing the total DC current injection from all WVSCs (using AC-side measurements) and then matching this to the cumulative output of the GVSCs via a central controller. The strategy is applied to the six-terminal MTDC test system as illustrated in Fig. 1. Configurable sharing factors are employed to enable the output power to be allocated to individual AC grids (or to different injection points when connected at multiple points to a single large AC grid) according to schedules that may be pre-determined. The remainder of this section describes the complete DCMC algorithm in detail, presents the characteristics of the required SCADA system, and outlines issues related to communications system latency and failures.

4.1. Estimating individual DC currents for all WVSCs

Based on the power balance between the AC and DC-sides of a VSC (assuming lossless conversion), the DC current contribution of each VSC can be estimated in real time from AC-side measurements as shown below [14]. This estimation technique is used to minimize sensor requirements and to predict WVSC-injected DC current independent of any DC-side capacitor influences:

$$ i_{DC} = \frac{3}{2} \left( \frac{U_{DC}}{U_{DC}} \right) \left( i_d + v_q \cdot i_q \right) $$

In practice, the VSC and its associated equipment are not lossless. However, by compensating for a relatively constant error that represents the losses in any particular converter, the accuracy of the DC current estimation can be high. By applying (9) to all of the WVSCs shown in Fig. 1, the individual DC current contributions from each of the three WVSCs are estimated as presented in (10):

$$ \begin{bmatrix} i_{DC1} \\ i_{DC2} \\ i_{DC3} \end{bmatrix} = \begin{bmatrix} 3/2 & v_q \cdot i_q & \frac{1}{U_{DC}} \\ 3/2 & v_q \cdot i_q & \frac{1}{U_{DC2}} \\ 3/2 & v_q \cdot i_q & \frac{1}{U_{DC3}} \end{bmatrix} \begin{bmatrix} v_{q1} \\ v_{q2} \\ v_{q3} \end{bmatrix} $$

4.2. Real-time matching of GVSC output currents with WVSC input currents

The estimated DC current inputs from all WVSCs, calculated using Eq. (10), are immediately sent to the matching control unit (also called “master terminal unit”), and summed. The process is illustrated in Fig. 5 along with the associated wide-area SCADA system used to communicate the data. Following the principle that $\sum i_{DCin} = \sum i_{DCout}$, the MTU immediately allocates the total input current from the WVSCs proportionally to the individual GVSCs, according to the predetermined sharing factors $K_1$, $K_2$, and $K_3$ as presented in (11). The communicated variables between the control server and GVSCs are the DC current output references $i_{DC4}$, $i_{DC5}$, and $i_{DC6}$ for GVSC1, GVSC2, and GVSC3 respectively:

$$ \begin{bmatrix} i_{DC4} \\ i_{DC5} \\ i_{DC6} \end{bmatrix} = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} \cdot \sum_{i=1}^{3} i_{DC} $$

where $K_1 + K_2 + K_3 = 1$. Note that in (11) the DC voltage regulating converter GVSC2 is not allocated with an actual current reference $i_{DC5}$, as the control is implemented using a DC voltage controller as described previously. However, Eq. (11), which effectively monitors the entire...
MTDC network, deduces the amount of DC current to GVSC2 using knowledge of the other DC currents in the MTDC network, with its sharing factor $K_2$ computed using $K_2 = 1 - K_1 - K_3$. As such, the DC voltage regulating converter’s DC current is also under full control. GVSC2, equipped with a DC voltage controller, is effectively acting as a DC “slack bus” and balances the DC power in the whole MTDC network. This effectively compensates for momentary network current imbalances that may be caused by network disturbances or by different communication path latencies.

In terms of physical implementation of the control algorithm within the SCADA system as shown in Fig. 5, in the MTU a local area network (LAN) connects a primary control server which implements the DCMC algorithms presented in (11) with configurable sharing factors which allow operators to set up and configure control actions, such as changing the share of power supplied to each AC system. Each of the three RTUs located at the wind farms collects data relating to the estimated DC currents from the individual WVSCs’ local controllers using Eq. (10), and sends this data to the MTU. The MTU collects the data and sends control signals to the RTUs of GVSC1 and GVSC3. As GVSC2 is a DC voltage regulating converter, there is no need to interface it directly to the SCADA system, although it will most likely be interfaced for other purposes. The communication media are likely to be radio, optical fiber or DC cable links, whereas satellite is less suitable because of its high latency for distant data transmission [22,23].

4.3. Alternative GVSC local control scheme over the conventional one

As shown in Fig. 2, AC-side $d$-axis current references $i_{d}^*$, which are input to the inner current controller, are computed by the active power controller using the assigned active power reference. When the DCMC strategy is applied to GVSC1 and GVSC3, $i_{d}^*$ is computed using the reverse implementation of Eq. (9), with $i_{dc}^*$ assigned centrally at the MTU:

$$i_d^* = \frac{2/3U_{dc}i_{dc}^* - v_d i_d}{v_d} (12)$$

$i_d^*$ is controlled simultaneously by regulating either the AC voltage amplitude or reactive power as is the case for any conventional
The equation for computing GVSC$_1$’s and GVSC$_2$’s $d$-axis current references within their local control systems is presented in (13):

$$
\begin{bmatrix}
i_{d4} \\ i_{q4}
\end{bmatrix} = \frac{2/3U_{dc4}K_{I1}\sum_{i=1}^{3}i_{q_i} - u_{q4}J_4}{2/3U_{dc4}K_{I1} - u_{q4}J_4} = \frac{2/3U_{dc4}K_{I1}\sum_{i=1}^{3}i_{d_i} - u_{d4}J_4}{2/3U_{dc4}K_{I1} - u_{d4}J_4}
$$

The entire DCMC process, as described in Sections 4.1–4.3, is depicted in a flow chart as shown in Fig. 4. As previously mentioned, the DCMC matches the output currents of the GVSCs with the input currents of the WVSUs using sharing factors assigned at the MTU. Sharing factors can instantaneously allocate required.controlled proportions of DC current references to each GVSC (apart from the GVSC equipped with a DC voltage regulator, which is not a power controller), and the local control systems at each GVSC converts the DC current references to power references. The three sharing factors used in this case study, which cumulatively sum to a value of 1, can be set at any time by the HVDC system operator to the values required for dispatching. For example, $K_1 = 0.2$, $K_2 = 0.5$, $K_3 = 0.3$ operates the MTDC with 20% of the total current/power to GVSC$_1$, 50% to GVSC$_2$, and 30% to GVSC$_3$. Updating the sharing factors to $K_1 = 0.4$, $K_2 = 0.2$, $K_3 = 0.4$ will immediately (or as fast as possibly) reallocate the total DC current with 40% for GVSC$_1$, 20% for GVSC$_2$, 40% for GVSC$_3$. The proposed DCMC scheme with this mechanism, which is not a replacement for the DC voltage droop control but acts effectively as a hierarchical higher-order controller which sits above “voltage margin control” or “master–slave control”, where only one VSC actually regulates the DC voltage, represents a more effective and flexible method of enabling complex dispatch patterns (e.g. simultaneous dispatch or power exchange involving two GVSCs or more) and addresses and reduces the complexity of droop characteristics applied to all GVSCs by applying DC current matching sharing factors when the number of GVSCs is increased above two.

4.4. Safety mode to cater for communication failures

The control system is designed with a back-up safety mode to ensure secure and continuous operation in the event of communications problems although the modern communication technology rarely has any issue for the majority of the time. The operational philosophy of this “safety mode” is inferred from the non-communicating DC voltage droop method [15–17]: all GVSCs are operated at preset drooped DC voltage levels, so they all partially share the total DC current, preventing excessive current flow through any individual GVSC and preventing over-voltage on the DC system.

In the employed SCADA system, as illustrated in Fig. 5, a signal health monitoring system detects any loss of signal and consequently enables safety mode. Detection modules in the central or local converter controllers would detect loss of communications signal and would activate auxiliary DC voltage controllers in the local controllers of GVSC$_1$ and GVSC$_2$, which control their terminal DC voltages at preset reference DC voltages $U_{dc}$, rather than being assigned with DC current reference $i_{dc}$ as specified in (11). The safety mode should be triggered every time there is a single communication error within the system in case the whole MTDC network is affected, and deactivated after the health monitoring system confirms the fine condition of the communication network.

4.5. Impact of communication latency on performance

The DCMC scheme is underpinned by a wide area (WA) control system. Such systems are already widely accepted by the power industry and are expected to continue to be used, and indeed to proliferate further in the future on both centralized and decentralized forms, to cater for the secure control and operation of future smart and micro-grids. As the system reported in this paper relies on a communications system for its normal mode of operation, it is important to consider the potential effects of latency on the performance of the system. Excessive delays in supplying the required data to the appropriate controllers could impair performance, particularly during transient situations involving AC or DC network faults. Communication latencies and well established methods to minimize the impact of latency impact on the performance of WA communication and control are discussed in [7,21,23,24]. In Ref. [7], a communication latency of 10 ms is adopted for the local coordination control between an HVDC converter and its integrated offshore WF, whereas in [21], a delay of 20 ms is estimated for the SCADA system in communicating with a number of remote power stations. For WA communication systems using satellite, the authors in [23] report on delays ranging from 100 ms to 540 ms. Satellite is not considered in this implementation – optical fiber-based, radio or power line-based communication approaches are more likely to be adopted for the proposed DCMC in a practical implementation.

Based on the above review of others’ work, a presumed communications latency in the order of tens of milliseconds is practically feasible, and this could be used in analyzing the performance of a practical implementation of the proposed DCMC system for MTDC networks that cover geographical distances of a few tens of kilometers up to hundreds of kilometers. To verify the robustness of the DCMC, a very pessimistic latency of 100 ms is adopted for all the simulation validation studies, whereas in practice it is anticipated the latency may be easy in the range of 10–30 ms (less than this is common for existing power system protection functions employing communications). The DCMC operates as an over-arching function “on top” of the master–slave control system already described, and this ensures that GVSC$_2$ acts as a master for DC voltage regulation, with an inherent fail-safe mode. It should be noted that excessive control latency (e.g. 500 ms) would of course significantly weaken the performance of the DCMC. This would result in the MTDC losing the ability to perform DC current matching; returning to the conventional master–slave control mode and consequentially higher magnitudes of DC voltage variation during network transients. This is very unlikely to happen in practice, as modern IEC61850-style communications within hard-wired (non-wireless)
networks typically have worst-case latencies of the order of 20 ms [28] (IEC61850 typically defines the communication protocol but it has the tendency to be implemented between substations/systems across large geographics).

5. Simulation verification and demonstration

The MTDC network using the DCMC system, as shown in Figs. 1 and 2, has been modeled using Matlab/Simulink to demonstrate the effectiveness of the strategy in terms of providing flexible power dispatch onshore AC grids using configurable sharing factors. It is also demonstrated how the system has the ability to permit exchange of power between onshore grids, and can ensure DC voltage stability by utilizing the fast dynamic response and bidirectional power flow capabilities of the VSCs. The operation of the DCMC is compared with the operation of a conventional DC voltage margin (advanced master–slave) control strategy. The parameters of the MTDC system and components are presented in Tables 1 and 2.

As illustrated in Fig. 6, the core DCMC algorithms, as presented in (11), are implemented in the MTU to facilitate direct current matching as well as power sharing for GVSCs, with a large (representing worst-case) communications latency of 100 ms included for each serial communications channel. A timer as shown in Fig. 6 is used to dispatch DC current/power for GVSCs by reconfiguring the set of sharing factors to demonstrate performance under a variety of scenarios and dispatch conditions.

Table 1
Parameters for the MTDC system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated VSC power, $S_{VSC}$</td>
<td>800 MW</td>
</tr>
<tr>
<td>Nominal DC voltage, $V_{DCO}$</td>
<td>±300 kV (600 kV)</td>
</tr>
<tr>
<td>Nominal 3-ph AC voltage, $V_{ACO}$</td>
<td>400 kV</td>
</tr>
<tr>
<td>DC capacitor, $C_D$</td>
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<tr>
<td>Total capacitor number, N</td>
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<tr>
<td>Switching frequency, $f_{sw}$</td>
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<tr>
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<td>750 MW</td>
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<tr>
<td>Rating of wind farm 3</td>
<td>700 MW</td>
</tr>
</tbody>
</table>

Table 2
Parameters for DC cables [19].

<table>
<thead>
<tr>
<th>DC cable parameters</th>
<th>Resistance $\Omega$ per km</th>
<th>Inductance $H$ per km</th>
<th>Capacitance $F$ per km</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC cables</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>X1</td>
<td>300</td>
<td>3.3e−4</td>
<td>3.1e−7</td>
</tr>
<tr>
<td>X2</td>
<td>300</td>
<td>X5</td>
<td>50</td>
</tr>
<tr>
<td>X3</td>
<td>50</td>
<td>X6</td>
<td>50</td>
</tr>
</tbody>
</table>

Fig. 7. Power dispatch under the proposed DCMC strategy and safety mode.

5.1. Flexibility and security of DC current dispatch

To demonstrate the increased flexibility of power dispatch using DCMC as an alternative approach to DC voltage droop control, four events have been investigated. These events presented below, and the response of the system, are shown at specific times on the results plotted in Fig. 7 and are described in the following text.

Event A. At $t = 0.5$ s, there is a commanded reduction of 10% in the power output of GVSC1:

In this scenario, the DCMC scheme acts such that the GVSC1 sharing factor $K_1$ is changed from 0.45 to 0.35 by the MTU at $t = 0.5$ s. As observed in Fig. 7(c), GVSC1 reduces its DC current from 0.5 pu
to 0.4 pu, and the DC voltage regulating converter GVSC₂ increases its DC current from 0.38 pu to 0.48 pu.

**Event B.** At \( t = 1 \) s, there is a modification of the output power share between GVSC₁ and GVSC₂:

The GVSC₁ sharing factor \( K₁ \) is changed from 0.2 to 0.4, with the sharing factor \( K₂ \) of GVSC₂ also modified from 0.1 to 0.3 simultaneously at \( t = 1 \) s. Therefore, GVSC₁ is controlled by the DCMC scheme to reduce its DC current by 0.2 pu and GVSC₂ is controlled to take this share simultaneously as observed in Fig. 7(c), whereas the DC voltage regulating converter GVSC₂ maintains the same DC current output.

**Event C.** At \( t = 1.5 \) s, a power flow reversal is commanded for GVSC₃:

At \( t = 1.5 \) s, \( K₃ \) is modified to reduce from 0.15 to \(-0.25\) and the direction of power passing through GVSC₃ is reversed. In response to this, there is automatically an increase in the DC currents of GVSC₁ and GVSC₂ through proportionally increasing \( K₁ \) and \( K₂ \); this reduces the risk of overloading GVSC₁ or GVSC₂ as GVSC₁ rapidly reduces its DC current output from the MTDC network and begins to import power to the network, as seen in Fig. 7(c). In contrast, using conventional DC voltage margin control, only the voltage regulating terminal GVSC₂ would respond to the power reversal of GVSC₃.

**Event D.** At \( t = 2.5 \) s, a failure of the communication link with WVSC₂ is experienced.

The signal health monitoring system in the MTU as shown in Fig. 5 detects the loss of the signal containing estimated DC current from WVSC₂ at \( t = 2.5 \) s. Consequently, the MTU instructs both GVSC₁ and GVSC₃ to enter safety mode as depicted in Fig. 4. As observed in Fig. 7(a), GVSC₁ and GVSC₂ are operated at predetermined DC voltage levels of 1.003 pu and 1.002 pu, with GVSC₂ still regulating DC voltage level at 1 pu. The DC current share for GVSCs in Fig. 7(c) is enabled by the conventional DC voltage droop approach. The DC voltage levels for all GVSCs when operating in safety mode must be properly set in advance according to desired "default" mode of operation under loss of communications.

For each of the four events, the DC currents injected by the WVSCs as observed in Fig. 7(b) are not affected by changes in their operating points. Fig. 7(a) presents DC bus voltage levels, with the DC voltage regulating converter GVSC₂ maintaining the voltage at 1 pu (±300 kV). DC voltage levels experience small variations due to momentary power mismatches, this illustrates that any temporary non-zero MTDC network summation of input and output DC currents, as shown in Fig. 7(d), is essentially related to the overall dynamic behavior of the DC system voltage. The algebraic sum of DC current is quickly reduced to zero by the DCMC for each contingency and consequently the amplitude of any DC voltage variations is restricted to less than 0.01 pu.

### 5.2. Reducing DC voltage overshoot/drop

In terms of DC voltage stability under wind power variations (resulting in significant DC power flow changes), the operation of DCMC and voltage margin control (an advanced version of the master–slave control scheme), as referred to in Section 1, are compared in Fig. 8. The voltage margin control schemes operate with GVSC₂ responsible for regulation of DC voltage (i.e. a similar arrangement as adopted with DCMC) but the other converters act as P&Q power regulators. To facilitate comparison, simulation results for the proposed DCMC (solid lines) and conventional control (dashed lines) approaches respectively are presented in Fig. 8, and the test MTDC network is simulated with the same initial conditions for both cases.

**Event A.** At \( t = 0.5 \) s, there is an increase in wind power output through WVSC₂:

Wind farm 1 increases its output power from 320 MW to 640 MW between 0.5 s and 1 s (a somewhat extreme increase, but which has been used to test the operation of the system under extreme circumstances), which results in an increase of WVSC₂’s DC current from 0.4 pu to 0.8 pu as shown in Fig. 8(b). It can be seen in Fig. 8(a) that the overall DC voltage levels under the control of DCMC vary less from the initial values than those under conventional control (indicated by the lines with box marks). This is because the DCMC scheme controls not only GVSC₂; but also GVSC₁ and GVSC₃ are controlled to respond to temporary DC power increases as observed in Fig. 8(c), whereas under conventional voltage margin control, GVSC₂ is solely responsible for managing power.
imbalances. Accordingly, the algebraic sum of DC current mismatch between total input and total output as illustrated in Fig. 8(d) using DCMC are much lower than under conventional control due to a reduction in the “trapped” energy in the DC-side capacitors. Eq. (8) also incorporates this phenomenon.

**Event B.** At \( t = 1.5 \text{s} \), a decrease in wind power supplied through WVSC\(_3\) is experienced:

A wind power decrease from wind farm 2 is simulated between \( t = 1.5 \text{s} \) and \( t = 1.7 \text{s} \), from 560 MW to 240 MW, which results in WVSC\(_2\)’s DC current decreasing from 0.68 pu to 0.28 pu as shown in Fig. 8(b). As before, lower overall DC voltage variations from the initial values for DCMC are obtained, compared to operation under conventional voltage margin control.

Note that the mechanism employed by the DCMC to restrict DC voltage variations is essentially the same as that used by DC voltage droop control: all GVSCs share any temporary power imbalance in the network. However, it is simpler to dispatch power using the DCMC for systems with relatively high numbers of terminals than the droop control which would involve a more complicated operating characteristic design.

**5.3. Operation during major disturbances: (i) AC grid fault; (ii) loss of wind farm**

In terms of fault-ride through capability, the proposed DCMC is tested under AC grid fault conditions (where the fault is correctly cleared) and separately in the event of a wind farm loss. These are executed as follows: at \( t = 0.5 \text{s} \) a solid three-phase fault is applied to the PCC of GVSC\(_1\) for 0.14 s (7 cycles) and cleared at \( t = 0.64 \text{s} \); at \( t = 1.5 \text{s} \), the wind farm connected to WVSC3 is lost and not restored.

**Event A.** At \( t = 0.5 \text{s} \), solid 3-ph fault is applied at GVSC\(_1\)’s grid connection point. The fault clears at \( t = 0.64 \text{s} \).

The DCMC central control triggers the safety mode on detecting the large difference between the assigned reference DC current and the actual inhabited DC current output of GVSC\(_1\) via the SCADA communications. It can be noted from that the DC current output of GVSC\(_1\) decreases to 0 due to the fault as seen in Fig. 8(c). By detecting the event and activating the safety mode as introduced in Section 4.4, the MTU immediately resets \( K_2 \) and \( K_3 \) to 50–50% covering the total power output to support GVSC\(_1\)’s inability to transmit power. The fault on the AC-side of GVSC\(_1\) inevitably causes a significant temporary DC current mismatch in the MTDC network. Therefore, it can be observed in Fig. 8(a) that all terminals’ DC voltage levels experience large transient variations. However the MTDC system, when operating under the DCMC scheme, continuously delivers power to the un-faulted GVSC\(_2\) and GVSC\(_3\) during the fault, and the overall DC voltage restores to steady state immediately after the clearance of GVSC\(_1\) fault.

**Event B.** At \( t = 1.5 \text{s} \), wind farm 3 is removed from the system.

As shown in Fig. 8(b), the total wind power being input to the MTDC network via WVSC\(_3\) is reduced to zero. As the sharing factors for all GVSCs (\( K_1 = 0.3 \), \( K_2 = 0.63 \) and \( K_3 = 0.37 \)) remain the same in the DCMC MTU, all GVSCs briefly decreases their individual output DC currents proportionally as observed in Fig. 8(c). There are small and negligible DC voltage variations and the MTDC voltage under the control of DCMC remains stable.

6. Conclusion

This paper has proposed a communication based direct current matching control (DCMC) strategy for multi-terminal HVDC (MTDC) transmission networks. The proposed DCMC strategy uses a SCADA system aims to estimate the total DC current injection by WVSCs and then matches this to the cumulative output of the GVSCs via a the central control unit. The major advantages, in terms of the operational performance of the DCMC scheme, are summarized below:

Information relating to real-time DC current/power flows is obtained and monitored by the DCMC central control via SCADA communications. The configurable sharing factors provide flexibility in dispatching grid-side VSCs’ DC currents. Previously reported control schemes [11–13,15–17] either do not possess such features or involve complicated operating characteristics to be designed.

The scheme has the ability to implement near-real-time matching of the DC current outputs of GVSCs with those of the WVSCs,
resulting in reduced DC voltage variations, when compared to DC voltage margin/master–slave control schemes [11–13].

It is proposed that the DCMC scheme employing communications, with further demonstration and prototyping, will be suitable as a primary or back-up control scheme for efficient operation of a practical MTDC system, and operates most effectively on systems incorporating several terminal converters. For anticipated future grid code requirements that may stipulate that MTDC systems are able and/or required to provide ancillary services such as frequency response, the dispatch functionality of the proposed DCMC using sharing factors can act as a base to achieve such objective.

References