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Enhanced master/slave control strategy enabling grid support services and offshore wind power dispatch in a multi-terminal VSC HVDC transmission system

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ABSTRACT

New high voltage direct current (HVDC) installations are expected to be able to provide stability support to the main synchronous networks to which they are connected. In multi-terminal HVDC (MTDC) schemes incorporating offshore wind farm this issue could be addressed by setting aside a reserve of wind energy by the curtailment of wind turbine generators (WTGs).

This paper proposes a communication-less dc voltage cooperative control strategy for MTDC transmission systems. A grid side converter, the master, and a wind farm are designed to work cooperatively to maintain a stable dc link voltage, facilitating normal power dispatch orders and the provision of frequency support. The proposed control maintains a wind energy reserve and uses a flexible dc link voltage at the master converter. Allowing the local master dc voltage to vary within certain limits encourages the wind farm to participate in dc link voltage control and hence no communication system is required. The master converter automatically assumes control of the dc link voltage in the absence of wind or when the wind reserve is used up.

A four terminal MTDC system comprising one master converter, two active/reactive power converters and one wind farm is studied. The effectiveness of the proposed control strategy is validated through simulation using MATLAB®-SIMULINK®.

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1. Introduction

High Voltage Direct Current (HVDC) connections have been in operation since the 1950s. The vast majority of these are point to point connections and use Line Commutated Converter (LCC) technology. Since the late nineties Voltage Source Converter (VSC) technology has become a feasible choice for HVDC transmission systems [1]. Research is now focused on the development of multi-terminal-HVDC (MTDC) system which will collect energy from distant dispersed renewable energy resources and transport this energy to load centres. Although some multi-terminal systems currently exist, they are rare, with two of them using LCC technology (SACO and Quebec – New England Transmission) and two of them (Nanao and Zhoushan), recently commissioned, using VSC technology.

In point-to-point VSC HVDC connections, typically, one conv-

erter station controls the dc link voltage and the other is modulating the active power. Additionally the two converters can control separately the reactive powers at both ends. In MTDC systems the control of the dc voltage is still a focus of research [2–5]. Existing VSC MTDC systems adopt an extension of the point-to-point scheme, having just one converter dealing with the DC voltage control [6] while the other converters in the system operate either in fast active/reactive (PQ) mode or in grid forming mode. The PQ converters control the active and reactive power flows to the grid and the grid forming converters control the voltage magnitude and frequency at an ac busbar. The configuration for a MTDC scheme with only one converter controlling the dc voltage is sometimes associated with the so-called voltage margin method proposed in Ref. [7] which selects a new dc voltage controller when the original reaches its limit of power range and so of regulation.

A notable different method for dc voltage control in MTDC systems is proposed in Ref. [8], the so-called droop control approach. It is an extension of the power frequency droop characteristics adopted for synchronous generators. The main drawback of this control logic is the loss of the exact command of the MTDC

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power flow if a constant droop coefficient is adopted. To change the droop coefficient to match the power needs of the main synchronous network, fast communication between converters is required.

One of the main drivers for the development of several MTDC grids worldwide is the collection of power from dispersed offshore wind farms. In this regard [9] presents different MTDC projects to be implemented in Europe. Several papers such as [8,10,11] apply droop characteristics to dispatch the entire wind energy, produced by the dc connected wind farms, to the grid side converters, according to the droop coefficient adopted.

The recent rapid growth of variable renewable energy resources in the transmission system is driving the introduction of stricter network regulations. In particular [12] states that future HVDC connections in Europe must be able to support the stability of the main synchronous network to which they are connected. Under these new regulations future HVDC converter stations connected to the synchronous grid will be expected to provide the relevant Transmission System Operator (TSO) with a control mode capable of supporting network stability. This will apply whether wind farms are present or not on the MTDC system. This means that each of the grid side converters must be provided with an independent control mode to modulate active and reactive power output to assist in maintaining stable system frequency and voltage.

The requirement for each grid connected converter to be able to provide ancillary services and to dispatch wind energy in a MTDC system containing wind farms can be met by regulating the wind power output. In Refs. [13,14] it has been shown that wind turbine generators (WTGs) are able to increase production above the available wind power by extracting kinetic energy from the rotor. This rotational energy is only available for a short period and a following phase of energy shortage to re-accelerate the rotor is unavoidable. As a result [15,16] state that only WTGs operating in a reduced or curtailed power mode are able to participate effectively in the grid primary frequency regulation. Additionally in Ref. [17] it has been demonstrated that in the short to medium term curtailment can become an optimal economical solution. Different wind power regulation methods have already been adopted by system operators for WTGs connected directly to the ac grid. A comprehensive review is presented in Ref. [18]. All of these methods envisage a difference between the available aerodynamic power and the delivered electrical power when the frequency moves from the optimal.

In this context this paper develops a dc voltage cooperative control scheme between a grid side converter, called the master, and a dc connected curtailed wind farm. The dc network voltage is allowed to fluctuate in between specific limits under the supervision of the master converter. Within this dc voltage range the master converter operates in a slow PQ control mode as a result of the cascaded PI structure used for the master controller. The standard control scheme used on all the other grid side converters allows them to be operated in fast PQ mode, i.e. able to deliver frequency and voltage regulation. An energy reserve, in the form of curtailed WTGs on the wind farm, allows the wind farm to participate in the stabilization of the network dc voltage. The wind farm control scheme responds to the dc link voltage fluctuations hence no fast communication system is needed.

The remaining sections of the paper are organized as follows: Section 2 describes the topology and control method employed for the wind farm, master and PQ converters. Section 3 provides the simulation results for two operating scenarios: Case I, considers normal operation where a wind power reserve is maintained on the wind farm and the energy is dispatched by the grid side converters according to market requirements and, Case II, considers an emergency situation where the wind energy reserve is deployed for

meeting frequency support requests. The analysis of the simulation results and conclusion are presented in the last Section 4.

2. MTDC system description

A four terminal MTDC system is considered consisting of one dc connected offshore wind farm and three converters connected to the grid. The three grid side converters consist of two standard PQ converters and one master converter station. Fig. 1 shows the model of MTDC system, symmetrical monopole connection at ± 200 kV with three-level converters are used. Converter dc side equivalent capacitance is sized at 2 mF and cable connections are modelled as distributed parameter transmission lines, distances and cable details are given in Fig. 1.

HVDC PQ converter stations are usually controlled with a standard voltage oriented control technique [19], capable of fast power ramp in the order of 1 GW/s. Here current references I_d^* and I_q^* for both the PQ converters are directly linked to the reference values of active and reactive power P_g^* and Q_g^* specified by the relevant TSO, refer to Fig. 2 for details. The d - and q -axis current PI regulators are usually called inner current controllers and they show very fast response.

2.1. Wind farm

An offshore wind farm connected through an HVDC connection to the main network is an ac offshore grid driven by its converter station in grid-forming mode control, i.e. controlling voltage magnitude and frequency as an ideal voltage source. The wind farm model is composed of ninety six WTGs rated at 3.3MVA each at the base wind speed of 9.4 m/s, giving a total rated generated wind power of 288 MW. Squirrel cage induction generators (SCIG) in fixed speed wind turbine configuration were chosen for simplicity, in fact the base wind speed corresponds to an average value of the real wind speed measurement used in the next simulations. Table 1 gives the individual WTG details.

The wind turbine coupled to each SCIG is as per the standard described in Ref. [20]. The mechanical torque T_m driving the

Fig. 1. Four terminals used on the present simulation.

Fig. 4. Power curve as a function of the rotational speed, (a) in relation to wind speed with $\beta = 0$ and (b) in relation to pitch variations at 9.4 m/s wind speed.

station, needs to be communicated to each WTG through a local offshore communication system. This kind of local communication network is easily obtainable using commercially available composite offshore ac cables with optical fibre. Another advantage of an offshore local network is the collection of WTG on-line data to allow the manufacturer to remotely check the turbine status in order to avoid malfunctioning.

As visible in Fig. 3 the dynamics of the pitch actuator is limited by a maximum rate of change, set for the next simulation at $\pm 7^\circ/\text{s}$.

2.2. Enhanced master control system design

The proposed master converter control strategy allows control of the active power output P_g^m by deviating the local dc link voltage reference V_{dc}^{m*} . The control logic adopted derives from the standard dc voltage/reactive power control as shown in Refs. [25,26]. In order to achieve active power control, an additional outer loop, hereafter called the power loop, is added as shown in Fig. 5 and given by:

$$V_{dc}^{m*} = \tilde{V}_{dc} + k_{p,P} (P_g^m - P_g^{m*}) + k_{i,P} \int (P_g^m - P_g^{m*}) dt, \quad (5)$$

where P_g^m is the power dispatched at the master converter terminal (generator convention), P_g^{m*} is the reference value as requested by the relevant TSO and the feedforward rated dc voltage $\tilde{V}_{dc}$ ensures the local dc voltage V_{dc}^m deviates around $\tilde{V}_{dc}$.

Active power output and dc voltage control are two conflicting objectives and indeed the power loop is needed to shift the local dc voltage up and down from the rated $\tilde{V}_{dc} = 400$ kV, to indirectly communicate to the WTGs to inject more or less power. The dc voltage deviation at the master converter is set at $\tilde{V}_{dc} \pm 5\%$. This value was chosen by assuming that the other MTDC converters connected to the system would not be disturbed by a corresponding deviation of their modulation indices. Similarly, the commonly allowed ac voltage variation at the transmission level, where HVDC installation would normally be connected, is at least $\pm 5\%$.

The dc voltage limitation locally on the master converter

terminal ensures that a given power reference P_g^{m*} from the TSO is only allowed if the local dc voltage V_{dc}^m is within the range. An anti-windup on the power loop ensures a prompt recovery of the PQ operability of the master converter once the available and the delivered powers match each other. Considering the above

Fig. 5. Master converter control, the anti-windup PI (AWPI) controller is bounded at $\tilde{V}_{dc} \pm 5\%$.

description a three zone operation range results for the master converter as follows:

- **Zone I:** $380 \text{ kV} < V_{dc}^m < 420 \text{ kV}$, master in PQ mode
When the local dc voltage at the master terminal is within zone I a percentage of the available wind energy is curtailed by pitch angle control with the bulk of the wind energy being dispatched at the master and PQ terminals, in accordance with market requirements. In this zone the master converter controls the power output analogously, but slower, to a PQ converter, dispatching a defined amount of active and reactive power set by the TSO. The local dc voltage at the master converter terminal V_{dc}^m finds an equilibrium within the chosen range of $\tilde{V}_{dc} \pm 5\%$ because the integral part $k_{i,\beta}$ of the pitch angle β controller nullifies the error $V_{dc}^{wf} - \tilde{V}_{dc}$. In this way it is the wind farm which controls the dc voltage although the master converter ensures the voltage does not exceed a specific range. As a result in zone I the grid side converters are capable of providing a pre-defined amount of reserve in the form of an ancillary service. However the slew rate for the grid side converter power injections depend upon the converter topology and the control logic adopted, the wind farm and the reserve dimensions, and finally the WTG slew power rate capability.
- **Zone II:** $V_{dc}^m = 380 \text{ kV}$ lower threshold, deficit in wind power reserve
When the local master converter dc voltage V_{dc}^m reaches the lower threshold $\tilde{V}_{dc} - 5\% = 380 \text{ kV}$ the master converter assumes full control of the dc voltage and maintains it at 380 kV. At this point the wind farm is dispatching the maximum available power because the reference for the pitch angle β would be driven to 0° by its PI controller as given in Eq. (4). In this zone the master converter does not fulfil the active power delivery request, because the available power is not enough. Depending on the overall capacitance of the dc network and on the prompt response of the WTGs, an ac frequency regulation intervention could lead the dc voltage reaching the lower threshold forcing the master terminal to partially take on the frequency regulation burden. However only the continuity of V_{dc}^m at the lower threshold signals that either an abnormal forecast error of the wind energy has occurred or there is a total absence of wind power reserve because of low wind speed.
- **Zone III:** $V_{dc}^m = 420 \text{ kV}$, upper limit zone
Similar to zone II when the local master dc voltage V_{dc}^m reaches the upper threshold $\tilde{V}_{dc} + 5\% = 420 \text{ kV}$ the power loop on the master converter is bypassed and the master converter maintains the dc voltage at the upper limit of 420 kV. To reach the upper threshold implies one or more of the grid side converters are exceeding the down-regulation of the power output. Contrary to the zone II, upon reaching the upper bound the master converter is forced to deliver more power than its reference P_g^{m*} . However only the continuity of V_{dc}^m at the upper level would lead to the complete shut down of the wind farm because of the pitch regulator continuous integration. This possibility can be easily avoided setting a maximum pitch angle β_{max} corresponding to a minimum wind farm power output P_{min}^{wf} . In fact a wind farm start up could take a considerable time. To conclude applying the energy exchange close to real time rules, as recently introduced in intra-day markets, would likely avoid the operation in Zone III. As a result the simulation section of this paper will not consider operation in this zone.

The adopted master control technique uses two outer loops in cascade on the current d -axis. An outer controller must be tuned with a relative response time (RRT) slower than the inner controller to avoid interaction [27]. As a result the PQ converter, with only

inner controllers, can dispatch power at a faster rate than the master converter both in case of frequency regulation and in case of power re-distribution between the terminals. In the next simulation different power ramps are then adopted for the reference values of the active power dispatched by the grid side converters.

A summary of the operability of the proposed MTDC is provided in Table 2.

3. Simulation

Two different scenarios are presented starting from an equilibrium setpoint with a wind power reserve of about 100 MW ($\beta \approx 8^\circ$) and 150 MW ($\beta \approx 11^\circ$), as shown in Figs. 6 and 7a-(iii), respectively. As mentioned, the maximum rate of change of pitch is adopted conservatively to $\pm 7^\circ/\text{s}$. The wind speed data shown in Figs. 6 and 7a-(iv) is taken from real measurement recorded at a DIT wind speed measurement station at a sampling rate of 10 Hz.

The simulations include both normal market-based operations, as shown in Fig. 6, and sudden (not previously agreed) frequency regulation operations, as shown in Fig. 7. Normal market-based procedures consist of power flow redistribution between the HVDC converter stations connected to different points of the main grid. On the other hand frequency regulation operations are in this case addressing ac grid frequency rapid changes referred in the form of grid side converter active power output rapid changes. Power ramp orders of $\pm 1200 \text{ MW/s}$ are used in the simulations when the PQ converters change their power output, either for power redistribution or for frequency response. Differently, when the master converter is involved in power variations a different power ramp of $\pm 300 \text{ MW/s}$ is used because of the cascaded PI structure of the master d -axis controller.

Section 3.1 comments on the simulation results for normal power redistribution operations in which the produced power by the wind farm is dispatched according to market rules by the three grid side converters. This scenario is provided to show that the presented MTDC system is able to fulfil all the market-based requests, i.e. to sell offshore wind energy and to transmit power to/from dispersed network points.

Section 3.2 shows a series of unpredicted active power requests for frequency support by both PQ converters and hence a ramp rate of $\pm 1200 \text{ MW/s}$ is used. The initial reserve of power within the wind farm is exhausted during this simulation, so the master converter loses the active power control reaching the lower dc voltage threshold. This second scenario shows that the stability of the MTDC dc voltage is maintained even under severe demands of frequency up-regulation.

The operation of the multi-terminal VSC-HVDC transmission system is tested through simulations in MATLAB®-SIMULINK® using SimPowerSystems™ library.

3.1. Case I, normal operation

In normal operation the local dc voltage at the master converter

Table 2

Summary of operability conditions of the master converter and the wind farm with reference to zones described in Sec. 2. Details in text.

	V_{dc}^m in Zone		
	I	II	III
dc voltage control	wind farm	master	master
master P control	Yes	No	No
V_{dc}^{m*}	Eq. (5)	$\tilde{V}_{dc} - 5\%$	$\tilde{V}_{dc} + 5\%$
pitch angle β	Eq. (4)	0	max

(a) Wind farm quantities during normal operation scenario. (i) ac RMS p-p voltage on wind farm offshore grid (ii) torque of one machine (iii) pitch angle β and (iv) wind speed

(b) dc link and grid sides quantities. (i) local dc voltage at master converter V_{dc}^m (ii) injected active power by wind farm (iii) active power dispatched by grid sides (iv) reactive power dispatched by grid sides

Fig. 6. Normal operation scenario showing power redistribution between two PQ converters at 10s and master-PQ2 at 20s.

(a) Wind farm quantities during reserve usage scenario. (i) ac RMS p-p voltage on wind farm offshore grid (ii) torque of one machine (iii) pitch angle β and (iv) wind speed

(b) dc link and grid sides quantities. (i) local dc voltage at master converter V_{dc}^m (ii) injected active power by wind farm (iii) active power dispatched by grid sides (iv) reactive power dispatched by grid sides

Fig. 7. Reserve usage scenario showing a complete depletion ($\beta = 0$) between 30s and 60s. The increase of the power output by PQ1 converter at 40s makes the dc voltage to drop at the lower threshold and the master to lose the active power control.

terminal V_{dc}^m remains within Zone I as described in Section 2.2. As explained above a spinning reserve of about 100MW ($\beta \approx 8^\circ$) is maintained comprehensively on all the WTGs. The operations in this simulation scenario have to be thought as market-based so the wind reserve is used only to adjust power mismatches due mainly to wind speed variations and different power losses on the connections. The simulation commences with the master converter dispatching 50 MW, converter PQ1 dispatching -50 MW and converter PQ2 dispatching 150 MW.

Fig. 6 shows the complete results of Case I simulation with wind farm quantities in Fig. 6a and dc voltage and grid power flows in Fig. 6b. Fig. 6a-(i) shows the offshore ac grid voltage V_g^{wf} controlled at 220 kV whereas Fig. 6a-(ii) shows the electromagnetic torque of one machine. Pitch angle β and wind speed complete Fig. 6a. Fig. 6b-(i) displays the local dc voltage at the master converter V_{dc}^m and Fig. 6b-(ii) shows the dispatched power by the wind farm P^{wf} . Fig. 6b-(iii) shows the active power delivered by the three grid side converters with the two power redistribution operations. At 10s a 350 MW power exchange between the two PQ converters at a ramp rate of ± 1200 MW/s occurs. As expected the dc voltage does not show any relevant fluctuations and also the pitch angle β remains steady. At 20s a new power exchange of 100 MW between the master and a PQ converter occurs. This time the ramp rate is ± 300 MW/s being involved the master converter. There is a minor dc voltage deviation, visible at the instance of this second power exchange. This is needed to allow the active power to change according to Eq. (5). Consequently the wind turbine pitch angle β deviates smoothly to follow the dc voltage until a new equilibrium is reached. The difference between the initial and the final steady state pitch angles responds to different losses occurring on the dc connections and different wind speed. Finally Fig. 6b-(iv) shows the reactive powers delivered by each of the grid side converters. The three reference values are fixed at zero to provide unity power factor operation.

3.2. Case II, shortage of reserve

Case II shows how the developed dc voltage cooperative control technique responds in the case of sudden requests of active power totalling a magnitude larger than the wind power reserve. As a result this scenario simulates the total consumption of the wind power reserve in response to unexpected frequency regulation requests. Two successive power injections of 50 MW occurring at 10s intervals for each of the PQ converters are considered in this simulation.

As mentioned above the initial wind power reserve of about 150 MW ($\beta \approx 11^\circ$) is obtained by curtailing the WTGs output through pitch angle regulation. A series of four successive active power increments by the PQ converters are occurring between 10s and 40s, see Fig. 7b-(iii), those are at a ramp rate of ± 1200 MW/s. As visible in Fig. 7a-(iii) the pitch angle β decreases at every power increment following the local dc voltage V_{dc}^{wf} at the wind farm terminal. In the time range between 30s and 40s the power reserve is almost completely used up so at the fourth power increment at 40s the dc voltage starts to decrease linearly reaching the lower threshold. Once the dc voltage reaches the lower bound the master converter bypasses automatically the power loop showing a drop on its power output in order to keep the dc voltage constant at 380 kV (zone II). Only the power step to decrease the injected power of converter PQ2 at 50s triggers the master converter to return to Zone I, i.e. the available power is enough to recharge the dc connections. Subsequent power steps in converters PQ1 and PQ2 show the response of the wind turbine pitch angle control as PQ1

and PQ2 return to their starting points.

Throughout this second simulation the active power reference of the master converter P_g^{m*} is fixed at 150 MW and indeed the actual measured power P_g^m deviates from the reference only between 40s and 50s when the dc voltage V_{dc}^m is locked at the lower threshold. As mentioned above this second scenario is not concerned with market based power redistribution but with regulation operations. Hence the final stage of simulation over 80s resumes the initial power flow in all the three grid side converters even if the wind speed is slightly lower.

4. Conclusion

A novel technique for dc voltage regulation on a MTDC transmission system consisting of a master converter, two PQ converters and a wind farm that does not require any communication link has been demonstrated. An outer power loop on the master converter controller and a pitch blade controller have been developed to cooperatively use a reserve of wind power to maintain a stable dc link voltage. The control system proposed allows the wind energy to be dispatched at the grid side converters under normal market rules and also facilities ac grid support services. The master converter, because of its cascaded controller design, operates at a slightly slower ramping rate than a standard PQ converter. However the design of a master converter controller ensures the stability of the MTDC system dc voltage even when the wind power reserve is used up, or indeed when no wind energy is available.

In future implementations of MTDC networks collecting renewable energy, in competitive energy markets, it is very likely that the grid connection points will be expected to provide an array of grid support services. The overall control scheme should be flexible, in the sense of being able to cope with sudden changes in demand without spreading the burden to other grid connection points. However the infrastructure itself cannot rely on a fast communication system. As a result the participation of the renewable energy sources in providing ancillary services to the grid point connections looks unavoidable. In this regard a recent European Wind Energy Association (EWEA) position paper [28] on priority dispatch for wind energy suggests that this will not be needed in mature markets. In fact it is anticipated that voluntary curtailment must be understood as an ancillary service in terms of providing downward reserve capacity or balancing energy, that will enable the system operators to define appropriate rules and share cost calculation.

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