Control of Multi-Terminal VSC-HVDC for Wind Power Integration Using the Voltage-Margin Method

Christian Ismunandar, Arjen A. van der Meer, Madeleine Gibescu, Ralph L. Hendriks, Wil L. Kling

Abstract-- **In Northern Europe, the development of wind power is foreseen to continue in the future with erecting a number of large-scale wind power plants (WPPs) on the North Sea and the Baltic Sea. In order to efficiently integrate offshore WPPs into onshore power systems, implementation of multi-terminal high-voltage direct-current transmission based on voltage sourced converters is considered a promising solution. These multi-terminal networks must be able to manage various dispatch schemes and market mechanisms, as well as the variability of wind power.**

In this paper, a control strategy based on the voltage-margin method is proposed to evacuate the WPP's power as well as to correctly dispatch the power traded between the adjacent onshore power systems. The control strategy is implemented on a test network and its capability is explored through simulation studies. The model and simulation studies are developed in the SimPowerSystems toolbox of MATLAB / Simulink.

Index Terms-- **multi-terminal VSC-HVdc, offshore wind, voltage-margin method, transnational offshore grids**

I. INTRODUCTION

THE growing interest in large-scale offshore wind power plants (WPP) may require strategic rethinking how they are connected to the mainland power systems. Future WPPs may be larger in size and situated further from the shore than projects currently realized and, hence, the costs for grid connection may become a critical factor for these projects. A possibility to reduce the per-MW transmission costs is to increase the utilization ratio of the offshore transmission equipment, being the actual full-load hours to the maximum full-load hours. For the dedicated grid connection of offshore WPPs the utilization ratio is relatively low when compared to onshore transmission lines. The utilization ratio can be increased by sharing a single offshore grid infrastructure for multiple WPP and/or other offshore renewable energy sources and offshore loads. In such a scheme the transmission capacity not used for renewable energy can be used for power transfers between interconnected power systems. This leads to the development of multi-terminal topologies that may gradually develop into transnational offshore networks [1].

The operation of such a network will require a degree of controllability that cannot be achieved with conventional ac transmission. A promising choice is high-voltage dc transmission based on voltage sourced converter technology (VSC-HVdc). The technical realization of such multi-terminal networks must be capable to support any required dispatching scheme, resulting from market transactions or regulatory incentives, and at the same time deal with wind power variability. Generalized VSC-HVdc control schemes are therefore required, which are preferably universally applicable and independent of network topology.

This paper explores the capabilities of the voltage-margin method (VMM) to dispatch the available wind power in addition to pre-scheduled power flows among multiple VSC-HVdc terminals. The particular benefit of this method is its robustness: by applying a voltage margin between the onshore terminals, control hunting is prevented. Moreover, single VSC-terminal failures only insignificantly affect the operation and control of the entire system, and the VMM does not rely on communication links between the VSC-HVdc terminals. In this research dynamic simulations are applied to study the performance of different implementations of the VMM and to show the load-sharing capabilities in the time domain. Examples are shown for a small test network.

The paper is organized as follows. First, the applied test network and VSC model are described. Next, the VMM is introduced and it is described how it can be used to implement different dispatching methods. The next section shows simulation results for different dispatching schemes, illustrating the applicability of the VMM. The paper ends with conclusions and recommendations.

II. NETWORK AND MODEL DESCRIPTION

A. Test network

To illustrate the proposed control strategies, a small test network has been used (Fig. 1). It represents a situation of two independent onshore grids, which are coupled through a VSC-HVdc link. Along the link two offshore WPPs are

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connected. The onshore VSC terminals (GSVSC1, GSVSC2) and the offshore VSC terminals (WPPVSC1, WPPVSC2) are all rated 440 MW. The WPPs consist of 200 wind turbine generators (WTG) of 2.2-MW rating, which are represented by an aggregated equivalent. A generalized model of a variable speed WTG has been used [2], providing a quasi steady-state representation of the conversion of mechanical to electrical energy, including basic rotational dynamics [3]. The WPP collection network and main transformers are modeled as a series reactance. The dc submarine cables are modeled by their π-equivalent circuit. This simple modeling allows the study of dynamic phenomena with relatively low frequencies (≤ 10 Hz), which are the most pronounced in power balancing problems.

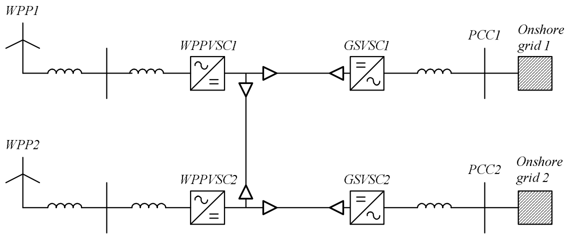


Fig. 1. Test network

B. VSC dynamic model

Fig. 2 shows the VSC model used for the dynamic simulations. As the frequency range of the phenomena of interest for this study is low compared to the typical switching frequency, an averaged model has been applied. It is assumed that the VSC can generate any desired voltage waveform instantly, based on the reference provided by the control system. Thus, the ac side of the converter can be represented by a fundamental frequency controlled three-phase ac voltage source in which the voltage reference value is dictated by the control scheme [4]. Furthermore, on the assumption that the converter is lossless, the active power exchanged at the ac side is equal to the power on the dc side. This enables the dc side of the converter to be represented by a controlled current source, i.e.

$$i_{dc} = \frac{P}{u_{dc}} \tag{1}$$

in which i_{dc} is the direct current exchanged at the dc side of the converter, P is the three-phase active power delivered from the ac network to the converter and u_{dc} is the direct voltage across the dc capacitors.

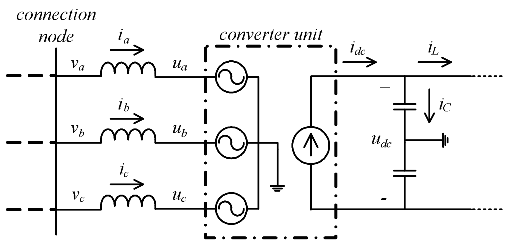


Fig. 2. Averaged VSC-terminal model

C. GSVSC control scheme

The GSVSC controller has the objectives to regulate the active and reactive power exchange with the onshore grid as well as to regulate the direct voltage in the offshore network. In order to achieve a decoupled control of active and reactive power, vector control is applied [5]. The control scheme of the GSVSC therefore consists of a phase-locked loop (PLL), an inner current controller, a current limiter, and two outer controllers. They control the direct voltage and the ac-side voltage (Fig. 3).

The direct-voltage controller has the objective to maintain the direct voltage at its reference by regulating the active current (d-axis) reference i_d*. The direct-voltage controller implemented in this paper will be described in more detail in section III.

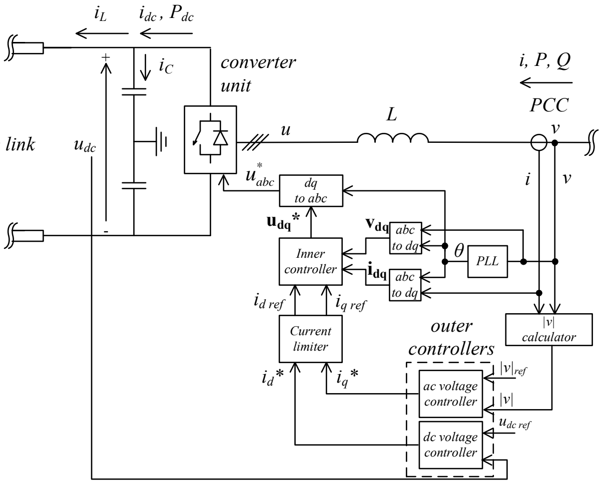


Fig. 3. GSVSC control scheme

The objective of the ac-side voltage controller is to maintain the amplitude of the point of common coupling (PCC) voltage equal to a given reference value by regulating the q-axis current-reference i_q^* according to

$$i_q^* = K_{p,v}(|v|_{ref} - |v|) + \int K_{i,v}(|v|_{ref} - |v|)\,dt + i_{q,0}^* \tag{2}$$

where $K_{p,v}$ and $K_{i,v}$ are the proportional and the integral controller constants, $|v|_{ref}$ is the reference value for the amplitude of the PCC voltage, $|v|$ is the actual amplitude of the PCC voltage and $i_{q,0}^*$ is the initial q-axis current-reference.

To avoid excessive current flowing through the converter valves the magnitude of the current reference is limited by the current limiter. The magnitude of the current-reference is expressed as

$$|i| = \sqrt{i_d^{*2} + i_q^{*2}} \tag{3}$$

The limiting strategy which is applied in this paper gives priority to i_d^* (Fig. 4), because the onshore systems are modeled as infinitely strong grids. For weaker grids, reactive-current priority may improve the dynamic behavior [6].

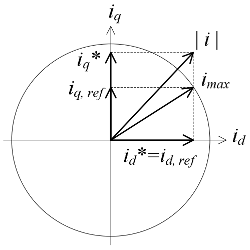


Fig. 4. Current limiting strategy

The inner current controller has the objective to track the current-reference values generated by the outer controllers, to produce the converter voltage reference values (u_d^* and u_q^*). In this way, the VSC acts as a current-controlled voltage source.

D. WPPVSC control scheme

Although it is an effective control strategy for connection to onshore (strong) power systems, vector control cannot be applied offshore as the WPPVSC must provide a voltage reference for the connected WTGs. Therefore, the WPPVSCs require a different control approach, see Fig. 5. It consists of an oscillator to provide the grid frequency and an ac-voltage controller to keep v at a reference value. This direct control method enables the WPPVSC to absorb all power generated by the WTGs.

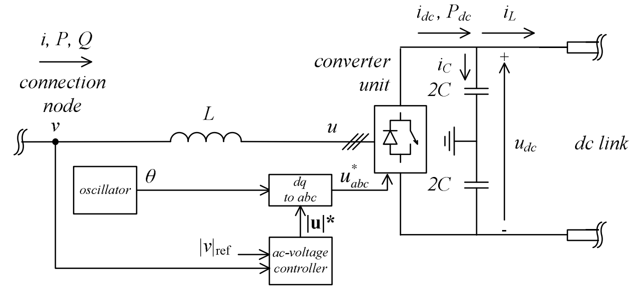


Fig. 5. WPPVSC control scheme

III. VOLTAGE-MARGIN METHOD

The concept of the VMM has been proposed earlier in [7, 8, 9]. In [7], the VMM was introduced and simulated for point-to-point medium-voltage dc VSCs. It was also explained to what extent the method could also be useful for multi-terminal connections. The benefits of this concept have been underlined by actual field tests in [8]. More recently, the VMM has been introduced for offshore multi-terminal VSC-HVdc, where it was used in an offshore dc network consisting of one oil platform and two WPPs, which were connected through a radial submarine cable to the mainland system [9].

In this paper, the concept is further developed towards a general control strategy for VSC-HVdc networks which may contain multiple onshore connection points as well as offshore WPPs, as would be the case for transnational offshore networks. The fact that these networks may span multiple countries, each with its own requirement for a dispatching scheme, necessitates to examine how schemes can be realized through by VSC control systems.

A. Operation principle

The basic control scheme of the VMM is composed of a direct-voltage controller and a dynamically adjustable limiter as shown in Fig. 6. As the VMM is based on vector control, it can only be applied to converters connected to strong ac grids, in this case to both GSVSCs.

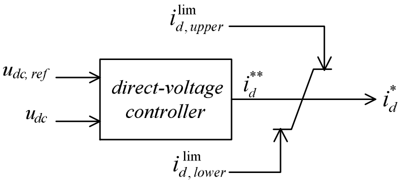


Fig. 6. VMM: active-current controller consisting of a direct-voltage controller and an adjustable limiter

The direct-voltage controller maintains the direct voltage equal to a provided reference value by regulating the d-axis current reference according to

$$i_d^{**} = K_{p,udc}(u_{dc,ref} - u_{dc}) + \int K_{i,udc}(u_{dc,ref} - u_{dc})\,dt + i_{d,0}^{**} \qquad (4)$$

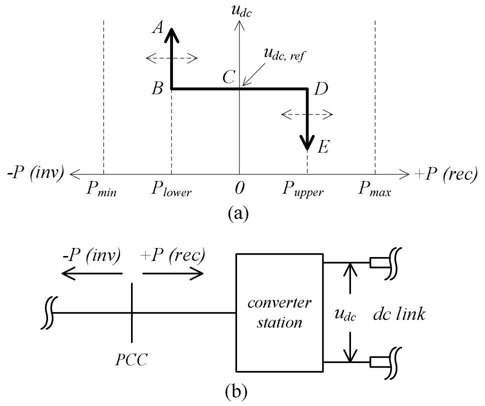
where i_d^{**} is the unconstrained d-axis current reference, $K_{p,udc}$ and $K_{i,udc}$ are the proportional and the integral controller constants, $u_{dc,ref}$ is the direct-voltage reference, u_{dc} is the actual direct voltage, and $i_{d,0}^{**}$ is the initial value of the active current reference.

The limiter acts on the output of the direct voltage controller and limits i_d* to an upper and a lower value in order to bound the power flow through the converter to an upper and a lower value. The upper and the lower value of the limiter are dynamically adjustable and may be set locally or be sent from a supervisory dispatch controller. These limits are related to the power output limits by

$$\begin{cases} i_{d,upper}^{lim} = \dfrac{P_{upper}}{v_d} \\ i_{d,lower}^{lim} = \dfrac{P_{lower}}{v_d} \end{cases} \qquad (5)$$

where $i_{d,upper}^{lim}$ is the upper limit and $i_{d,lower}^{lim}$ is the lower limit of the i_d^*, v_d is the d-axis voltage at the PCC, and P_{upper} and P_{lower} are the upper and the lower limit of the active power drawn from the ac system. It is assumed that these active-power limits are provided as an input to the VSC controller and that subsequently the corresponding current limits are calculated according to (5).

For normal operating modes, the scheme of Fig. 6 results in the u_{dc}–P characteristic as shown by the *A–B–C–D–E* line of Fig. 7a. As long as the control error can be maintained zero, the converter operates on the *B–C–D* line and the direct voltage is kept at the reference. The converter is inverting when it operates on the *B–C* line and is rectifying when it operates on the *C–D* line. However, if the active-current controller hits one of the limits, the direct voltage cannot be controlled any longer by this VSC terminal. When the active-current controller hits the lower limit (point B) the VSC cannot maintain the direct voltage and, while the power is maintained constant, the direct voltage may rise along the *B–A* line. Similarly, when the upper limit (point D) is reached the rectified power is maintained constant and the direct voltage may drop along the *D*–*E* line.



(a)

(b)

Fig. 7. Converter operation characteristic: (a) u_{dc}–P characteristic (b) power direction reference

For multi-terminal operation, the scheme given in Fig. 6 is implemented into the active-current controller of two or more converters. In addition, the direct-voltage reference values are set differently from each other by a particular voltage margin. This enables the possibility for other converters to control the direct voltage after one converter has reached one of its limits. As a matter of fact, the VSC terminals can be set in such a way that all but one converter operate in their power limit region while the only remaining VSC terminal actually controls the direct voltage, which prevents control hunting.

By adjusting the upper and lower power limits of each converter to the required values, the converters can be set to implement different power dispatching schemes. An example of the u_{dc}–P characteristics of two converters operating with a voltage margin are given in Fig. 8.

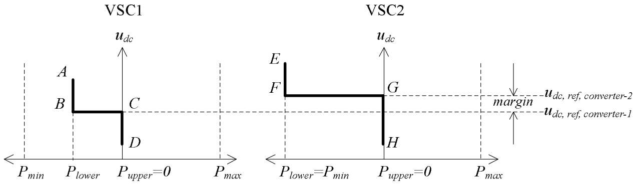


Fig. 8. u_{dc}–P characteristics of two VSC terminals in multi-terminal operation

It can be seen that the direct-voltage reference value of the two converters are displaced by a particular margin. When the actual direct voltage is at *C*, VSC1 will control the direct voltage in the network and will perform inversion operation on the *B*–*C* line. However, when VSC1 reaches its lower power limit at point *B*, it is no longer able to control the direct voltage and thus the direct voltage will rise following the *B*–*A* line. When the direct voltage at VSC2 reaches point *G*, it starts to control the direct voltage along the *F*–*G* line, while delivering power to the ac system. This will also occur when VSC1 is suddenly disconnected.

It should be noted that always one VSC must control the direct voltage in a multi-terminal network to compensate for the power imbalance and losses in the network. Besides, during the period when the direct voltage controlling duty is transferred form one converter to the other, a small voltage rise or drop will occur due to the voltage margin, depending on the direction of power flow. Moreover, the voltage margin is to be chosen larger than the expected voltage drop between the VSC terminals, which is an important boundary condition.

1) *Two-stage direct voltage controller*

Fig. 8 shows that VSC2 will perform direct voltage control when VSC1 reaches its limit or trips. However, in the case VSC1 has reached its limit and VSC2 is suddenly disconnected, there will be no converter controlling the direct voltage unless the lower limit of VSC1 (*B*–*A* line) is adjusted further to the left of the u_{dc}–P characteristic, which is unlikely to happen fast enough when performed through a centralized supervisory controller (e.g. due to communication delays). As a result, the direct voltage may rise uncontrollably causing the whole dc network to trip. This can be resolved by equipping both VSCs with a two-stage active-current controller as shown in Fig. 9.

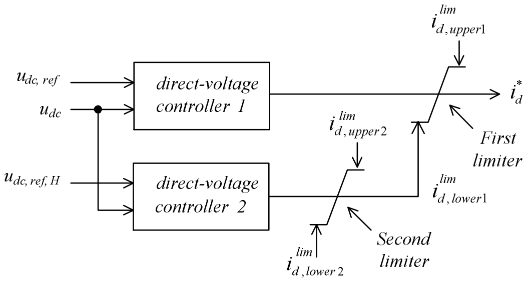
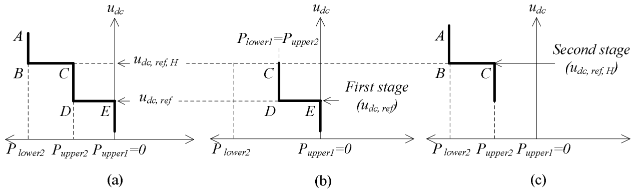


Fig. 9. Two-stage active-current controller



(a)

(b)

(c)

Fig. 10. u_{dc}–P characteristic of the two-stage active-current controller: (a) u_{dc}–P characteristic (b) first stage operation (c) second stage operation

It consists of two (identical) direct-voltage controllers, each with a separate direct-voltage reference value. During normal operation, the first controller maintains the direct voltage equal to its reference value and performs operation in the first stage (the *D*–*E* line in Fig. 10b). When the limit P_{lower1} is hit, the direct voltage rises above the reference value of the second controller ($u_{dc,ref,H}$). This controller will subsequently adjust the lower value of the first limiter to the left side of the u_{dc}–P characteristic. In this way i_d^* is controlled by direct-voltage controller 2, and the VSC operates on line *B*–*C* (Fig. 10c).

An example of the u_{dc}–P characteristics of two converters using the two-stage active-current controller is depicted in Fig. 11. The upper and the lower value of the second limiter in VSC1 are set differently while the upper and the lower value of the second limiter in VSC2 are set equal. In case VSC1 hits a limit, VSC2 will control the direct voltage and will operate along the *A*–*B*–*C*–*D* line. If VSC2 is suddenly disconnected, the direct voltage rises above the reference value of the second controller of VSC1 and direct-voltage controller 2 starts to control the direct voltage along the *E*–*F* line.

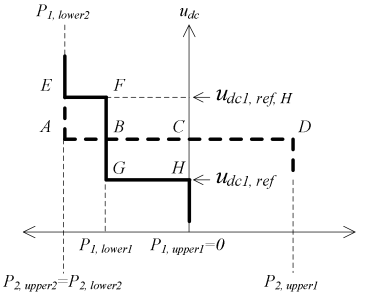


Fig. 11. u_{dc}–P characteristic of two converters using the two-stage active-current controller: VSC2 (*A–B–C–D*); VSC1 (*E–F–G–H*)

2) *Three-stage direct voltage controller*

The abovementioned controls work well in case the VSCs are operating in inversion mode. When the most critical converter trips, which is the direct-voltage controlling converter, the direct voltage will rise until one of the other connected VSCs enters its direct-voltage control region. However, when the direct-voltage controlling VSC draws power from the ac network, the direct voltage will drop after disconnection while the other VSCs operate in their pre-scheduled limits, which cannot be adjusted quickly enough. As VSCs in future transnational grids should be capable to draw and deliver power and to quickly change power flow directions in case of emergencies, these situations must be avoided. Therefore, a three-stage active-current controller is introduced here, in which the upper and lower limits of the first stage direct-voltage controller are automatically adjusted, as shown in Fig. 12 and Fig. 13.

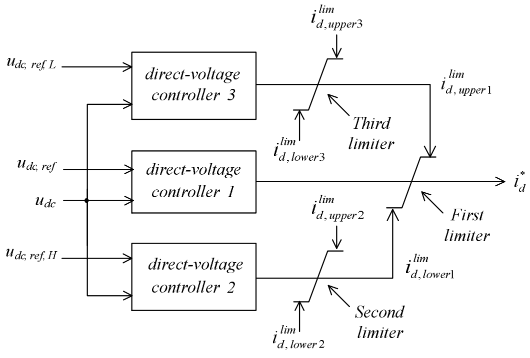


Fig. 12. Three-stage active-current controller

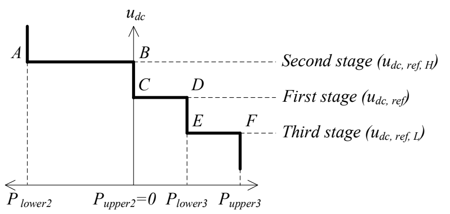


Fig. 13. u_{dc}–P characteristic of the three-stage active-current controller

B. *Control strategy for power dispatching*

The GSVSCs in the test network of Fig. 1 are equipped with a three-stage active-current controller and in order to perform different dispatch schemes, the upper and the lower limits as well as the voltage margins of each GSVSC can be adjusted. The dispatch schemes considered here, which have a particular focus on co-operation with variable wind generation, are priority power sharing, fixed power exchange, and proportional wind power sharing. The explanation of these schemes as well as the implementation into the controllers of both GSVSCs of Fig. 1 is described below. It should be noted that the proposed control methods can be jointly applied in any multi-terminal network; the network of Fig. 1 is chosen for illustration purposes only.

1) *Priority power sharing*

With priority power sharing, one onshore grid gets the first priority to obtain the WPPs' power until a particular limit is reached. Then the other onshore grid receives the remaining available wind power. In other words, the second prioritized onshore grid will not receive power from the WPPs as long as the power delivered to the first prioritized onshore grid has not reached the predefined limit.

The u_{dc}–P characteristics of the GSVSCs, which both perform priority power sharing, are depicted in Fig. 14.

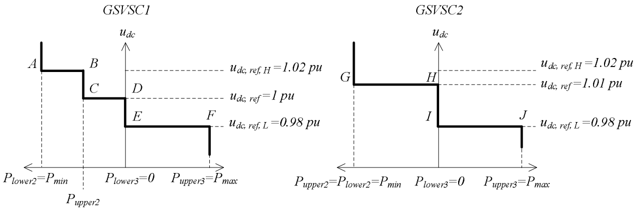


Fig. 14. u_{dc}–P characteristics for priority power sharing

As is shown, the first-stage upper limit of GSVSC1 and GSVSC2 are fixed to zero so that these deliver power to the ac grid only when the direct voltage exceeds the reference value. The direct voltage reference value of the GSVSC1 is set lower than that of the GSVSC2 by a voltage margin. According to this control setup, GSVSC1 will have precedence to deliver power to its onshore grid, whereas GSVSC2 will start to deliver power to the other onshore grid after the direct voltage controller of GSVSC1 has reached its lower limit (line *B–C*) and the direct voltage rises above the reference value of the GSVSC2 (line *G–H*).

2) *Fixed power exchange*

By adapting fixed power exchange, one GSVSC inverts or rectifies a pre-scheduled amount of power. The source may be from the offshore WPPs, the other onshore grid or both. This control mode can be used for situations that will probably be experienced in transnational offshore grids: electricity trade between countries with WPPs in-between.

The u_{dc}–P characteristics in case the two GSVSCs perform this dispatching scheme are given in Fig. 15. Both limits of the second stage of the direct-voltage controller of GSVSC1 are made equal to a negative value (inverter mode), whereas the upper limit of the third stage and the lower limit of the second stage of GSVSC2 are set to the VSC maximum and minimum rated power respectively. In this way, GSVSC1 will constantly supply the scheduled amount of power to its connected onshore grid while GSVSC2 controls the direct voltage and absorbs the wind power variability.

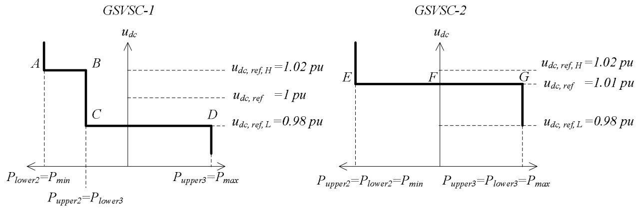


Fig. 15. u_{dc}–P characteristics for fixed power exchange

3) *Proportional wind power sharing*

The proportional wind power sharing scheme intends to control the GSVSCs in such a way that these share the WPP output by a pre-scheduled ratio. Such a scenario may be part of agreements between countries to share the total amount of wind. It is difficult for the VMM to perform proportional wind power sharing without knowing the actual WPP outputs. In order to perform proportional wind power sharing, the VMM control strategy is to be extended with a supervisory dispatch controller, which dynamically adjusts power set points by adjusting the corresponding control limits.

The u_{dc}–P characteristics of two GSVSCs performing proportional power sharing are depicted in Fig. 16. Initially the direct-voltage controller limits and voltage margins are set in the same way as priority sharing or fixed power exchange.

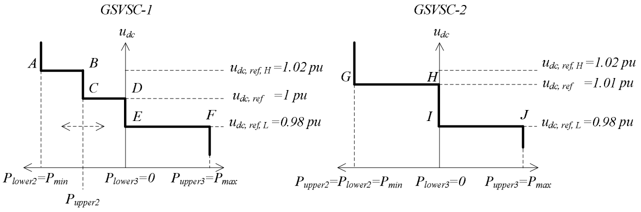


Fig. 16. u_{dc}–P characteristics for proportional power sharing

A supervisory dispatch controller measures the actual WPP output power rectified by the WPPVSCs and signals this to GSVSC1. The upper limit of the second stage of the direct-voltage controller is dynamically adjusted according to the pre-scheduled wind power ratio. In this way, the control scheme of GSVSC1 will always operate in a limit region (*B*–*C*) and will deliver power according to the assigned portion, whereas GSVSC2 controls the direct voltage and thus delivers the remaining percentage minus losses.

This concept can be easily extended to multiple GSVSCs that deliver a predefined share of the wind to the mainland system each. However, adjustment of the GSVSC set points will lag the changes in the actual WPP's power in practice due to measurement inaccuracies and/or communication delays.

IV. SIMULATION STUDIES

To explore the capability of the control strategy to dispatch the output of the WPPs and the pre-scheduled flows between the onshore grids, several simulation studies have been performed: priority power sharing, fixed power exchange and proportional wind power sharing. The control strategies explained in section III are implemented into the network model shown in Fig. 1. The simulation studies have been performed using MATLAB/simulink using the SimPowerSystems toolbox. The direct-voltage reference values for the GSVSC1 and the GSVSC2 are set equal to 1 pu and 1.01 pu, respectively, and have therefore a voltage margin of 0.01 pu. The robustness of the VMM is assessed by simulation of converter tripping.

A. *Normal operation*

1) *Priority power sharing*

To illustrate the priority-sharing control method, the control scheme shown in Fig. 14 is applied to the test network. Both GSVSCs share the power from the WPPs in priority order. The simulation results for priority power sharing are presented in Fig. 17. GSVSC1 is scheduled to receive the first 200 MW. The additional wind power will be inverted by GSVSC2.

Initially, the WPPs deliver 50 MW to the offshore network each and GSVSC1 delivers 100 MW to the ac system, whereas no power is delivered to onshore grid 2 yet. At *t*=2 s, the power output of WPP1 increases to 150 MW and subsequently GSVSC1 delivers 150 MW to the onshore power system. Between *t*=4 s and *t*=6 s the wind power output of WPP2 increases to 200 MW. At *t*=5 s GSVSC1 reaches its programmed power limit of 200 MW. The direct voltage rises above the reference value of GSVSC2, which now takes over the direct-voltage controlling duty and acts as a dc slack node.

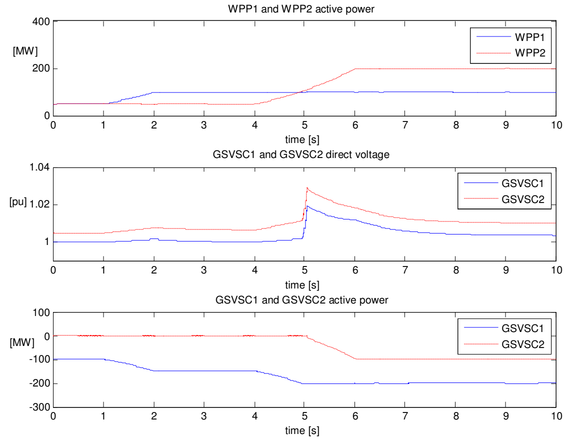


Fig. 17. Simulation results for priority power sharing

2) *Fixed power exchange*

Now, the scheme shown in Fig. 15 is applied to the three-stage active-current controllers at both GSVSCs. One VSC terminal (GSVSC1) is pre-set to deliver 200 MW to the onshore grid, while GSVSC2 controls the direct voltage. The results are shown in Fig. 18.

Initially, GSVSC1 delivers 200 MW to the onshore power system. The WPPs deliver 50 MW to the offshore network each and therefore GSVSC2 absorbs 100 MW from the mainland system. After *t*=2 s, the wind power output of WPP1 increases to 100 MW and thus the power delivered to the offshore network by GSVSC2 decreases to 50 MW. Between *t*=4 s and *t*=6 s the wind power of WPP2 increases to 200 MW, which implies that GSVSC2 delivers 100 MW to its onshore network.

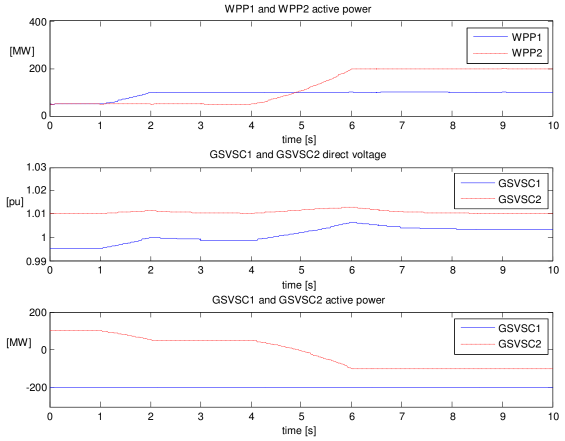


Fig. 18. Simulation results for fixed power exchange

3) Proportional wind power sharing

To illustrate the behavior of the supervisory dispatch controller in a multi-terminal network, GSVSC1 and GSVSC2 are pre-scheduled to receive 75% and 25% of power from the WPPs respectively. The u_{dc}–P characteristics of Fig. 16 are applied to both onshore VSC terminals, which are provided with a power set-point delayed by 2 s. The simulation results are shown in Fig. 19.

Initially, the WPPs deliver 50 MW to the offshore network each, which is divided among GSVSC1 (75 MW) and GSVSC2 (25 MW). The control system of GSVSC1 has reached its power order limit (75 MW) and therefore GSVSC2 controls the direct voltage at 1.01 pu. Between *t*=2 s and *t*=3 s the wind power of WPP1 increases to 100 MW.

Due to the simulated communication delay, the limit of GSVSC1 is not yet adjusted and thus the excess power is absorbed from the dc system by GSVSC2. From *t*=4 s to *t*=5 s the limit of GSVSC1 is adjusted, which restores the scheduled sharing of the wind power. From *t*=8 s to *t*=10 s the WPP2 power increases to 200 MW. Again, it takes 2 s before the final power set point of GSVSC1 is reached, which takes place between *t*=10 s and *t*=12 s. Finally, GSVSC1 now delivers 225 MW to the connected onshore grid while GSVSC1 supplies nearly 75 MW.

B. Converter failure

A major advantage of the VMM is its robustness. To illustrate this, the response of the system is examined upon losing the direct-voltage controlling VSC.

Both GSVSCs provide power to the onshore ac systems according to pre-scheduled power set-points. In this case, the fixed power exchange control mode is applied, with GSVSC2 behaving as the direct-voltage controlling VSC. The simulation results following the failure of GSVSC2 at *t*=0.2 s are shown in Fig. 20. The power outputs of the WPPs remain constant during the simulation time as the goal is to show the response of both GSVSCs. It can be seen that GSVSC1 quickly takes over the direct-voltage control functionality according to line *A*–*B* in Fig. 15.

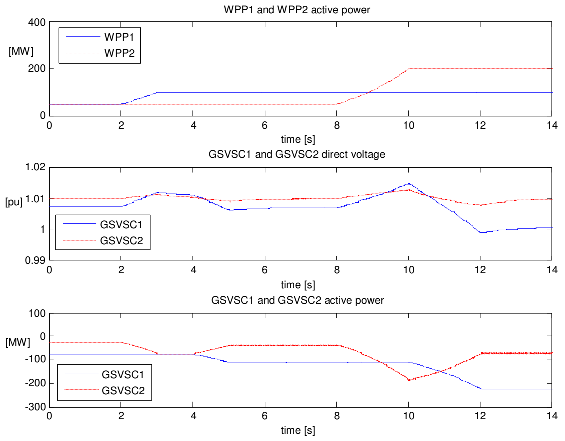


Fig. 19. Simulation results for proportional wind power sharing

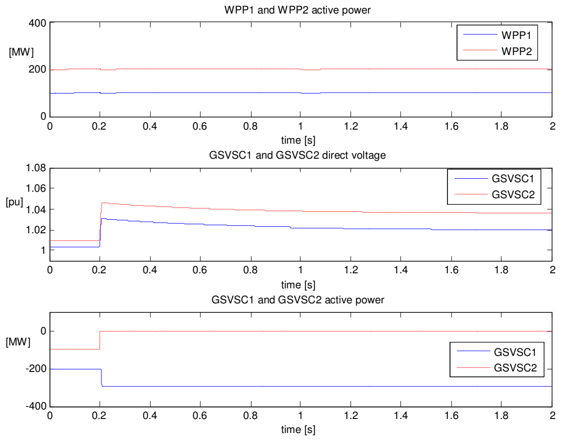


Fig. 20. Simulation results for fixed power sharing using the VMM

V. CONCLUSIONS

Transnational offshore networks may play an important role in the grid connection of future large-scale offshore wind generation. The application of multi-terminal VSC-HVdc in these networks offers a higher degree of controllability than conventional ac networks. As interconnections between wind power plants, offshore loads and multiple onshore systems are considered, these networks must be capable to support any market/regulation mechanism or dispatching scheme.

This paper explored the capabilities of the voltage-margin method to dispatch wind power among the connected countries (points of coupling) and to facilitate trade. The control method has been described and the implementation of three fundamentally different wind power dispatching schemes has been elaborated. A small test network was developed to test the proposed control method during normal operations.

The results show that the control strategy is capable of performing fixed power exchange and priority power sharing without depending on communication, which offers a high degree of flexibility and reliability that cannot easily be obtained otherwise. It turned out that some control modes cannot be realized without supervisory dispatch, i.e. proportional wind power sharing. On one hand this reduces the flexibility in operation. On the other hand, it is likely that a supervisory controller will be present in future transnational offshore grids. Two other benefits of the voltage-margin method were exposed by simulation results, namely its robustness to converter failure and communication delays.

The research will be continued to achieve more flexibility by combining the presented load-sharing and dispatching methods, especially for more complex networks. Moreover, the interaction between the voltage-margin method and other aspects of VSC control, such as fault-ride through mechanisms, are currently being studied.

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VII. BIOGRAPHIES

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