INTEROPERABILITY ASSESSMENT OF MMC AND DRU CONNECTED OFFSHORE WINDFARMS IN MESHED MULTI-TERMINAL DC GRIDS

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Abstract

In the last decade, a number of academic and industry studies have identified diode rectifier unit (DRU) as a potential replacement for offshore modular multilevel converter (MMC) of DC connected offshore windfarms. However, side-by-side operation of DRU and MMC connected windfarms in multi-terminal DC grid will present new operational challenges. Therefore, this paper will study the interoperability of a minimum meshed DC grid, which includes MMC and DRU connected offshore windfarms. To identify any potential issues that may arise from introduction of DRU, the system performance during onshore AC faults are simulated using PSCAD models. Simulation results show that the DRU connected windfarm exhibits different behaviours with the MMC based equivalent, but does not adversely impact the DC grid performance. Instead, the use of DRU improves DC grid performance with its inherent sensitivity of active power transmission to DC voltage variation.

1. Introduction

To fully utilize the potential large offshore wind energy, several project such as “Twenties” “Offshore Grid” [1] etc., have been carried out to explore the feasible solution to collect the offshore wind energy over last decades. Among several transmission system technologies, voltage source converter (VSC) based high voltage DC (HVDC) transmission technology offers a cost-effective solution for connecting remote offshore wind farms. To date, there are large numbers of offshore wind farms already in operation and many new plants and new connection are under construction or at planning stage [2]. The most popular existing projects are mainly based on the modular multilevel converter (MMC) offshore station compose with type-4 windfarm connection system such as the Bolwin and Dolwin projects [3] .

However, to reduce the cost related to the offshore windfarm integration, the diode rectifier unit (DRU) based HVDC technology has recently received notable interest [4]. By replacing the large expensive MMC-VSC station with the DRU station, the volume and weight of the platform can potentially be reduced by 80% and two-third, respectively [5]. The transmission losses and total cost can also be potentially reduced by up to 20% and 30% [5]. The DRU-HVDC provides a potential solution for future offshore wind energy transmission.

With more and more offshore windfarms integrated to the onshore, several distributed offshore windfarms can be interconnected to form a multi-terminal HVDC system, which increases the transmission capacity and provide higher flexibility to reduce the maximum power outage in case of DC disturbance [6]. However, such a big system may contain serval issues during grid disturbances. Considering one of the most common onshore AC grid faults, the power imbalance between the offshore grid and onshore grid will result in increased DC voltage, potentially leading to a lengthy outage of the complete DC system.

To address this problem, several fault ride-through (FRT) methods are proposed and discussed [7-9]. Based on the communication system between onshore and offshore grid, [7] proposes five methods to dissipate the excess energy in DC grid to control the DC voltage rise. In [6], the authors propose to use the V_{dc}-P or V_{dc}-f droop control to distribute the power stress among local wind farm stations to enable low voltage ride through capability. However, those papers focus offshore windfarms connected with only MMC.

Hybrid DC transmission systems with DRUs as front-end interfacing converters at offshore are perceived as cost-effective solution for connection of future offshore windfarms. However, the passivity of DRU raises several reservations and presents significant control and operational challenges for multi-terminal DC (MTDC) grid that worth investigating.

Therefore, this paper investigates the technical feasibility of integrating DRU connected offshore windfarm into MTDC grid, with particular focus on behaviour during onshore AC faults. The investigation uses a minimum meshed DC grid with converter terminals are MMCs as a benchmark scenario, and additional scenario in which one of the MMC connected windfarms to be replaced by DRU connected windfarm. Moreover, this paper proposes incorporation of auxiliary droop based fault ride-through controller on each offshore MMC to adjust the active power from the windfarm based on inverse relationship with MTDC DC voltage. The system responses under the two scenarios will be compared in effort to identify any technical and economic opportunities and potential risks that may pose by the introduction of DRU to MTDC grid. The findings and observations drawn from this investigation will be highlighted and summarized.

The rest of this paper is organized as follows: Section 2 presents the behaviours for the DRU connected windfarm under onshore AC faults and compares two FRT methods. Case studies are carried out and different behaviours of windfarms without and with DRU under different FRT methods are discussed in Section 3. Finally, conclusions are drawn in Section 4.

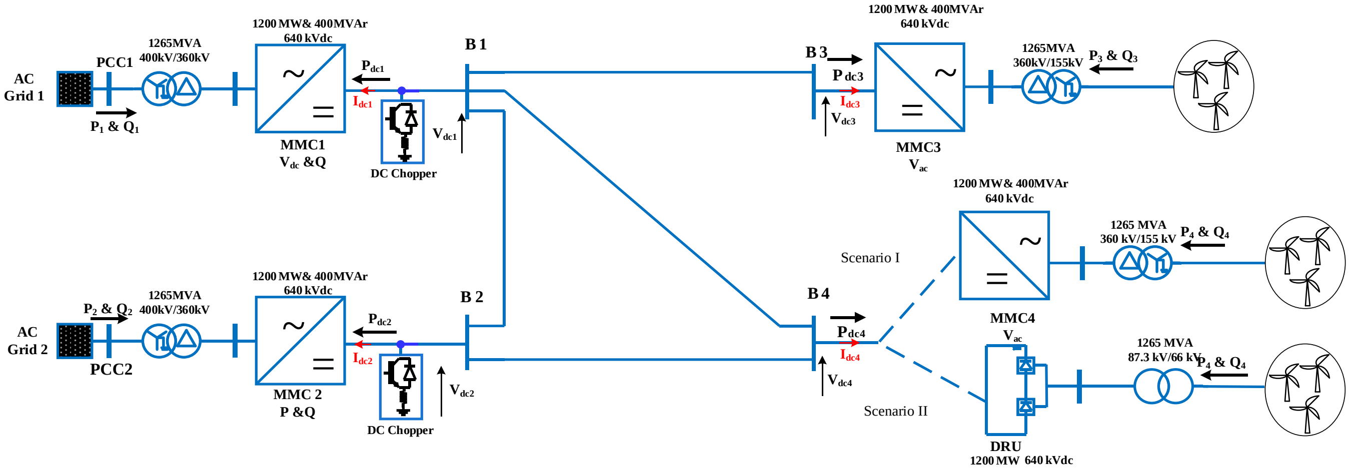

Fig. 1 Minimum meshed DC grid

2. Meshed MTDC system considering onshore grid faults

2.1. Offshore DC grid

Fig. 1 shows a minimum meshed offshore DC grid which will be used to assess the interoperability of DRU and MMC connected offshore windfarms in a DC grid. The DC grid shown in **Fig. 1** is constructed as symmetrical monopole, with its positive and negative DC cables operate at ±320kV from ground level.

2.2. Onshore stations

MMC1 and MMC2 are two onshore converters, in which the MMC1 controls the DC voltage level at DC bus B1 at 640kV pole-to-pole and reactive power exchange with AC grid 1 at PCC1, while MMC2 regulates active and reactive powers exchange with AC grid 2 at PCC2. Both MMCs are modelled using Thevenin Equivalent Model (TEM) available in PSCAD library, with each MMC uses 350 submodules per arm. The full converter parameters are listed in Table 1. The MMCs are controlled in double synchronous reference frame and its main loops are:

- Outer controllers with selectable modes between P and V_{dc} in d-axis and Q and V_{ac} in q-axis.
- Inner double synchronous reference frame current controllers that regulate both positive and negative sequence currents.
- Auxiliary controllers such as circulating current, and horizontal and vertical energy controllers [10-12].

DC chopper is installed on the terminals of each of the onshore converter, i.e., MMC1 and MMC2 shown in Fig. 1. These DC choppers are activated based on the local DC voltage threshold of 110% of the rated DC voltage. Although detailed DC chopper sizing is out of scope of this paper, high-level discussions of the potential saving in the power ratings of the DC choppers of the onshore MMCs that the DRU based windfarms may bring to system will be presented.

Table 1 System parameters

Parameters	**Values**
Onshore and offshore MMC stations	
Rated DC voltage	±320 kV
Rated AC voltage	360 kV
Rated active power	1200 MW
Rated reactive power	400 MVAr
Onshore interfacing transformer	
Voltage ratio	360 kV /400 kV
Leakage reactance	0.18 pu
Offshore transformer voltage ratio	360 kV /66 kV
Leakage reactance	0.18 pu
Arm inductance	42 mH
Submodule capacitance	8.8 mF
Number of submodules per arm	350
Offshore DRU	
Rated active power	1200 MW
Interfacing transformer voltage ratio	87.3 kV/66 kV
Interfacing transformer leakage reactance	0.18 pu
DRU AC filter rated power	0.3 pu
Wind Turbine Generator (WTG) aggregates	
WTGs aggregate rated power	3×400 MW
Transformer voltage ratio	0.69kV/66kV
Transformer leakage reactance	0.18 pu
Filter capacitor	0.1 pu
Converter reactance	0.15 pu

2.3. MMC based offshore windfarm

Fig. 2 shows details of the MMC connected offshore windfarm displayed in **Fig. 1**. It consists of an offshore MMC3 that regulates the AC voltage and frequency of offshore AC networks, and absorbs the power generated by WTGs. The MMC3 inner and auxiliary controllers have identical structures as that of the onshore MMCs described earlier; except, its outer controllers regulate the direct and quadrature components of AC voltage. Each aggregate WTG is assumed to be of type 4 and equipped with a DC chopper which can be activated on demand to prevent excessive DC link overvoltage during severe AC fault, and several auxiliary controllers to instigate rapid active power reduction. Therefore, each aggregate WTG is described by averaged model of the grid side converter, and controlled in double synchronous frame with P and Q in the outer loops, and positive and negative sequence current controllers in the inner loops. The parameters of the MMC3 and WTGs are shown in Table I.

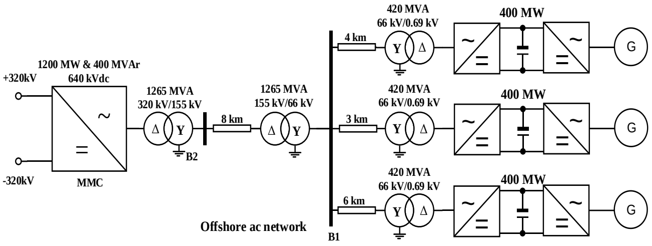

Fig. 2 MMC connected offshore windfarm configuration

2.4. DRU connected offshore windfarm

The offshore wind farm connected via DRU connected HVDC link is shown in **Fig. 3**. It consists of three 12-pulse series connected DRUs, each rated at 400MW and 213.3kV DC to enable operation at 640 kV DC voltages. DRUs transformers and AC filters are shown in **Fig. 3** and their parameters are shown in Table 1.

The control arrangement of DRU connected windfarm differs from MMC described earlier. This is due to the fact that the uncontrollability of the DRU necessitates the WTGs' grid side converters to operate as grid-forming converters to participate in defining offshore AC voltage and frequency, in addition to power dispatch. Detailed control arrangement of DRU connected windfarm can be found in [13].

The potential increase of the DC voltage as a result of AC fault at the PCC of one of the onshore MMCs will reduce the conduction period of the DRUs [14]. This phenomena reduces the power dissipation at the installed DC choppers at the onshore converters, and improves DC grid dynamics.

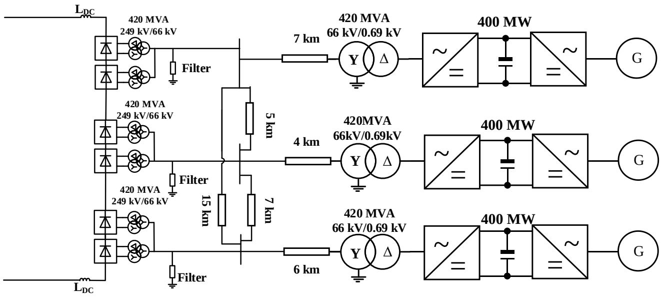

Fig. 3 DRU connected offshore windfarm configuration

2.5. Enhanced onshore AC fault ride-through strategy

To further minimize the power dissipations on the onshore converters' DC choppers and reduce the rise of DC grid voltage during onshore AC faults, auxiliary controller that uses DC grid voltage to initiate autonomous curtailment of active power from MMC connected windfarm is incorporated into Offshore MMC.

The block diagram of the proposed enhanced onshore AC fault ride-through (OAC-FRT) method is shown in Fig. 4. The proposed OAC-FRT method uses DC voltage (V_{DC}) – AC voltage (V_{AC}) droop plus integral term to eliminate steady-state error. A hysteresis band with suitable upper (1.1 pu) and lower (1.05 pu) thresholds is added to the droop plus integral terms in Fig. 4 to prevent activation of the proposed OAC-FRT during normal operation, i.e., keeping MMC to operate as grid forming converter with constant AC voltage as explained earlier. When the DC grid voltage exceeds the upper threshold, e.g. 1.1 pu during an onshore AC fault, the proposed OAC-FRT method is triggered and forces the MMC to reduce the offshore AC voltage in effort to curtail active power from the windfarm. In this way, MMC can minimize the DC over-voltage problem in MTDC grid by controlling the DC voltage at safe level according to droop characteristic shown in Fig. 4. After AC fault is cleared, the main DC voltage regulator (MMC1) will restore the DC grid voltage to be within the normal operation band as seen by the proposed OAC-FRT method. It worth emphasizing that as the MMC reduces offshore AC voltage, WTGs will hit their current limits imposed at outer controllers, which will result in reduction of their power outputs.

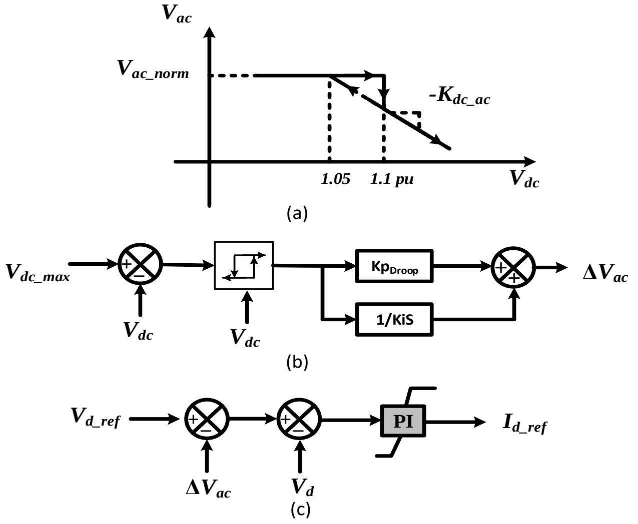

Fig. 4 Hysteresis fault ride through controller a) Hysteresis loop b) DC_AC voltage reduction loop c) Enhanced outer voltage control loop

3. Simulation

This section uses comparison to assess the interoperability of DRU windfarm with MMC based MTDC grid, with particular focus on onshore AC faults. In this assessment, the MTDC grid as shown in **Fig. 1** is simulated when the lower offshore windfarm is first connected using a MMC which is subsequently replaced by a DRU. The former and latter scenarios are referred as I and II. Three simulation cases used in this interoperability assessment are:

1) No action from onshore and offshore MMCs. This test represents the base-case which aims to highlight the key differences between natural responses of the two scenarios.
2) Facilitation of onshore AC fault ride-through activations of DC choppers is installed at MMC1 and MMC2. This test case aims to articulate that the introduction of DRU may bring potential savings on the onshore DC chopper ratings.
3) Activation of the proposed OAC-FRT method. This test case aims to demonstrate the effectiveness of the proposed OAC-FRT in MMC and DRU embedded DC grids.

The system operation condition for all three test cases are summarized as follows:

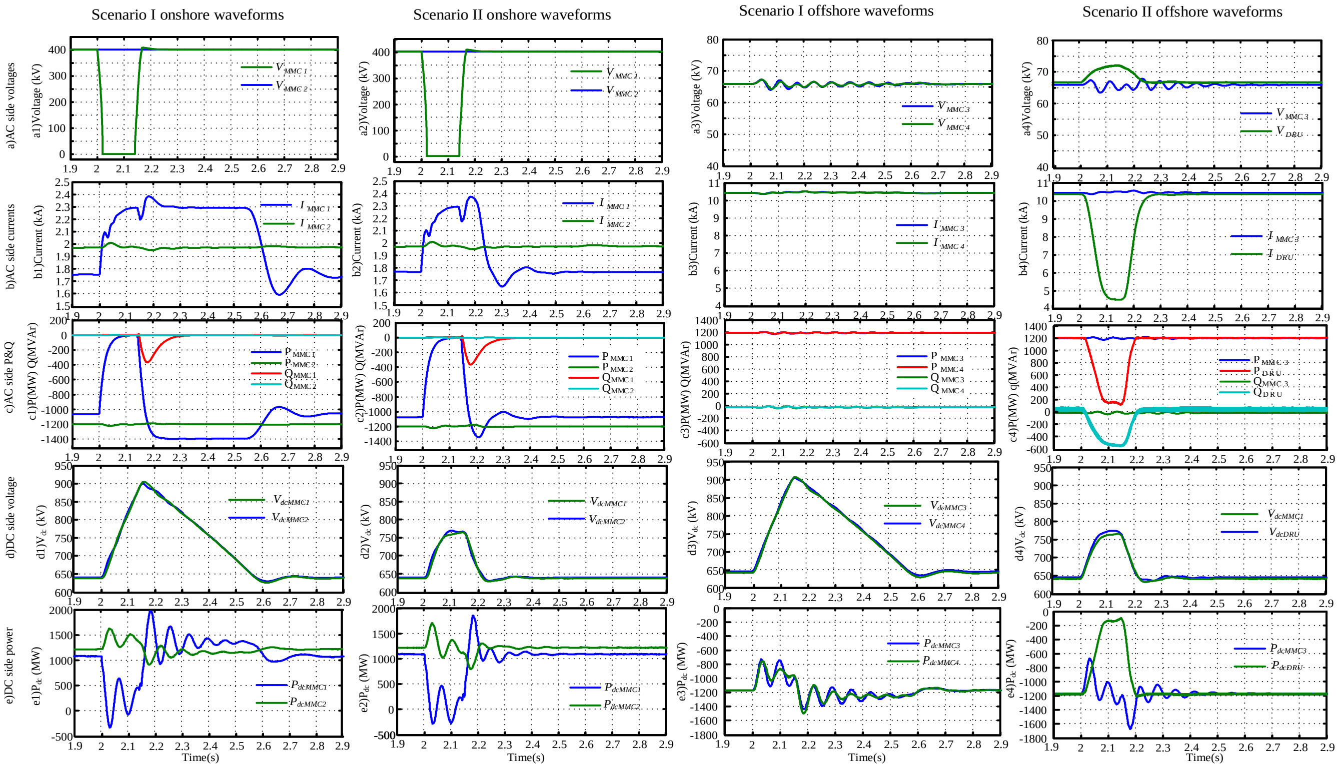

Fig. 5 Case I: No action from both onshore and offshore grid waveform

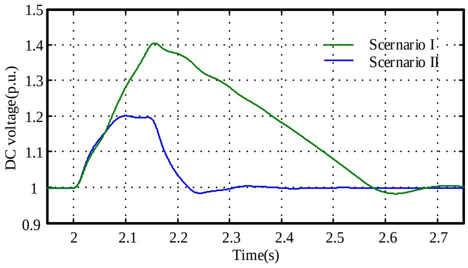

Fig. 6 DC voltage profiles at the MTDC grid

- The main DC voltage regulator (MMC1) is subjected to a symmetrical three-phase AC fault at t= 2 s and cleared after 140 ms.
- MMC 2 operates at constant power, injecting 1200 MW into PCC2 at unity power factor.
- Each offshore windfarms injects 1200 MW.

3.1. No action from onshore and offshore converters.

Error! Reference source not found. shows the simulation results for the base-case, in which the results of scenarios I and II are shown side-by-side. The AC side waveforms of both scenarios are shown in the rows 1 to 3, which include: AC voltages, AC currents, and active power and reactive powers measured at PCCs. The DC side waveforms are displayed in rows 4 and 5.

For further illustration of the differences in the DC dynamics between the two scenarios, MMC1 DC voltage for scenarios I is superimposed on that of the scenario II as shown in Fig. 6 .

The key observations drawn from the base-case are:

- In scenario I, MMC1 recovers much slower and its current saturates for longer compared to that in scenario II. The active and reactive power outputs from the MMC2 and MMC3 remain largely unaffected, including their AC voltages and currents.
- Unlike the MMC connected windfarm where the offshore AC network is decoupled from other asynchronously connected AC grids, the DRU connected windfarm has exhibited small AC voltage increase in effort to push more power, and substantial drop in the AC current and active power during onshore AC fault as stated earlier. On another hand, the rise of offshore AC voltage of DRU connected windfarm has resulted in excessive reactive power from AC filters which will be absorbed by WTGs.
- It is apparently clear that the scenario II exhibits lower DC over-voltages compared to scenario I, see Fig. 5 and Fig.6. The maximum DC over-voltages for scenarios I and II are 1.4 pu and 1.2 pu respectively.
- The MMC connected windfarms retain rated DC powers, while the DC power of DRU connected windfarm collapses to near zero.

3.2. With activation of DC chopper on onshore MMCs.

The selected waveforms in scenarios I and II are shown in Figs. 7, 8 and 9. With one terminal replaced by DRU, the DC overvoltage in scenario II is lower than that in scenario I, as observed in Fig. 7. The energy dissipated in the DC chopper of MMC1, calculated as $E=\int_{t-chopper\_enabled}^{t-chopper\_disabled} I_{Chopper}^{2} R dt$, is displayed in Fig. 8. The DC chopper of the DRU integrated

MTDC grid consumes less energy. This is because the DRU connected windfarm naturally reduces its power output as the DC voltage increases as shown in Fig. 9, and hence reduces the amount of excess power or energy in the DC grid. However, this means that the excess power within the WTGs in the DRU connected windfarm must be dissipated by distributed DC chopper at WTGs. For scenario I, the OWF side behaviors remain the same as previous case. Thus, no simulation result is given here.

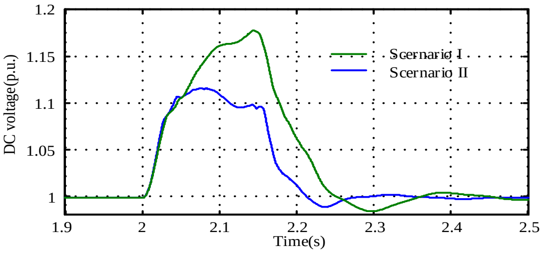

Fig. 7 Two scenarios DC voltage profiles at the MTDC grid

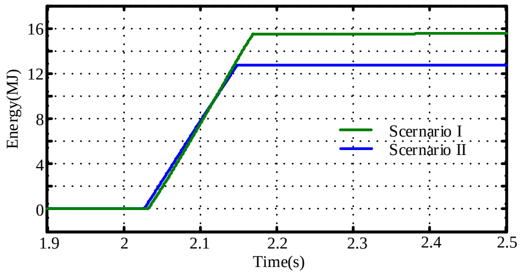

Fig. 8 Two scenarios disppated energy in DC chopper

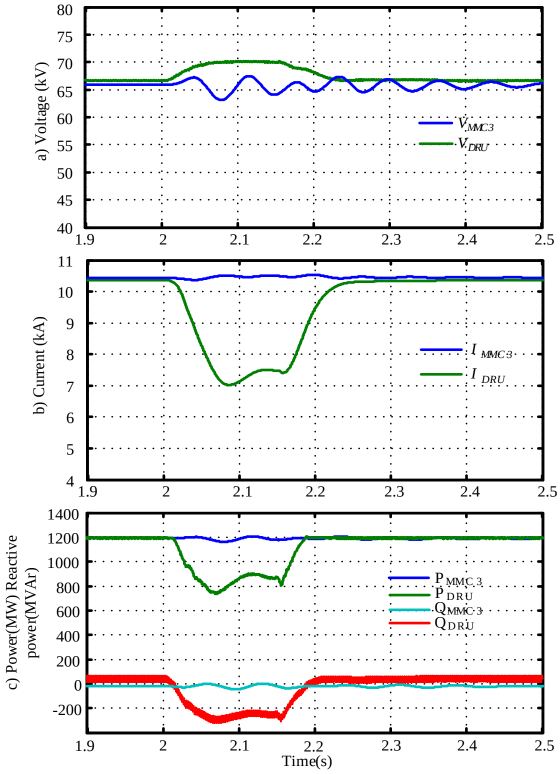

Fig. 9 OWF waveforms in scenario II where one offshore MMC station is replaced by DRU a) OWF AC voltage, b) OWF AC current, c) OWF active and reactive power

3.3. *With proposed FRT method*

The selected waveforms for two scenarios are shown in Fig. 10 and Fig. 11. With the proposed FRT control, the DC overvoltage in both scenarios is similar to that in the case equipped with DC choppers and is lower than that in the uncontrolled case, as observed in Fig. 10. After the fault clearance, the DC voltage quickly restores to the pre-fault operating condition.

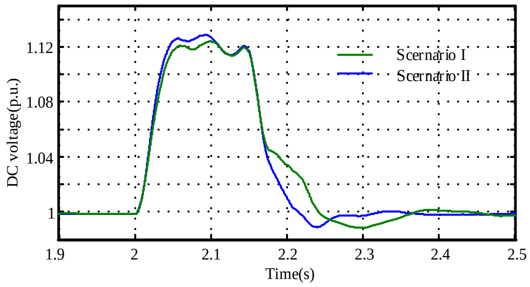

Fig. 10 Profiles of DC voltage of the MTDC grid in the two scernarios

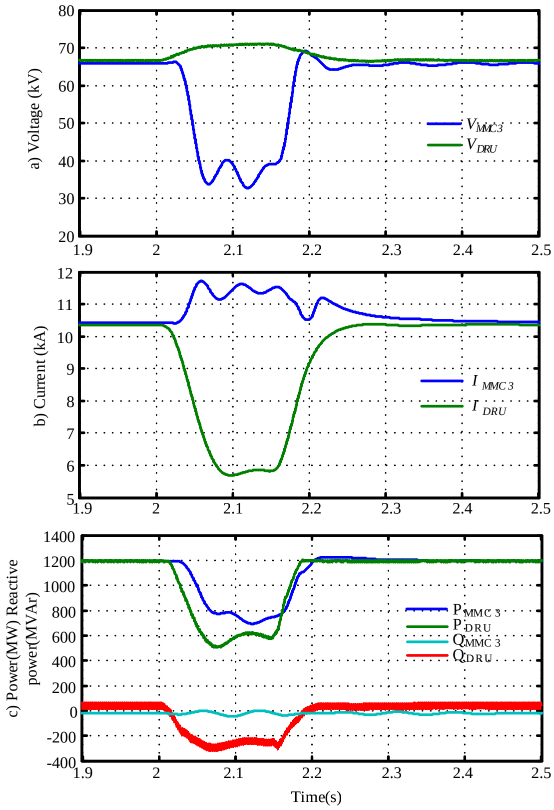

Fig. 11 OWF waveforms with the proposed FRTcontrol in scenario II a) OWF AC voltage, b) OWF AC current, c) OWF active and reactive power

The simulation results at the windfarm side are present in Fig. 11. Benefiting from the proposed controller, the MMC connected offshore AC voltage is reduced when the DC voltage exceeds the threshold of the hysteresis loop as shown in Fig.11 (a). Due to the reduced AC voltage, the outer power loop of offshore MMC station saturates, leading to slight increase on the AC current, as displayed in Fig.11(b). However, the total power is still significantly reduced as in Fig.11(c). After the onshore AC fault clearance, the DC voltages and offshore AC voltage gradually recover to the rated values. Then the proposed controller is deactivated and the system restores the pre-fault state.

3.4. Suggestion and future works

In summary, under both system configurations, the existing hardware FRT and the proposed FRT method can maintain the DC grid stable and mitigate the over-voltage phenomena during onshore AC disturbance. The comparison for DC voltages during three test cases confirm that the integration of the DRU system does not bring any penalties into the MTDC grid system during onshore grid disturbance. Instead, the voltage sensitivity characteristics of the DRU system helps DC grid to reduce the DC chopper size and share the energy reduction stress for the offshore MMC connected system with FRT method. However, such a feature mainly depends on maximum voltage setting from the outer control loop which needs careful design and tuning. A local droop control with hysteresis loop can also be explored to improve the behaviors on DRU side.

4. Conclusion

This paper presented a comprehensive assessment of a meshed MTDC grid behaviours without and with DRU connected offshore windfarm during onshore AC grid faults. Two investigated scenarios are: both offshore windfarms are integrated into MTDC grid using MMCs; and one of the windfarms connected by MMC is replaced by DRU. It has been found that the DRU connected windfarms reduces the rise of DC voltages across the MTDC grid during onshore AC fault, and speeds up recovery of the faulted converter terminal. Moreover, the presented simulation results show that the proposed OAC-FRT represents a good practical alternative to the installation of classical DC choppers at onshore converters, in which distributed DC choppers at WTGs will be sufficient for riding through onshore AC faults.

Acknowledgments

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