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Published in:
PEDG 2023 - 2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems

DOI (link to publication from Publisher):
10.1109/PEDG56097.2023.10215201

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Coordinated Converter Control with Current Differential Protection under Unbalanced AC Fault in Offshore Wind Farm

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***Abstract*— The modular multilevel converter (MMC) based high-voltage dc (HVDC)-connected offshore wind farm (OWF) is with converters on both sides of the offshore ac grid. After a short-circuit fault on the offshore ac grid, the fault current from the MMC station can be controlled with a high flexibility to coordinate with the current differential protection. In this paper, the converter uncontrollability and overcurrent problems caused by the coordinated control during unbalanced faults are revealed. Thus, a coordinated fault control of the MMC suitable for the unbalanced fault is proposed to solve the uncontrollability problem. In addition, the proposed coordinated control is further modified to solve the MMC overcurrent problem. The simulation results indicate that the proposed coordinated control can ensure the operation of the current differential protection during unbalanced faults without the converter uncontrollability and overcurrent problems.**

Keywords*— *Current differential protection, unbalanced fault, offshore wind farm, MMC, coordinated control.

I. Introduction

Due to the concerns of sustainability and pollution of using conventional fossil fuels, the offshore wind farm (OWF) is a promising and reliable alternative for future energy systems [1]. For large offshore wind farm far from the coast, the high-voltage dc (HVDC) transmission has many advantages over its high-voltage ac (HVAC) counterpart, including enhanced controllability, reduced cost and power loss [2]. In HVDC-connected OWFs, the offshore ac grid is dominated by power converters since both sides of the grid are connected with wind turbine converters and the offshore modular multilevel converter (MMC) station, respectively [3]. Fault currents in offshore grids are different from the fault currents in conventional grids supported by synchronous generators (SGs), which poses new challenges to the control and protection of OWFs.

The fault currents of SGs are fully circuit dependent according to the equivalent impedance behind voltage source model. Therefore, the fault currents of SGs are usually inductive with high magnitudes, e.g., six times of rated fault current. Besides, the significant negative and zero sequence currents can be generated during an unbalanced fault [4]. In contrast, the fault current magnitudes of converters are strictly limited to avoid the thermal damage to power electronic devices. Besides, the fault current sequence components and the corresponding phase angles are highly controlled by the vendor-specific algorithms [5].

The decoupled sequence control [6] provides convenience for the independent and flexible control of the positive and negative sequence currents. Thus, the current reference setting strategies of converters after unbalanced faults can mainly be classified as two categories, namely from the converter point of view and from the grid support point of view. From the converter point of view, the fault current control mainly focuses on the mitigation of dc-link voltage ripple, and the supply of constant active or reactive power [7], [8]. In addition, with the increasing penetration of the converter interfaced power generation, the low-voltage ride-through capability is required for converters during faults. Thus, from the grid support point of view, the fault current control of converters should follow the grid codes in order to be connected to the grid [9]. For example, the fault current control of wind turbine converters should follow the grid codes on the positive and negative sequence currents injection during an unbalanced fault [7], which is a tabulated function of the magnitudes of the terminal positive and negative sequence voltages.

Different from the offshore wind turbine converters, there are no grid codes on the fault current injection for the offshore MMC station. The response of an offshore MMC station to the short-circuit faults should be carefully coordinated with wind turbine converters under the supervision of the transmission system operator (TSO) [10]. To protect the offshore facilities and improve the wind farm efficiency, the protection systems take priority over the operational control systems in the event of a short-circuit fault [11]. Therefore, the fault currents of an offshore MMC station can be injected from the protection point of view to coordinate with the protection relays.

The coordination between the protection relays and the fault current control of an offshore MMC station mainly involves two aspects. Firstly, the coordinated fault control of the MMC should limit the fault current magnitude to avoid the thermal damage to power semiconductor devices. Secondly, the fault current sequence components and the fault current phase angles of the MMC can be controlled with high flexibility to coordinate with the equipped protection relays [12]. A coordinated fault control of the MMC is proposed in [13] to improve the efficacy of the current differential protection after a balanced short-circuit fault. However, the coordinated fault control of the MMC could conflict with the sequence network constraints during unbalanced faults. To deal with this challenge, the grid codes and the converter control are investigated in section II. A modified coordinated fault control of the MMC is proposed in section III and section IV to avoid the uncontrollability and overcurrent problems of the MMC during unbalanced faults.

II. System Description

A single-line diagram of the HVDC connected OWF is illustrated in Fig. 1. The offshore ac grid is interfaced with an offshore MMC station of the HVDC transmission system and the grid-side converters of permanent magnet synchronous generator (PMSG)-based wind turbines. The current differential protection relays R1 and R2 measure the current i_{R1} and i_{R2} to trip the circuit breakers in the event of a short-circuit fault on HV Feeder 1.

A simplified control diagram of converters in the offshore ac grid is shown in Fig. 2. During normal operation, the grid-side voltage-source converter (VSC) of wind turbines adopts the grid-following control to inject the required active and reactive currents [14], whereas the offshore MMC station adopts the grid-forming control to regulate the voltage and frequency of the offshore ac grid [15]. After a short-circuit fault, the injected fault current i_w from wind turbine VSCs should follow the grid codes. In addition, the MMC cannot regulate the terminal voltage during a low impedance short-circuit fault. Thus, the MMC will inject the fault current i_m with a limited magnitude and a flexible phase angle, which can be utilized as a degree of freedom to coordinate with the protection relays.

Since the positive and negative sequence fault currents are required to be independently controlled with possibly different dynamic responses [16], the decoupled sequence control is applied to both the MMC and wind turbine VSCs. The phase-locked loop (PLL) is not required for the MMC since the angular frequency is directly set as the nominal frequency ω_1 [17]. The double second-order generalized integrator (DSOGI)-based PLL is utilized to extract the positive and negative

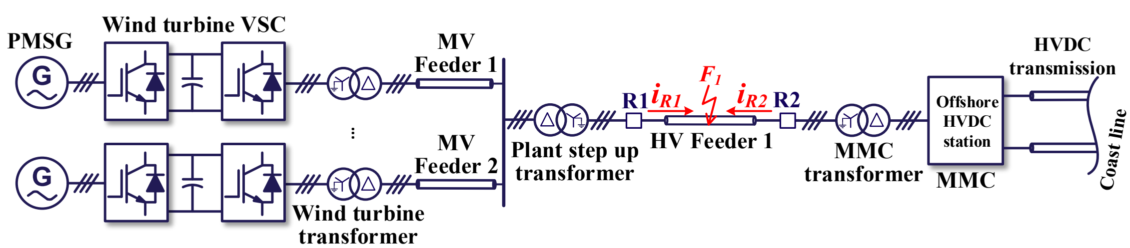


Fig. 1. A single-line diagram of the HVDC connected offshore wind farm.

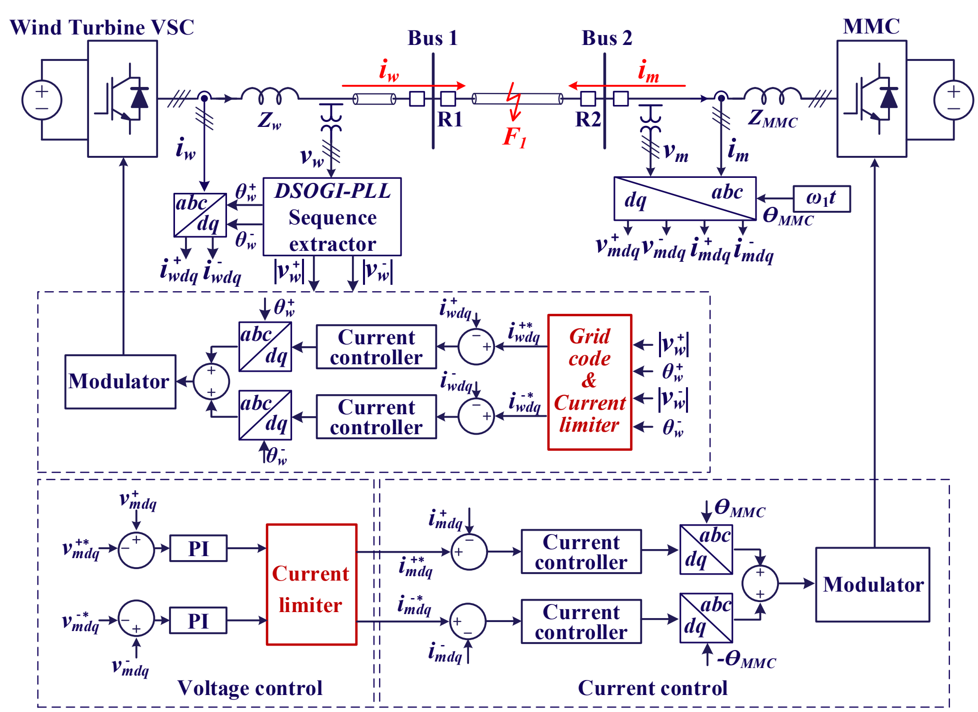


Fig. 2. A simplified control diagram of converters in the offshore ac grid after a short-circuit fault.

sequence phase angles and magnitudes of the VSC terminal voltage, which are used to generate the fault current references according to the grid codes and the current limiter. The details of the grid codes and the current limiter for wind turbine VSCs are introduced below.

A. *Grid codes on fault current injection*

To boost the positive sequence voltage and reduce the negative sequence voltage after the inception of an unbalanced fault in the offshore ac grid, the wind turbine VSCs are required to inject the positive and negative sequence reactive currents according to the grid codes [9], [18]. As illustrated in Fig. 3, the positive and negative sequence reactive currents are proportional to the positive sequence voltage drop and the negative sequence voltage magnitude, respectively, within the current rating limitation. The default slope of the proportional characteristic is k=2, which can also be adjusted in the range of 2 – 6 or even 2 – 10 [9].

B. *Current Limitation*

Power electronic devices undergo irreversible damage when the current exceed the hardware limits $I^{\lim}$. Thus, power converters strictly limit the fault current within a safe range, e.g. 1.1 p.u. to 2.0 p.u.. In the event of a short circuit fault, the reactive current injection is given in priority, while the remaining capacity is reserved for the active current injection. The limit of the reactive current injection $I_q^{\lim}$ varies in different countries [18].

After the inception of an unbalanced fault, the required positive and negative sequence reactive currents of wind turbine VSCs according to the grid codes shown in Fig. 3 can be expressed as (1)-(2).

$$i_q^+ = f_{GridCode}^+\left(v_w^+\right) \tag{1}$$

$$i_q^- = f_{GridCode}^-\left(v_w^-\right) \tag{2}$$

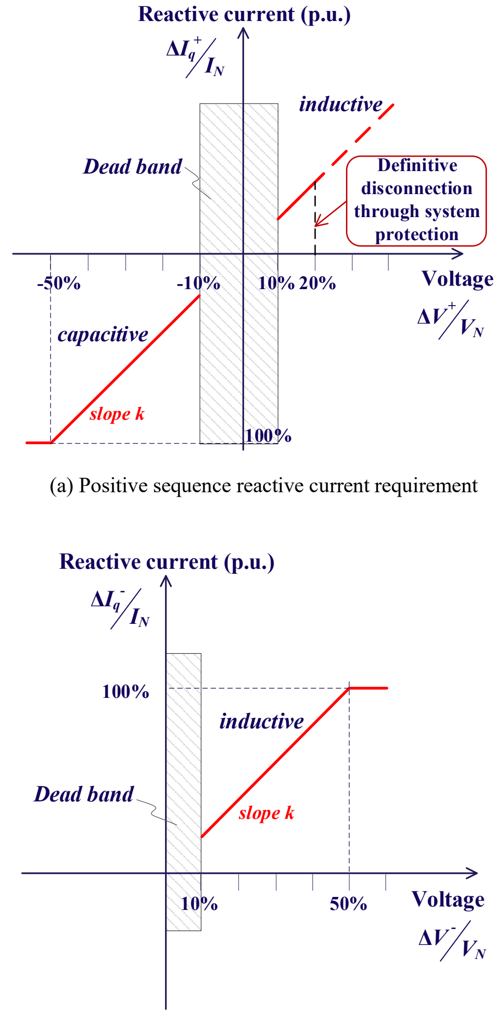
If the sum of the reactive currents $\left|i_q^+\right|+\left|i_q^-\right|$ is greater than the reactive current limit $I_q^{\lim}$, the positive and negative sequence reactive currents should be limited and revised as (3) -(4).

$$i_q^{'+} = i_q^+\left(\frac{I_q^{\lim}}{\left|i_q^+\right|+\left|i_q^-\right|}\right) \tag{3}$$

$$i_q^{'-} = i_q^-\left(\frac{I_q^{\lim}}{\left|i_q^+\right|+\left|i_q^-\right|}\right) \tag{4}$$

The remaining capacity of wind turbine VSCs is reserved for the positive sequence active current injection [19], which can be expressed as (5).

$$i_d^+ = \sqrt{\left(I^{\lim}\right)^2-\left(\left|i_q^{'+}\right|+\left|i_q^{'-}\right|\right)^2} \tag{5}$$



(a) Positive sequence reactive current requirement

(b) Negative sequence reactive current requirement

Fig. 3. Grid codes on the voltage support during a grid fault.

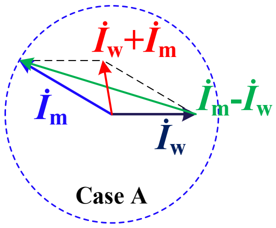
III. Uncontrollability Problem and the Proposed Solutions

A. *Current differential protection for balanced fault*

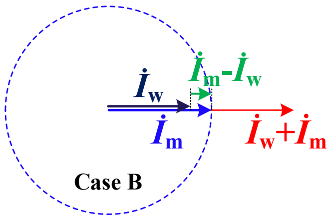
As illustrated in Fig. 2, the current differential protection relays R1 and R2 on both sides of the protected feeder measure the fault currents, which are assumed as i_w and i_m for simplicity. If the operation criterion of (6) is satisfied, relays R1 and R2 will trip the circuit breakers to isolate the fault in the event of a short circuit fault on location F.

$$\begin{cases} I_{diff} > kI_{res} \\ I_{diff} > I_{op[0]} \end{cases} \tag{6}$$

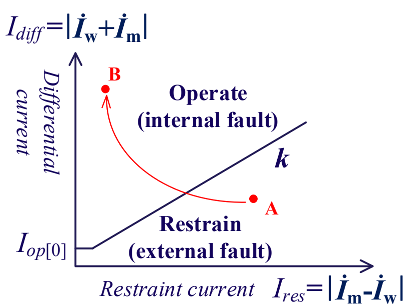
where $I_{res} = \left|\dot{I}_m - \dot{I}_w\right|$ and $I_{diff} = \left|\dot{I}_m + \dot{I}_w\right|$ are the restraint current and differential current, respectively. $I_{op[0]}$ is the threshold value to avoid the mal-operation due to current measurement errors. The bias factor k is typically set as 0.8 for feeder protection of the OWF [20].



(a) MMC with random fault control



(b) MMC with coordinated fault control



(c) Operation characteristic of the current differential protection

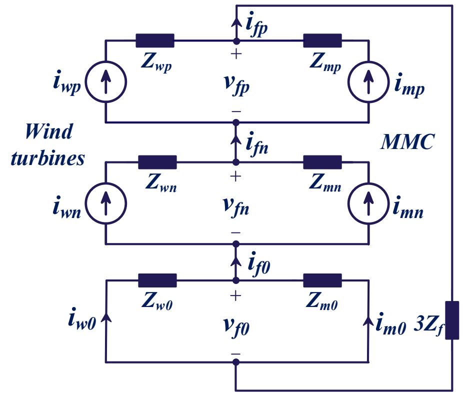
Fig. 4. Coordinated fault current control of the MMC with the current differential protection.

The current differential protection is designed based on the characteristic that the fault current phase angles of both sides of the protected line are similar. Since the phase angle of the fault current i_w from wind turbine VSC is determined by the grid codes, a coordinated fault control of the MMC is proposed [13] to align i_m with i_w catering a successful tripping of the current differential protection during a balanced fault. The basic principle of the coordinated fault control of the MMC is illustrated in Fig. 4. After fault inception, the protection relay jumps from state A (corresponding to case A) to state B (corresponding to case B) when the coordinated fault control of the MMC is applied. According to the operation criterion of the current differential protection, the protection relays successfully trip in this case.

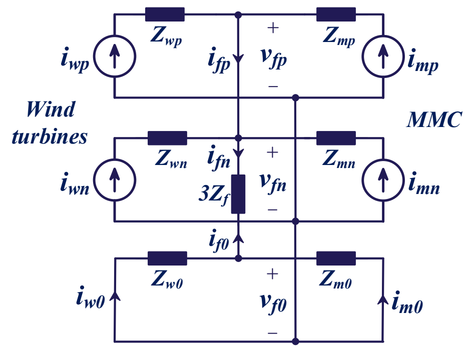
B. Uncontrollability problem during unbalanced fault

The equivalent sequence networks of the MMC connected OWF with different kinds of unbalanced faults in the offshore ac grid are derived in Fig. 5. Thus, the sequence components of the fault current at fault location should satisfy the following constraints:

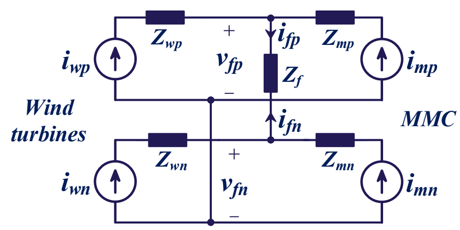
- $i_{fp} = i_{fn} = i_{f0}$ (single line-to-ground (SLG) fault)
- $i_{fp} + i_{fn} + i_{f0} = 0$ (double line-to-ground (2LG) fault)



(a) Single line-to-ground (SLG) fault



(b) Double line-to-ground (2LG) fault



(c) Line-to-line (L-L) fault

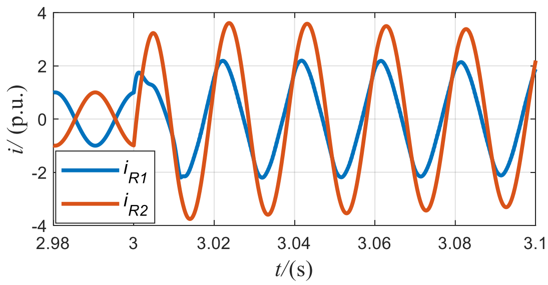
Fig. 5. Equivalent sequence networks of the offshore MMC station connected wind farm with different unbalanced faults.

- $i_{fp} + i_{fn} = 0$ (line-to-line (L-L) fault)

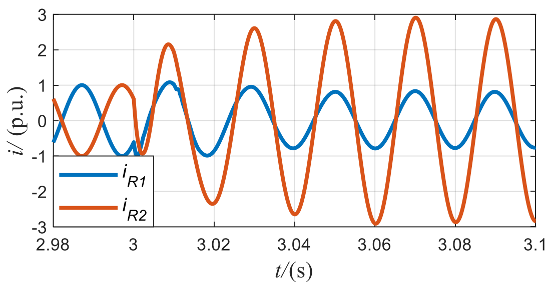
The positive sequence component i_{wp} and the negative sequence component i_{wn} of the fault current from wind turbine VSC is determined by the grid codes. To apply the coordination method for the balanced fault as illustrated in Fig. 4 to the unbalanced fault, the positive and negative sequence fault currents of the MMC should follow the similar rules as the grid codes for wind turbine VSC to align i_m with i_w. However, the highly controlled i_{wp}, i_{wn}, i_{mp}, and i_{mn} could conflict with the sequence current constraints for different unbalanced faults, especially the SLG and L-L faults. This conflict could lead to the uncontrollability of the MMC or the wind turbine VSC.

C. Proposed solutions

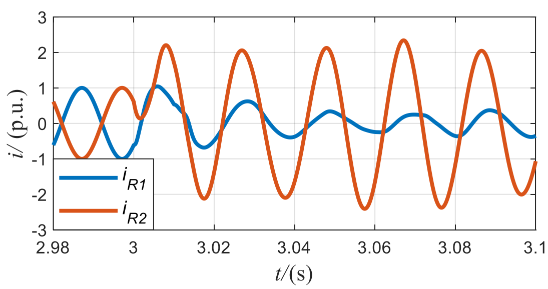
To avoid the uncontrollability of the MMC or wind turbine VSC during an unbalanced fault, the conflict of the highly



(a) Single line-to-ground (SLG) fault



(b) Double line-to-ground (2LG) fault



(c) Line-to-line (L-L) fault

Fig. 6. Fault currents measured by relays when the coordinated unbalanced fault control of the MMC is applied.

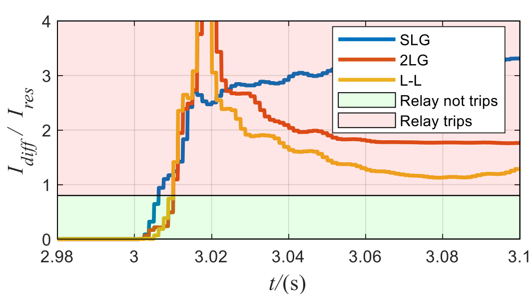


Fig. 7. The ratio of the differential and restraint currents when the coordinated unbalanced fault control of the MMC is applied.

controlled fault currents with the sequence network constraints should be solved. The proposed solutions are as follows:

- The positive sequence fault current control of the MMC should follow the same grid codes for wind turbine VSC to align i_{mp} with i_{wp}.
- The negative sequence fault current of the MMC is not controlled and therefore determined by the sequence network constraints to avoid the conflict.

TABLE I
MAIN SYSTEM PARAMETERS USED IN SIMULATIONS

Symbol	Meaning	Values
P	Power rating of the offshore wind farm	100 MW
V_m	RMS value of the rated ac voltage of the MMC	210 kV
f_1	Nominal grid frequency	50 Hz
V_w	RMS value of the rated ac voltage of wind turbine VSC	0.69 kV
I_{lim}	The limit value of the current from converters	1.2 p.u.
X_{tr}	The leakage reactance of transformers	0.12 p.u.
Z_f	Fault impedance	40 Ω

When the abovementioned coordinated fault control of the MMC is applied, the measured fault currents i_{R1} and i_{R2} by relays R1 and R2 after the L-L, 2LG, and SLG faults with system parameters of TABLE I are shown in Fig. 6. The phase differences between the measured fault currents by relay R1 and R2 are very limited after fault inception at 3 s. Besides, the ratio of the differential current and restraint current I_{diff}/I_{res} can exceed the bias factor k=0.8 within 10 ms after the inception of different unbalanced faults as shown in Fig. 7. Thus, the current differential relay can successfully trip after the different unbalanced faults with the proposed coordinated fault control of the MMC.

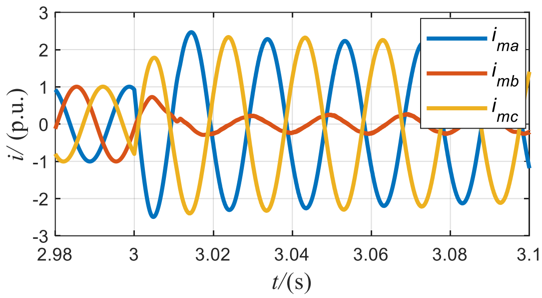
IV. OVERCURRENT PROBLEM AND THE PROPOSED SOLUTIONS

A. *Overcurrent problem*

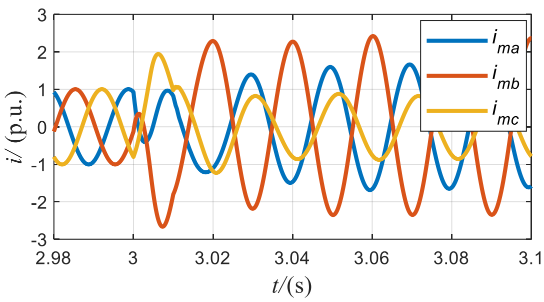
The capacity of the offshore MMC station is typically larger than that of the OWF. Since the offshore MMC station could be designed for future connections of wind farm clusters, the capacity ratio r between the MMC station and the OWF could be three [10], i.e., $r=S_{MMC}/S_{OWF}$ =3. In addition, the limited fault current I_{lim} of power electronic devices is typically in the range from 1.1 p.u. to 2.0 p.u. [21]. Therefore, the magnitude of the fault current from the MMC, i.e., $r* I_{lim}$, could reach 6 p.u. if the capacity of the OWF, i.e., S_{OWF}, is regarded as 1 p.u..

The limited fault current I_{lim} of power electronic devices in the MMC and wind turbine VSCs is assumed to be 1.2 p.u. in this paper. Besides, the capacity ratio r between the MMC station and the OWF is assumed as two, i.e., $r=S_{MMC}/S_{OWF}$ =2. Thus, the magnitude of the fault current from the MMC, i.e., $r* I_{lim}$, should not exceed 2.4 p.u..

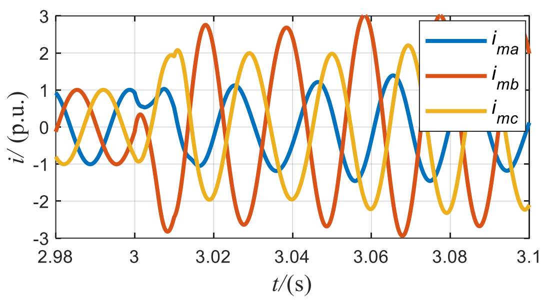
When the coordinated fault control of the MMC is applied, the fault currents of the MMC after the L-L, 2LG, and SLG faults are shown in Fig. 8. It worth noting that the fault current of the MMC after the L-L fault could reach 3 p.u. as shown in Fig. 8 (c), which could damage the power electronic devices of the MMC.



(a) Single line-to-ground (SLG) fault

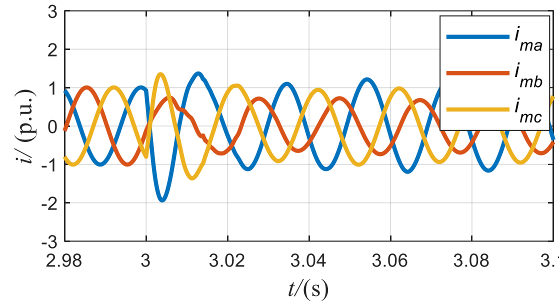


(b) Double line-to-ground (2LG) fault

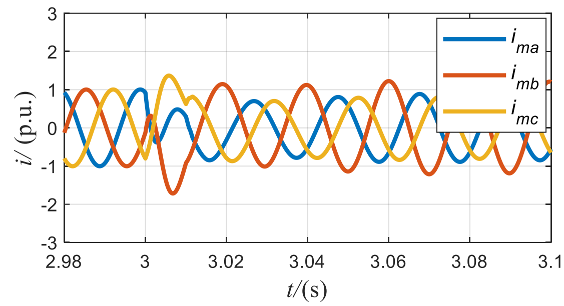


(c) Line-to-line (L-L) fault

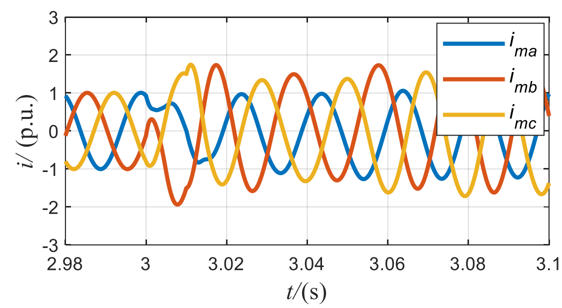
Fig. 8. Fault currents of the MMC after an unbalanced short circuit fault in the offshore ac grid when the coordinated control is applied.



(a) Single line-to-ground (SLG) fault



(b) Double line-to-ground (2LG) fault



(c) Line-to-line (L-L) fault

Fig. 9. Fault currents of the MMC after an unbalanced short circuit faults in the offshore ac grid with the reduced current reference.

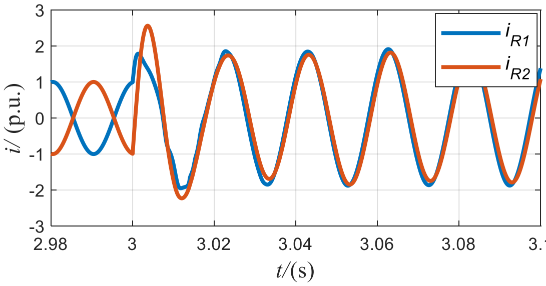
B. *Proposed solutions*

The large fault currents of the MMC could lead to an overcurrent problem or even an overvoltage problem, which could damage the equipment of the offshore ac grid. To solve these problems, a modified fault control of the MMC is proposed by reducing the reference of the fault current from the MMC. It is worth noting that the modified fault control of the MMC in this section is based on the proposed coordinated fault control in section III and the only change is the reduced fault current reference.

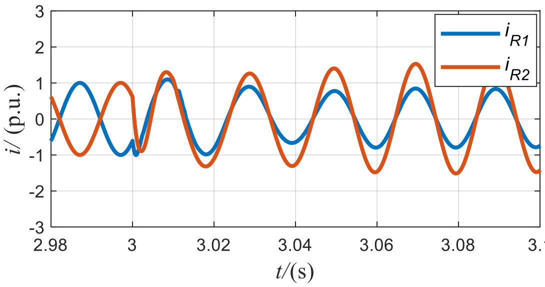
When the fault current reference of the MMC is reduced to a quarter of the original value, the fault currents of the MMC after the L-L, 2LG, and SLG faults are illustrated as Fig. 9. The maximum fault current is less than the limit of 2.4 p.u. and therefore is possible to protect the power semiconductor devices of the MMC.

C. *Efficacy of the current differential protection with the modified fault control of the MMC*

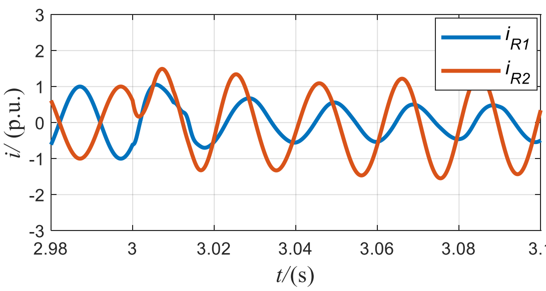
When the modified fault control of the MMC with the reduced current reference is applied, the measured fault currents i_{R1} and i_{R2} by relays R1 and R2 after the L-L, 2LG, and SLG faults are shown in Fig. 10. The fault currents measured by relay R1 and R2 are aligned with each other after the inception of SLG and 2LG faults at 3 s. Besides, the phase difference between i_{R1} and i_{R2} is also very limited within two fundamental power cycles after a L-L fault. As illustrated in Fig. 11, the ratio of the differential current and restraint current I_{diff} / I_{res} exceeds the bias factor k=0.8 within 10 ms after the inception of different unbalanced faults. The ratio I_{diff} / I_{res} maintains a large value within two fundamental power cycles after fault inception, which caters a successful tripping of the current differential relays.



(a) Single line-to-ground (SLG) fault



(b) Double line-to-ground (2LG) fault



(c) Line-to-line (L-L) fault

Fig. 10. Fault currents measured by relays when the coordinated unbalanced fault control of the MMC with reduced reference is applied.

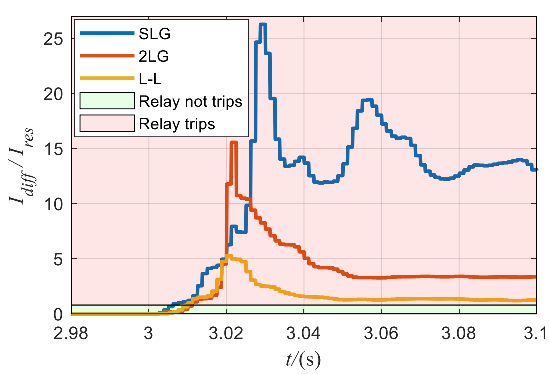


Fig. 11. The ratio of the differential and restraint currents when the coordinated control of the MMC with reduced fault reference is applied.

V. Conclusion

After a short-circuit fault on the offshore ac grid of the MMC connected offshore wind farm, the wind turbine converters inject the fault currents following the grid codes. Different from a balanced offshore fault, the sequence networks of an unbalanced fault have restraints on the injected fault currents on both sides. The coordinated control of the MMC could conflict with the sequence network constraints and further lead to the uncontrollability and overcurrent problems during unbalanced faults. To solve the uncontrollability problem, the negative-sequence current of the MMC is uncontrolled and determined by the sequence network. Besides, the overcurrent problem is solved by reducing the fault current reference of the MMC. The simulations validate that the modified fault control of the MMC can coordinate with the current differential protection to trip the unbalanced faults.

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