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Published in:
2021 56th International Universities Power Engineering Conference (UPEC)

DOI (link to publication from Publisher):
10.1109/UPEC50034.2021.9548154

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

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***Abstract*—Development of MMC-HVDC grids, as a new generation of VSC-HVDC systems, has been considerable through the past decade. Emerging of multi-terminal MMC-HVDC networks makes integration of multiple large-scale sustainable sources and asynchronous power grids quite feasible. However, protection and control of the multi-terminal HVDC grids under fault situations have always been a vital issue. On the other hand, while modern AC grids get benefits of applied Fault-Ride-Through (FRT) operation and capabilities under AC fault conditions, the multi-terminal HVDC grids lack a systematic DC FRT operation. As the multi-terminal HVDC networks are going to become a backbone grid for the future power systems, it is necessary to define grid code requirements and standardizations considering DC FRT regulations. This paper presents potential DC FRT operations and possible profiles from HVDC grid point of view under DC fault conditions. A systematic DC FRT based on voltage against time profile is proposed. Different characteristics of voltage-based DC FRT are investigated in this study and results can be applicable to DC grid code definitions and requirements.**

Keywords—MMC-HVDC grids, multi-terminal HVDC systems, DC fault-ride-through (FRT), voltage source converter (VSC), DC protection, grid code requirement

I. Introduction

With high penetration of (Power Electronic Converter) PEC interfaced RES (Renewable Energy Sources) in the modern power grid, system stability is threatened by low short-circuit strength and reduction in synchronous inertia. In order to avoid complete interruption of the RES under fault conditions, the FRT operation of HVDC transmission system integrated with large-scale RES, e.g. offshore wind farms, is concerned recently [1]. The FRT capability provides the system with possibilities for power delivery to the main grid even under fault circumstances. Moreover, the FRT operation improves AC grid capability to maintain transient stability under fault condition using injection of reactive power [2]. The characteristic of the FRT profile is slightly different in grid codes defined in different countries. For example, in the Danish grid code, wind power plants must be able to withstand voltage drop down to 20% of the nominal voltage in Point of Common Coupling (PCC) over a period of minimum 0.5 sec without disconnection [3]. The grid code for the FRT operation should be developed as more RES are connected to the main grid with different structure i.e. HVDC transmission systems.

Until now, the FRT capability is usually defined for the condition of AC fault happening in AC grids. There is not a well-stablished definition or standard for the FRT capability in HVDC power grids when a DC fault happens [4]. Therefore, it is vital to develop the concept of DC-based FRT capability and define its standard for the DC grids including the multi-terminal HVDC grids [5]. Although, there have been many studies and research works on the AC FRT capability, there are not enough studies regarding the DC FRT capability and its grid code requirements in the multi-terminal HVDC grids. In particular, there are very rare works considering a systematic DC FRT operation for the multi-terminal VSC-HVDC grids [6], [7]. The AC FRT definition is usually based on system stability consideration. However, it seems that the definition of the DC FRT characteristics will depend more on system protection consideration. Meanwhile, because of different dynamics of HVDC systems to HVAC systems, the DC FRT can be totally different from what is usually presented and defined for the AC FRT capability.

DC grids including the multi-terminal HVDC systems can face instability problems based on disturbance severity and type of the system control. In ref [8], it is shown that outage of one PEC can cause the HVDC grid to be unstable. Thus, continuous operation of MMCs in a multi-terminal HVDC grid under DC fault situation can improve the HVDC system security. Behaviour of MMCs in the multi-terminal HVDC network plays a major role in system dynamics and response to DC faults. However, there is no definition or standard for the systematic DC FRT capability in HVDC power grids when a DC fault happens.

This paper sheds light on the concept of DC FRT capability for the multi-terminal MMC-HVDC grids including possible systematic FRT operation and potential grid code requirements. The DC FRT is categorised into two parts based on being a component-based function, e.g. MMC FRT function, or a systematic FRT regulations defined by operators. In addition, DC-voltage-based FRT operation is discussed, and different characteristics of the possible DC FRT profiles are investigated in this study.

This work was supported by the Sino-Danish Center for Education and Research (SDC), University of Chinese Academy of Sciences.

II. DC FRT Capability For MMC-HVDC Grids

As mentioned before, the AC FRT characteristics are usually based on system stability consideration. However, the characteristics of the DC FRT rely on system protection consideration rather than the stability issue. As there is lower impedance in HVDC links comparing to HVAC ones, the rate of change of fault current magnitude is remarkably high in case of DC faults. On the other hand, power semiconductors in MMC converter are vulnerable to fault current rising under DC fault conditions [9]. That is why the DC FRT operation should consider the system protection issues. The DC FRT capabilities and regulations of the multi-terminal MMC-HVDC grids are discussed and categorized in the following subsections.

A. Component-based DC FRT Functions and Capabilities

Component-based DC FRT functions refer to the capabilities provided by power components, e.g. MMC converter, to handle the fault situation. For example, DC choppers are a common power component used to act under fault condition to mitigate DC link over voltage [10]. However, in the multi-terminal MMC-HVDC grids, the MMC converters are the main power component to handle and interrupt DC faults, in particular for the fault-blocking MMC type [11]. The new generation of the MMCs, i.e. the fault-blocking MMC, provides the multi-terminal HVDC grids with advanced FRT capabilities [12]. However, both two-level VSC and Half Bridge (HB) MMC are not capable of interrupting DC faults and they need DC Circuit Breakers (DCCB) to interrupt fault current or blocked and disconnected from the AC network [13]. The most common types of the fault-blocking converters are Full Bridge (FB) MMC and Hybrid MMC converters [14]-[15]. Usually, these kinds of the MMCs generate inverse voltage to suppress DC fault current. There are also other types of the fault-blocking MMCs including Clamp-Diode MMC and Cross-Connected MMC, which use different structures of power switches and capacitors in their converter modules [16]. However, cost and power loss of such converters are remarkably high compared to the HB-MMC converters.

B. Concept of systematic DC FRT Regulations (HVDC Grid Code Requirements)

The systematic (system-based) DC FRT regulation refers to DC FRT operation from networks points of view i.e. from HVDC grid points of view. This may include grid code requirements of FRT and LVRT (Low Voltage Ride Through) under fault condition defined by TSOs. The systematic DC FRT regulations can be defined based on two perspective:

- First perspective: First, DC protection strategy is selected for the multi-terminal HVDC grid and then DC FRT operation is defined.
- Second perspective: First, DC FRT requirement is defined for the multi-terminal HVDC grid and then DC protection strategy is selected.

This study focuses on potential DC FRT from the first perspective for the HB-MMC based HVDC grid. Further studies including the second perspective is considered for future works. Concept of the systematic DC FRT operation and classifications based on DC protection strategies are discussed in the next section.

III. Systematic DC FRT Based on DC Votage Against Time Profile

Nowadays, common grid codes for the AC FRT capability is based on voltage against time profile. If PCC voltage magnitude is larger than a certain value during a defined time period, PEC can stay connected to the power grid. Otherwise, it is allowed to trip in order to become disconnected. On the other hand, DC FRT operation can be defined based on measured DC voltage signal in the multi-terminal HVDC grid. Under DC fault condition, the DC FRT profile determines whether MMC should stay connected to the DC grid or not.

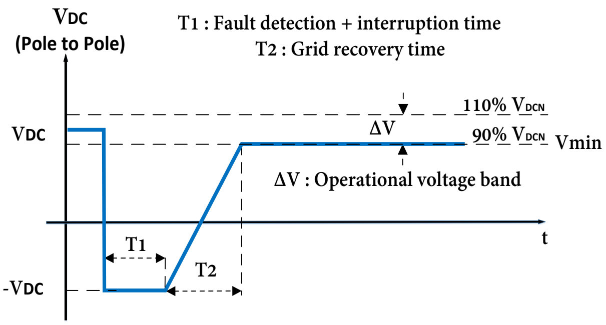
A. DC FRT profile, PCC and measurent basis

The voltage-time profile defined in the AC FRT capability is usually based on RMS of phase-to-phase voltage. For the systematic DC FRT profile, measured signal can be DC voltage on Pole-to-Ground (PG) basis or Pole-to-Pole (PP) basis. Location of DC Point of Common Connection (DC PCC) can be at converter DC terminals. Possible DC FRT profiles based on PG voltage and PP voltage measurements are shown in Fig. 1. As it can be seen from Fig. 1, there are two main stages in the DC FRT profile, 1. Fault Clearing Stage (FCS) 2. System Recovery Stage (SRS). The first stage and the second stage durations are T1 and T2 respectively. The T1 and T2 parameters can be defined as follow:

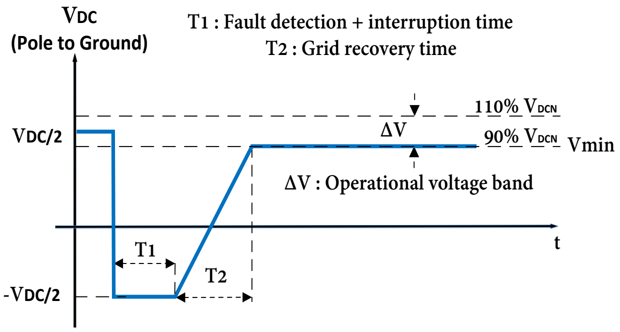
- T1 ≥ fault detection time + fault interruption time
- T2: grid recovery time after fault clearance

The fault detection and interruption times are related to speed of protection system applied to MMC-HVDC grid. In order to give enough time for the protection system to interrupt fault, the T1 parameter should be set to a value more than the time needed for fault clearance. However, the minimum value of T1 can be equal to protection function time. The grid recovery time is dependent on converter control and system layout of power grid. The recovery time in the MMC-HVDC grids can be in the range from several tens of milliseconds to several hundreds of milliseconds [17]-[18]. In addition, there can be an operational voltage band for the DC FRT profile defined for the MMC-HVDC grids. The minimum and the maximum voltages for operational condition are 90% and 110% of nominal DC voltage shown in Fig. 1.

There are two types of DC faults in HVDC grids: 1. PP fault 2. PG fault (including negative PG fault and positive PG fault). In AC FRT grid codes, there are usually different requirements and profiles defined for asymmetric faults, e.g. single-phase-to-ground fault, and symmetric faults, e.g. three-phase fault. Similar to AC FRT regulation, it can be



(a)



(b)

Fig. 1. Voltage-based DC FRT profile, (a) PP voltage basis (b) PG voltage basis.

different profiles for the PP fault and the PG fault in DC FRT definition. Consequently, PG-voltage-based profile can be defined for the cases of the PG faults and PP-voltage-based profile can be defined for the cases of PP faults.

When a DC fault happens in the multi-terminal MMC-HVDC grids, DC protection system is supposed to send trip order to DCCBs assigned to faulted line immediately after fault detection. If the protection system is successful to interrupt the DC fault, DC grid voltage comes back to normal value and the DC voltage signal does not exceed the DC FRT profile shown in Fig.1. If the protection system fails to interrupt DC fault, DC voltage cannot recover and the DC FRT profile will be exceeded. Consequently, MMC can be disconnected by opening of AC Circuit Breaker (ACCB) at the AC side of converter.

B. DC FRT profile definition based on MMC type

As discussed in the section II, there are different types of MMC including the HB-MMC and the fault-blocking MMC like the FB-MMC. As these types of the MMCs have different behaviours under DC fault conditions, DC FRT profiles assigned to them can be different. The fault-blocking converters can keep controllability under a severe voltage dip, i.e. DC voltage near to zero or even less than it. Therefore, the FRT profile shown in Fig. 1 can be applicable to the HVDC grids based on the fault-blocking MMCs. On the other hand, the HB-MMC will be usually blocked when DC voltage magnitude decreases to a certain level. This level is set by converter protection for the HB-MMC and it is usually about 0.8 p.u of nominal DC voltage [9]. There is also another threshold for blocking the HB-MMC based on overcurrent limitation of the converter semiconductors. This threshold is usually set on double of nominal current for the HB-MMC.

The DC FRT profile for the grid based on the HB-MMCs is depended on whether grid operator allows for temporary blocking of MMCs or not. If temporary blocking of converters is allowed under fault condition, the FRT profile is the same depicted in Fig. 1. On the contrary, if temporary blocking of converters is not allowed, it is necessary to move upward the minimum voltage limit defined in the FRT profile. Thus, the minimum limit of the FRT profile is equal to the minimum voltage to keep the HB-MMC unblocked. Fig. 2 shows an example of the FRT profile for the HVDC grid based on the HB-MMC, in which MMC blocking is not allowed. It can be seen that the minimum voltage limit in the DC FRT profile can be different based on the MMC type and grid operator regulations.

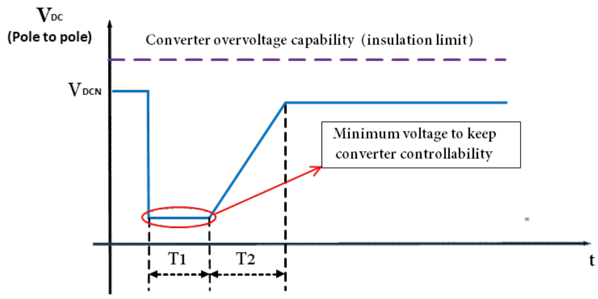


Fig. 2. Possible voltage-based DC FRT profile for HVDC grid based on the HB-MMC in which MMC blocking is not allowed.

C. DC-protection-oriented DC FRT

Based on the first perspective of the definition of the systematic DC FRT regulations presented in the section II, characteristics of the DC FRT profiles will depend on the features of the chosen protection strategy for the MMC-HVDC grids. Therefore, DC FRT definitions and profiles can be classified based on HVDC protection scheme. The multi-terminal MMC-HVDC grid can have different protection strategies as the following [13]:

- Fully selective strategy using fast DCCBs
- Fully selective strategy using slow DCCBs
- Partially selective strategy using fault-blocking MMCs
- Non-selective strategy using ACCB on AC-side of MMCs

In the fully selective strategy, only faulted line is isolated from the multi-terminal HVDC grid and rest of the system can continue to transfer power through healthy lines. Usually, DCCBs are installed at both ends of DC link to interrupt faults. Hybrid and static types of DCCBs are so-called fast DCCBs in this study, as they are able to interrupt fault current within 5 ms [19]. Slow DCCB corresponds to mechanical types of DCCB that can isolate a faulted line in about 10 ms [9]. Protection strategy based on the fault-blocking MMC is considered a partially selective strategy, as other healthy lines connected to the MMC will be affected under fault condition in addition to the faulted line. Fast Mechanical Switches (FMS) are usually used to isolate the faulted line after fault current blocking by MMC. The last mentioned strategy is the non-selective protection scheme that uses the ACCB on AC-side of MMCs against DC faults. The whole HVDC grid will be shut down in this strategy in case of a DC fault. Thus, DC FRT definition is not feasible when a multi-terminal HVDC system uses this kind of protection strategy.

Based on MMC position to fault location in the multi-terminal HVDC grid, two types of DC FRT operation can be defined for each MMC. As shown in Fig. 3, suppose that a fault happens in line 12, MMC1 & 2 which are directly connected to the faulted line, can be considered as main MMCs. On the other hand, MMC3 & 4 which are indirectly connected to the faulted line, can be considered as adjacent MMCs. This difference in the MMC positions will lead to different expected behaviour of MMCs including different DC FRT profiles. Therefore, each MMC in the HVDC grid can have two types of DC FRT operation, regarded as the main FRT profile and the adjacent FRT profile. Calculation of the parameter T1 in the main and adjacent FRT profiles is as follows:

- T1 in the main FRT profile ≥ fault detection time + fault interruption time of DCCB assigned to faulted line.
- T1 in the adjacent FRT profile ≥ T1 in the main FRT profile + communication delay + fault interruption time of backup DCCB.

For example, for the MMC1 as the main MMC in Fig. 3, it is supposed that CB12 will be opened to interrupt the fault after fault is detected. Thus, the whole fault clearing time includes fault detection time and DCCB12 opening time. On the other hand, MMC3 as the adjacent MMC, will wait until the main FRT time, i.e. T1, defined for the MMC1 is finished. If DC voltage recovers to nominal value after this time, process will be finished and the HVDC grid will be recovered. On the contrary, if DC voltage does not recover to normal value, CB31 will be ordered to open after a communication delay to stop current feeding through line 14. Therefore, T1 in the adjacent MMC3 profile includes T1 of the MMC1, the communication delay and DCCB31 opening time. The main and adjacent DC FRT profiles are depicted in Fig. 4.

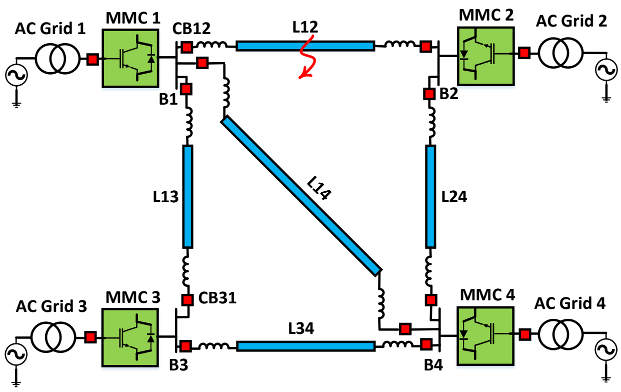


Fig. 3. A four-terminal MMC-HVDC grid (case study).

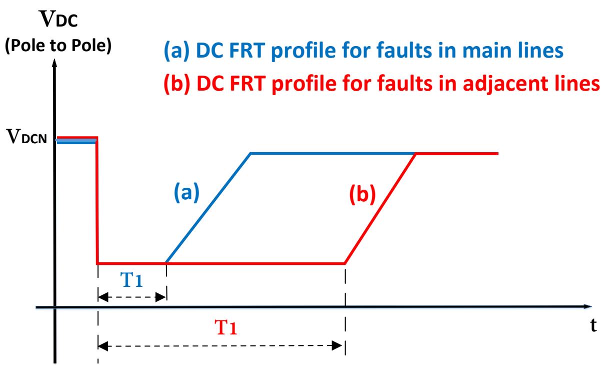


Fig. 4. DC FRT profile based on MMC position to fault location, (a) the main MMC (b) the adjacent MMC.

The systematic voltage-based DC FRT can be categorized into three classes based on the selected protection strategy:

a) Short Time DC FRT: for HVDC grids that use the fully selective protection strategy and the fast DCCBs, the parameter T1 defined in the DC FRT profile will have a relatively short time. Amount of the T1 parameter in this type of the DC FRT profile can be less than 10 ms for both the main and adjacent MMCs. As fast protection will lead to less disturbances in the multi-terminal HVDC grid, shorter grid recovery time (T2) is also expected in this class.

b) Medium Time DC FRT: for HVDC grids that use the fully selective protection strategy and the slow DCCBs, the time T1 defined in the DC FRT profile can have an aproximate amount of 10 ms for the main MMCs and 25 ms for the adjacent MMCs. However, this type of DC FRT operation has longer time compared to the short time DC FRT.

c) Long Time DC FRT: for HVDC grids that use the fault-blocking MMC and FMS to handle fault situation, DC voltage of all MMCs have to be reduced to zero to interrupt a DC fault. Therefore, it is not a selective strategy, as the whole DC grid will be affected when a fault happens in one of the DC links. Although, voltage of the whole DC grid is reduced to zero, the situation is different from complete shutdown, as DC voltage is actively controlled by the MMCs. Therefore, this function can be considered as a different type of FRT operation. After fault clearance and deionization time, FMSs related to faulted line can be opened to isolate faulted link. Although, the fault-blocking MMCs can reduce voltage to be zero within 5ms, fault current interruption and deionization usually take several hundred milliseconds [20]. Also, the FMS opening time is in the range from 300 ms to 450 ms [19]. Thus, the T1 parameter in this type of the DC FRT profile can be much larger than the ones in two previous DC FRTs. However, the T1 depends on fault blocking time of the MMC and FMS opening time. Possible classifications of the DC FRT operation based on time duration (T1) of the profile are depicted in Fig. 5.

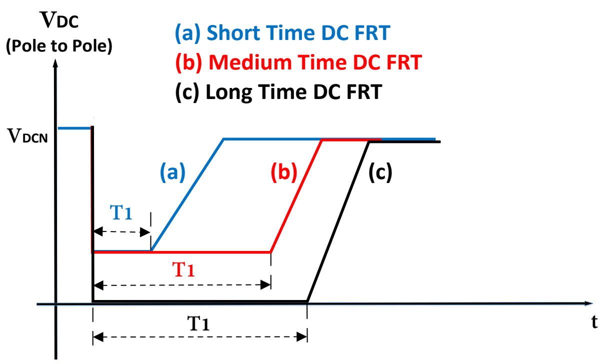
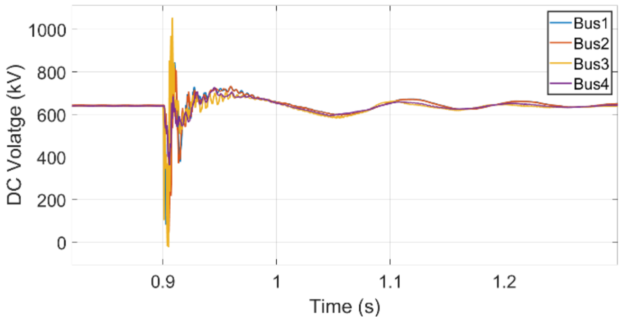


Fig. 5. DC FRT classes based on operation time, (a) short time (b) medium time (c) long time.

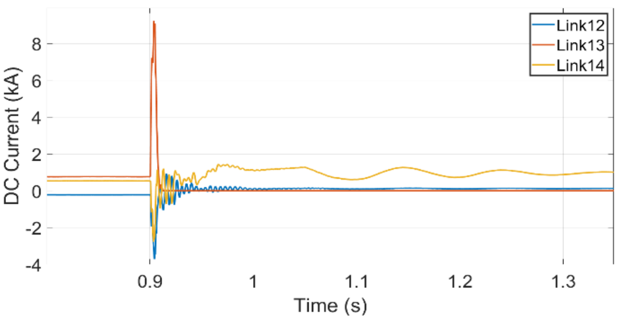
IV. Simulation Results

Fig. 3 shows the case study of a four-terminal HVDC grid with symmetric monopole configuration [21]. All MMCs of the grid are allowed to temporarily block under fault condition. The nominal voltage of the grid is ±320 kV and the HB-MMCs are simulated using the continuous converter model. The MMC1 and MMC2 are connected to offshore wind farms and transmit electrical power to onshore grids including the MMC3 and MMC4. The MMC1, MMC2 and the MMC3 have the rated power of 900 MW, while it is 1200 MW for the MMC4. Each DC link has a DCCB at each end of the link. There is the series DC reactor for each DCCB that has a value of 50 mH. The length of the link L13 and L14 is 200 km, while it is 100 km for the link L12 and L34. The DC links are XLPE cables simulated using frequency-dependant model. More details of the case study can be found in [21].

Fig. 6 (a) depicts voltages of all DC buses (B1, 2, 3 & 4) of the case study when a PP fault happens at the time 0.9 s in the middle of cable L13. After 5 ms, the fast DCCBs assigned to the link L13 are opened to interrupt the fault. As it can be seen, the grid voltage came back to the nominal value after fluctuations. DC currents of the faulted link and also other links connected to the bus1 are shown in Fig. 6 (b). The faulted link (L13) experienced a severe current rising after fault happening. Magnitude of the fault current reached to more than 8 kA in this link before the DCCB opening.



(a)



(b)

Fig. 6. Simulation results when a PP fault happens at the time 0.9 s, (a) DC bus voltages (b) DC currents.

Short time DC FRT profile and voltage signals for the case of PP fault happening in the link L13 are shown in Fig. 7. DC voltages of bus1 and bus3, related to the voltage of MMC1 and MMC3 as the main MMCs, can be seen in this figure. The fully selective strategy with fast DCCBs is applied to protect the grid in this case. The parameter T1 in the FRT profile is selected to be 5 ms including fault detection time of 2 ms and DCCB opening time of 3 ms. Also, the grid recovery time (T2) is selected to be 200 ms. As the DCCBs of link L13 were successful to interrupt fault current on time, the voltages of MMC1 & 3 did not exceed the FRT profile. Therefore, the MMCs can stay connected to the grid under fault condition. Fig. 8 shows the results when the fast DCCBs of the faulted link failed to interrupt fault current. It can been seen that the DC voltages did not come back to the nominal value and then exceeded the FRT profile. Therefore, the MMCs are allowed to be disconnected to stop feeding fault current from AC side.

Medium time DC FRT profile and voltage signals for the case of PP fault happening in link L13 are depicted in Fig. 9. In this case, the fully selective protection strategy with slow DCCBs is chosen. The parameter T1 in the FRT profile is selected to be 12 ms including fault detection time of 2 ms and DCCB opening time of 10 ms. Also, the grid recovery time (T2) is selected to be 300 ms. As the DCCBs of the faulted link were successful to interrupt fault current on time, the DC voltages of MMC1 & 2 did not exceed the FRT profile. Therefore, the MMCs can stay connected to the grid under fault condition in this case. The results for the case of a PG fault happening at time 0.9 s are shown in Fig. 10. Comparing the results in Fig. 10 to the ones in Fig. 9 demonstrates that PG faults are less severe rather than PP faults. Thus, DC voltage fluctuations in case of a PG fault in the multi-terminal MMC-HVDC system are comparatively smaller. Consequently, the recovery time of the HVDC system after a PG fault interruption is usually shorter than the one after a PP fault interruption. In addition, Fig. 11 depicts the results when a PP fault is happening at the beginning of the link L13. In general, the simulation results of the case study show that the selected parameters for the DC FRT profile are appropriate, as the voltage signals do not exceed the profile if the protection system is successful to do its duty.

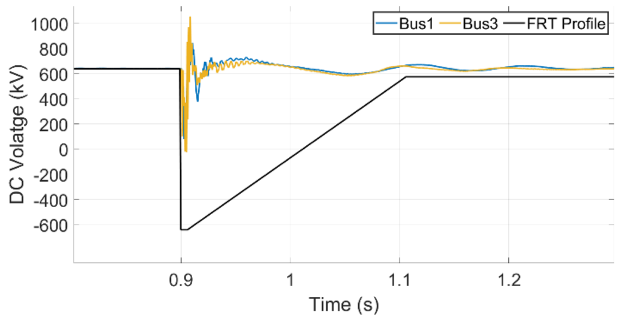


Fig. 7. Voltage-based DC FRT profile and voltage of bus 1 and bus 3 under DC fault condition with successful operation of fast DCCBs.

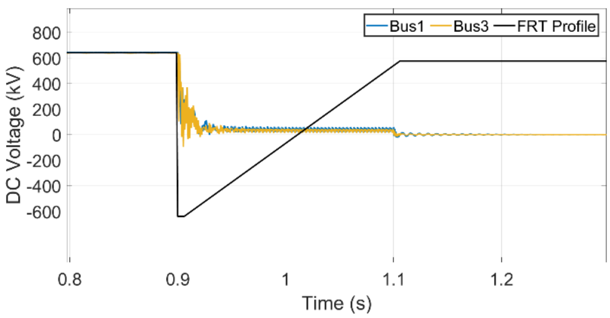


Fig. 8. Voltage-based DC FRT profile and voltage of bus 1 and bus 3 under DC fault condition with failed operation of fast DCCBs.

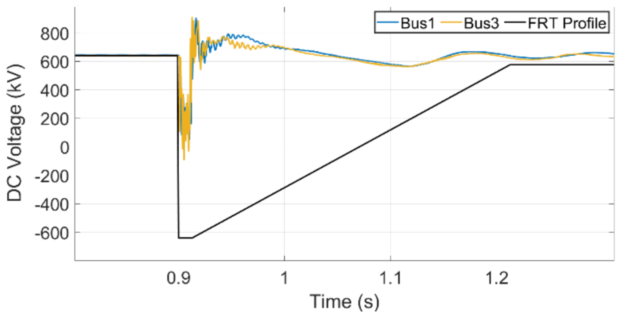


Fig. 9. Voltage-based DC FRT profile and voltage of bus 1 and bus 3 under PP fault condition with successful operation of slow DCCBs.

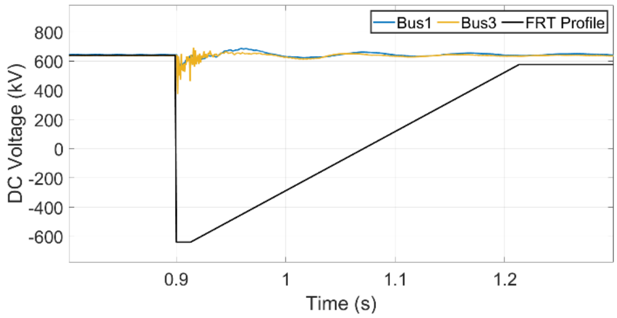


Fig. 10. Voltage-based DC FRT profile and voltage of bus 1 and bus 3 under PG fault condition with successful operation of slow DCCBs.

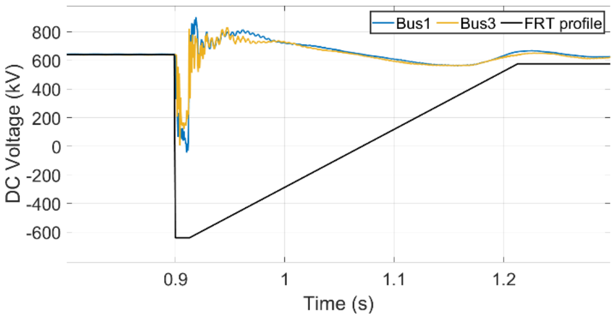


Fig. 11. Voltage-based DC FRT profile and voltage of bus 1 and bus 3 under DC fault condition with successful operation of slow DCCBs.

V. Conclusions

The multi-terminal MMC-HVDC system is going to become a backbone network for the future power grids. Therefore, it is vital to develop and enhance grid code requirements and standardizations related to modern HVDC system not as an AC grid component, but as a grid. This study presented the concept of systematic DC FRT operation for the multi-terminal MMC-HVDC grids. The systematic DC FRT can be defined and regulated by HVDC operators to have a better control of the system and achieve minimum affected area under DC fault condition. The differences between the DC FRT profiles of HVDC grid based on MMC types have been discussed. The DC-protection-oriented DC FRT is presented as a way to define the systematic DC FRT based on protection scheme selected for HVDC grid.

The characteristics of the DC FRT profile and possible parameter calculation have been analysed and investigated in this study. Also, the DC FRT operation has been categorized into short, medium and long time ones. The simulation result demonstrated that it is possible to define a proper DC FRT profile for the multi-terminal HVDC grids.

References

[1] F. Deng, Z. Chen, “Operation and Control of a DC-Grid Offshore Wind Farm under DC Transmission System Faults,” IEEE Transactions on Power Delivery, Vol. 28, No. 3, 2013.

[2] A. A. Van der Meer, M. Ndreko, M. Gibescu, et al. “The Effect of FRT Behavior of VSC-HVDC Connected Offshore Wind Power Plants on AC/DC System Dynamics,” IEEE Transactions on Power Delivery Vol. 31, No. 2, 2016.

[3] C. Liu, Z. Chen, C. L. Bak, et al. “Transient Stability Assessment of Power System with Large Amount of Wind Power Penetration the Danish Case Study,” 10th International Power & Energy Conference (IPEC), 2012.

[4] B. Nouri et al., "Comparison of European Network Codes for AC- and HVDC-connected Renewable Energy Sources," in *Proceedings of the 18th Wind Integration Workshop*, 2019.

[5] M. Wang et al., "Review and outlook of HVDC grids as backbone of the transmission system," in *CSEE Journal of Power and Energy Systems*, 2020.

[6] PROMOTioN project, "Requirement recommendations to adapt and extend existing grid codes," Deliverable 2.4, 2020.

[7] CIGRE, WG B4.56, "Guidelines for the preparation of “connection agreements” or “grid codes” for multi-terminal DC schemes and DC grids," May 2016.

[8] L. Meegahapola, A. Sguarezi, J. S. Bryantet, et al. “Power System Stability with Power-Electronic Converter Interfaced Renewable Power Generation Present Issues and Future Trends,” Energies, vol. 13, no. 13, pp: 1-35, 2020.

[9] M. Zaja and D. Jovcic, "Coordination of mechanical DCCBs and temporary blocking of half bridge MMC," *15th IET International Conference on AC and DC Power Transmission (ACDC 2019)*, Coventry, UK, 2019.

[10] X. Zhang, Y. Lu, D. Shi, “The Transient Distance Protection on Wind Farm Transmission Line with Crowbar Protection,” *2nd International Conference on Power and Renewable Energy*, 2017.

[11] J. Zhang and C. Zhao, "The Research of SM Topology With DC Fault Tolerance in MMC-HVDC," in *IEEE Transactions on Power Delivery*, vol. 30, no. 3, pp. 1561-1568, June 2015.

[12] W. Li, M. Zhu, P. Chao, X. Liang and D. Xu, "Enhanced FRT and Postfault Recovery Control for MMC-HVDC Connected Offshore Wind Farms," in *IEEE Transactions on Power Systems*, vol. 35, no. 2, pp. 1606-1617, March 2020.

[13] W. Leterme, D. V. Hertem, “Classification of Fault Clearing Strategies for HVDC Grids,” *Cigre, 21, rue d'Artois*, Paris, 2015.

[14] J. Hu, Z. He, L. Lin, K. Xu and Y. Qiu, "Voltage Polarity Reversing-Based DC Short Circuit FRT Strategy for Symmetrical Bipolar FBSM-MMC HVDC System," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1008-1020, Sept. 2018.

[15] S. Cui and S. Sul, "A Comprehensive DC Short-Circuit Fault Ride Through Strategy of Hybrid Modular Multilevel Converters (MMCs) for Overhead Line Transmission," in *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7780-7796, Nov. 2016.

[16] R. Marquardt, "Modular Multilevel Converter topologies with DC-Short circuit current limitation," *8th International Conference on Power Electronics - ECCE Asia*, Jeju, 2011, pp. 1425-1431.

[17] O. Cwikowski, H. R. Wickramasinghe, G. Konstantinou, J. Pou, M. Barnes and R. Shuttleworth, "Modular Multilevel Converter DC Fault Protection," in *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 291-300, Feb. 2018.

[18] M. Abedrabbo et al., "Impact of DC grid contingencies on AC system stability," *13th IET International Conference on AC and DC Power Transmission (ACDC 2017),* Manchester, UK, 2017.

[19] M. Barnes, D. S. Vilchis-Rodriguez, X. Pei, R. Shuttleworth, O. Cwikowski and A. C. Smith, "HVDC Circuit Breakers–A Review," in *IEEE Access*, vol. 8, pp. 211829-211848, 2020.

[20] S. Yan, Z. He, J. Yang, M. Kong and M. Hu, "Optimized Protection Strategies for HVDC Grid with Fault-blocking Modular Multilevel Converters for Overhead Line Applications," in *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 6, pp. 1168-1177, 2020.

[21] W. Leterme, N. Ahmed, J. Beerten, L. Ängquist, D. V. Hertem and S. Norrga, "A new HVDC grid test system for HVDC grid dynamics and protection studies in EMT-type software," 11th IET International Conference on AC and DC Power Transmission, 2015.