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Dynamic performance of series multiterminal HVDC during AC faults at inverter stations

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«HVDC», «LCC», «Series MTDC», «Dynamic performance», «AC faults»

Abstract

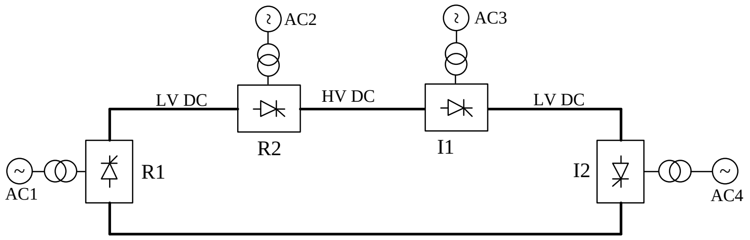
Multiterminal high voltage direct current (MTDC) system can be either a series type or a parallel type. Series MTDC concept is essentially developed from the two- terminal HVDC but with some unique characteristics. In this paper, the AC fault ride through capability of series MTDC is discussed. The AC fault at inverter stations, which are connected to electrically separated AC systems, will be highlighted. For AC fault happens at one inverter station of series MTDC, the DC voltage of the corresponding inverter station may decrease to zero due to commutation failure, while the operation status of the other inverter stations (the healthy inverters) may still remain power transmission capability to some extent, which increases the availability of the series MTDC system. However, the current controller design, the voltage dependent current order limiter (VDCOL) logic and the AC system strength will impact on the dynamic performance. In this paper, a +800kV/3.2GW 4-terminal line commutated converter (LCC) based series MTDC model is established to study the dynamic performance during AC fault occurs at one inverter. The controller of the series MTDC is designed; the VDCOL logic for series MTDC is developed; simulation results of the dynamic performance during AC faults at the inverter station are presented.

Introduction

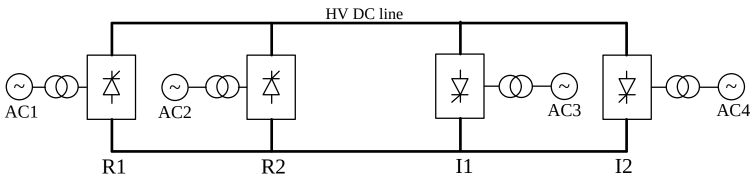
The MTDC system consists of more than two separated HVDC substations and interconnecting HVDC transmission lines [1]. MTDC technology is very attractive for bulk power transmission with dispersed energy resources or load centers. Generally speaking, A MTDC system can be based on either line commutated converter (LCC) or voltage source converter (VSC). LCC MTDC technology has been available for more than 20 years. One example is the 2000 MW New England- Hydro Quebec MTDC in operation in 1992 [2]. The most recent MTDC project is the 4-terminal 800kV LCC MTDC system in India, which will connect North East India with Agra rated at a maximum power of 8000MW [3, 4]. In China, the feasibility of using LCC MTDC for long distance HVDC transmission has also been discussed [5, 6]. Recent study results show that most of UHVDC projects to be constructed in the 12th Five-Year-Plan period can employ LCC MTDC technology [7]. On the other hand, the VSC MTDC employs self-commutated converter, which consists of gate turn-off components and thus brings more control flexibility[8]. In Europe, a regional multiterminal HVDC grid has been proposed, based on VSC technology [9, 10]. In China, a 4-terminal VSC MTDC transmission, used for wind power integration, was commissioned at Nan'Ao Island in 2013, while another 5-terminal VSC MTDC at Zhoushan Archipelago is under development.

Existing studies have shown that VSC MTDC provides significant advantages to transmission network, such as decoupled active power and reactive power control, support for weak AC systems and passive network power supply[4, 8, 11]. However, VSC MTDC is still limited by the transmission capacity whereas an LCC MTDC is capable of achieving higher power transmission up to up to more than 7 GW per converter bipole nowadays.

An LCC MTDC can be either a parallel or a series connection system [12], as shown in Fig. 1. Generally speaking, parallel type LCC MTDC (abbreviated as parallel MTDC) has lower power losses than series type LCC MTDC (abbreviated as series MTDC). Besides, parallel MTDC is easy for expansion. By far, most of existing studies focus on parallel MTDC.



(a) Series type MTDC



(b) Parallel type MTDC

Fig. 1. Basic LCC MTDC solutions: series and parallel

For parallel MTDC, all converters are connected to the same line and provided with voltage and current control. DC voltage is controlled by one converter (often the largest converter) while the other converters control their own DC currents. Experience of parallel operation of converters is well established within the HVDC history. By 1963, the basic principle was firstly proposed [13] and thereafter numerous literatures discussed the application of parallel MTDCs.

For series MTDC, the concept was proposed early in 1965 [14]. The series MTDC solution is essentially extended from two-terminal bipolar operation of HVDC but the converters are geographically far apart. In a series connected MTDC scheme, current is controlled by one terminal and all other terminals operate with a firing angle limit or DC voltage control mode.
Both series MTDC and parallel MTDC will have advantages over two-terminal HVDC when the transmission distance between different power resources or load centers is long. Since the line losses of series MTDC is higher than that of parallel MTDC whereas the total cost of series converter stations is lower, the series MTDC will have advantage of lower cost when the distance between converter stations at sending ends or receiving ends is within a certain value. In particular, compared with parallel MTDC, series MTDC is a competitive solution for high altitude application owning to the insulation cost for the converter station and transmission line at higher altitude area will be reduced greatly. The power generated at higher altitude area can be transmitted by lower voltage converter station and bundled with the power from series connected higher voltage converter stations, which are located at low altitude area and usually integrated with thermal power. One potential application is the power transmission from Tibet plateau, where the hydropower and solar power resources are abundant.

Another potential advantage of series MTDC is that is has superior AC fault ride through behavior, if the inverters in the MTDC system are connected to electrically seperated AC systems. When AC fault happens at one inverter station, the DC voltage of the corresponding inverter station may decrease to zero due to commutation failure, while the other inverter stations can operate normally, on the condition that AC systems of the inverters are strong enough and the current controller at the current setting terminal is designed properly. As a contrast, in the parallel MTDC, the commutation failure of any inverter will result in the DC voltage sag along the whole transmission line, and the power transmission of the whole MTDC system will be decreased to a rather low level temporarily and has longer recovery time after fault.

Although the concept of series MTDC was proposed 50 years ago, it hasn't been a hot topic until recent years. In the new emerging countries like China and Brazil, series MTDC technology is under evaluation because it is thought as an option for certain applications. In 2011, an estimation on the economic influence of two terminal HVDC system and series MTDC (or cascaded MTDC denominated by Chinese TSOs) with two sending stations was presented in [15]. Based on a ±800kV/7600MW and 2300 km series MTDC system, the paper illustrated that series MTDC will have lower investment than two-terminal HVDC, when the saved AC line investment is below a certain value. In 2012, reference [16] studied the insulation coordination for a ± 800 kV series MTDC system and concluded that except ± 400 kV medium voltage lines, the insulation coordination for the rest of the substation equipment and lines can be complied with those for conventional two-terminal ± 800 kV HVDC system; reference [17] discussed the DC line fault protection strategy of both parallel MTDC and series MTDC qualitatively and concluded that protection of series MTDC is more complex than that of parallel MTDC. In 2013, reference [18] proposed a hierarchical connection mode to form a multi-infeed UHVDC system, in which two converter stations at receiving end are located in the same place, but are connected to deferent AC systems, which can be regarded as a specific series MTDC case in which the length of the medium DC voltage line between the two inverter stations could be neglected.

To sum up, the series MTDC has potential application in the future for either multiple power supply integration or multi-infeed application, whereas the existing studies focus on techno-economic analysis, protection strategy and steady state analysis. In this paper, the dynamic performance of series MTDC during AC fault at inverter side is focused. Based on a 4-terminal +800kV/3.2 GW monopole series MTDC system model, the control method of series MTDC is introduced. The VDCOL for each station is designed. Finally, AC faults are implemented at the selected inverter station to observe the impact on the other inverter stations.

Modeling and control of series MTDC

Modeling

A +800 kV/3.2 GW monopole 4-terminal series MTDC model is established in Matlab/Simulink for the dynamic performance study in this paper. The single line diagram of the model is shown in Fig. 2. The main circuit parameters are primarily created from Xiangjiaba-Shanghai UHVDC project. The 4-terminal series MTDC has 2 rectifiers (R1 and R2) and 2 inverters (I1 and I2). The main parameters of the model are listed in Table 1.

Table 1 Main parameters of the +800 kV/3.2 GW monopole 4-terminal series MTDC model

AC systems		**DC systems**	
Nominal voltage at R1 and R2 (kV)	530	Nominal voltage of R1 and R2 (kV)	400
Nominal voltage at I1 and I2 (kV)	515	Nominal voltage of I1 and I2 (kV)	373
		Nominal DC current (kA)	4
DC Line parameters		**Control parameters**	
Resistance (Ω/km)	0.00665	Minimum firing angle α	5°
Inductance (H/km)	2.5e-3	Nominal firing angle of rectifier R1	15°
Capacitance (F/km)	1.2e-8	Nominal extinction angle of inverters	17°

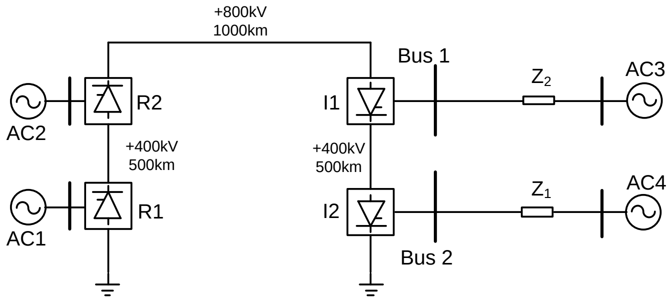
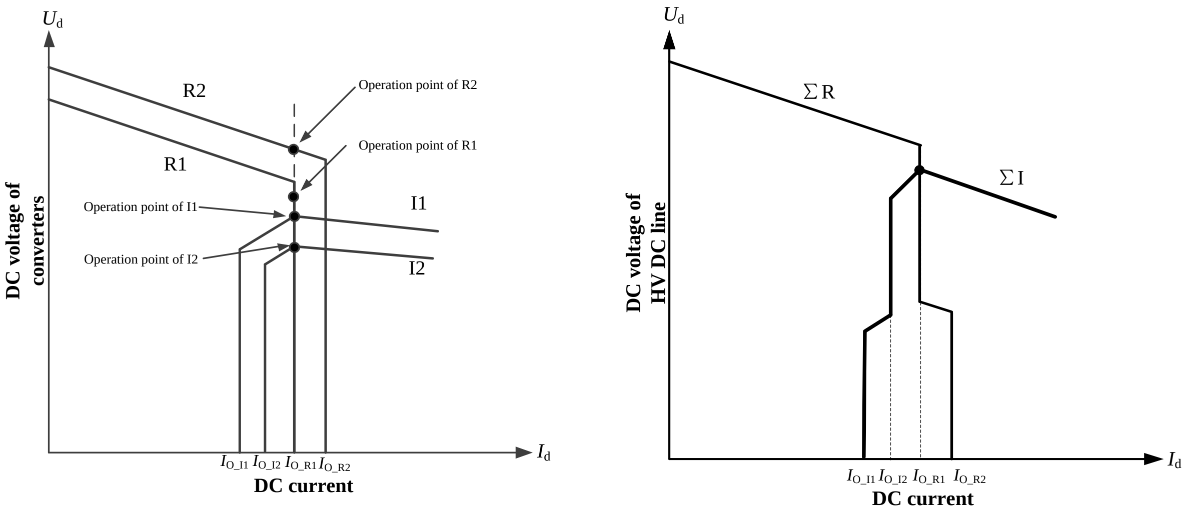


Fig. 2. +800 kV/3.2 GW monopole 4-terminal series MTDC model

The main circuit representation of the monopolar MTDC system includes the following equipment: four converter stations each with one 12 pulse converter, DC smooth reactors, AC filters and Shunt banks, DC filters and HVDC transmission lines.

Control

In a series MTDC control scheme, DC current is controlled by one terminal and all other terminals operate with firing angle or extinguishing angle limit ($\alpha_{min}/\gamma_{min}$ control). Generally, the DC current control is assumed by a rectifier, as shown in Fig. 3 (a). In this example, rectifier R1 assumes the current setting terminal (CST) and controls DC current during normal operation; other converters operate at $\alpha_{min}/\gamma_{min}$ control which will define their DC voltages respectively. Fig. 3 (b) shows the synthetic V-I characteristics of all the 4 converter stations. Note that to highlight the control principle, the VDCOL function is not reflected in Fig. 3.



(a) V-I characteristics of each station (b) Synthetic V-I characteristics

Fig. 3. V-I characteristics of the series MTDC

In the series MTDC system, a current margin sequence is also needed to be defined. The current order of CST rectifier should always be larger than that in inverters and smaller than that in the rectifier with DC voltage control. Therefore the current orders of R1, R2, I1 and I2 in the model have the following relationship to form current margins:

$$I_{O\_R2} > I_{O\_R1} > I_{O\_I2} > I_{O\_I1} \qquad (1)$$

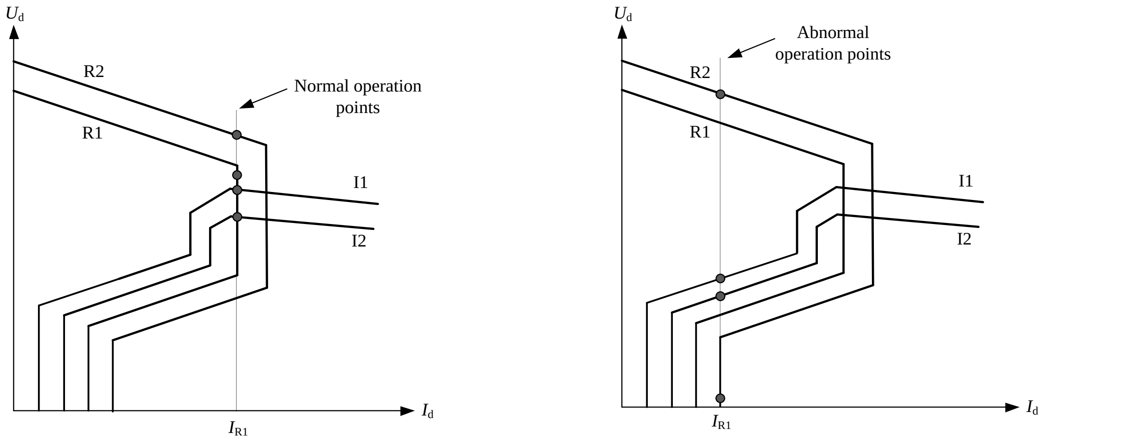
In each inverter controller of series MTDC, positive slope modification is added to avoid the coincidence between minimum firing angle and minimum extinction angle operation during unfavorable AC voltage conditions, which is similar to the control characteristics in two-terminal HVDC system.

Voltage dependent current order limiter (VDCOL)

The VDCOL function will reduce the current order *I*o during the reduction of the DC voltage. VDCOL has been widely used in 2-terminal HVDC systems and also necessary for series MTDC system. The main reasons for using the VDCOL function are:

- Avoid power instability during and after disturbances in the AC network.
- Define a fast and controlled restart after clearance of AC and DC faults.
- Avoid stresses on the thyristors at continuous commutation failure.
- Suppress the probability of consecutive commutation failures at recovery.

The basic V-I characteristics of each converter station in the series MTDC is shown in Fig. 4 (a). However, the existing VDCOL function, which is designed originally for the 2-terminal HVDC system, cannot be applied directly to a series MTDC system. For the series MTDC, the DC voltages in the VDCOL function are defined across the converters, and the decreased DC voltage at a the terminals with DC voltage control may not be measured by the CST directly and vice versa, the current margin rule will be destroyed without additional coordination of current orders, which will result in abnormal operation point of the series MTDC system. An example is given in Fig. 4 (b) to show the disorder of current margins during and the consequent abnormal system operation point finally. In Fig. 4 (b), R1 controls the DC current while the R2, I2 and I2 control respective DC voltages during normal operation. While an AC voltage depression at I1 happens, the DC voltage of I1 will decrease greatly. Subsequently, the DC voltage of R1will decrease and DC current I_d will also decrease, which is determined by VDCOL of R1. When I_d is lower than I_{O_I1} and I_{O_I2}, the current controllers in I1 and I2 will start de-saturation and begin current control. After the AC fault at I1 is cleared, both I1 and I2 will still control the DC current. Therefore, new steady operation points are established when R1, I1 and I2 operate at current control together, which will result in very low voltage of R1 and trigger DC undervoltage protection.



(a) Normal operation points

(b) Abnormal operation points after AC fault at I1

Fig. 4. Basic V-I characteristics of converter stations of the series MTDC based on existing VDCOL function

In contrast, such situation will not happen in a 2-terminal HVDC or even parallel MTDC system. For example, in a two-terminal HVDC system, the current reference of rectifier is always higher than that of inverter, because the DC voltage of rectifier and inverter are almost the same during steady or transient state, which makes the system return to the normal operation point finally.

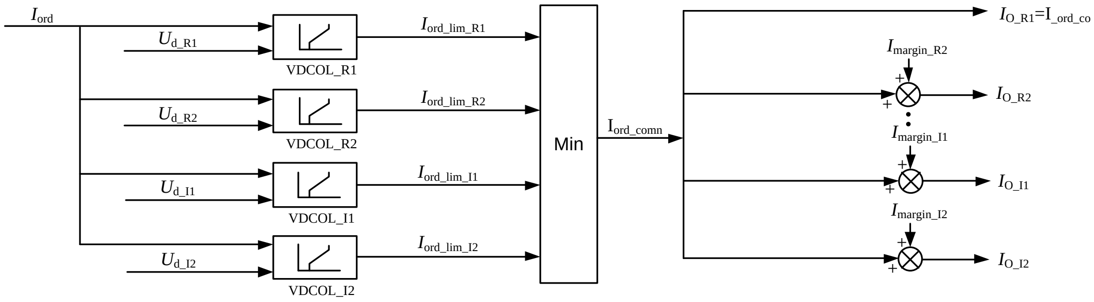


Fig. 5. VDCOL function and DC current order calculation of each converter in the series MTDC

To resolve this issue, one simple solution is to set current margins for current orders of every converter during both steady state and transient state of the series MTDC, while the sequence of current margins is still kept unchanged. The proposed solution is illustrated in Fig. 5. Each converter station in the series MTDC calculates the respective current order limit value I_{ord_lim} according to the respective DC voltage U_d. The minimum value among the current order limit values will be set as common current reference. The individual current order for each converter is obtained by the superposition of respective current margin.

Dynamic performance during AC faults at inverter

Based on the proposed control algorithm, the dynamic performance of series MTDC during AC faults at inverter stations has been studied.

1) AC fault at inverter I1

If the AC voltage of I1 decreases due to AC fault, the DC voltage of I1 will decrease as well. Consequently, the DC voltage of CST (rectifier R1) will also decrease because its firing angle α will increase to keep the DC current following its reference value. When DC voltage of R1 or I1 decreases below the threshold voltage of VDCOL, the current orders for each converter start to decrease proportionally. The current margins between each converter are not changed in order to ensure the current control for R1, α_{min} control (for R2) and γ_{min} control (for I1 and I2), as shown in Fig. 6. The V-I curve of I1 during AC fault is represented by I1´. The current order of R1 is changed from I_{R1} to I_{R1}´ by VDCOL function during the AC fault.

2) AC fault at inverter I2

The operation procedure of each converter station is similar to that of AC fault at I1. The object of the operation is to keep the current margins between each converter unchanged by following the VDCOL logic defined at each converter stations, as shown in Fig. 7. The V-I curve of I2 during AC fault is represented by I2´.

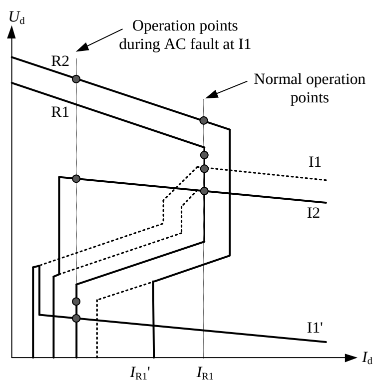


Fig. 6. V-I characteristic of each converter station during AC fault at Inverter I1

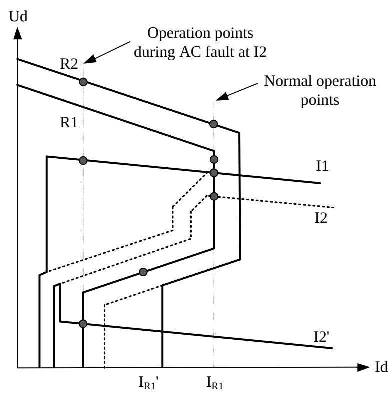
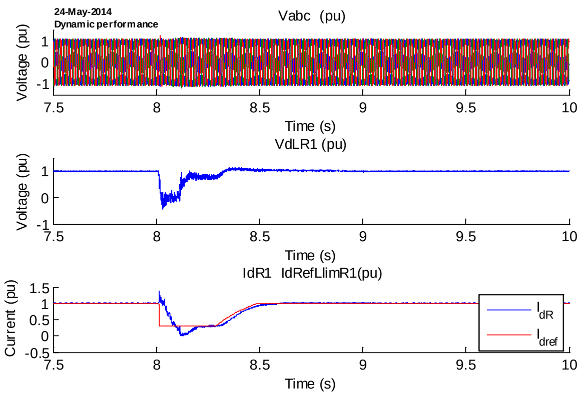


Fig. 7. V-I characteristic of each converter station during AC fault at Inverter I2

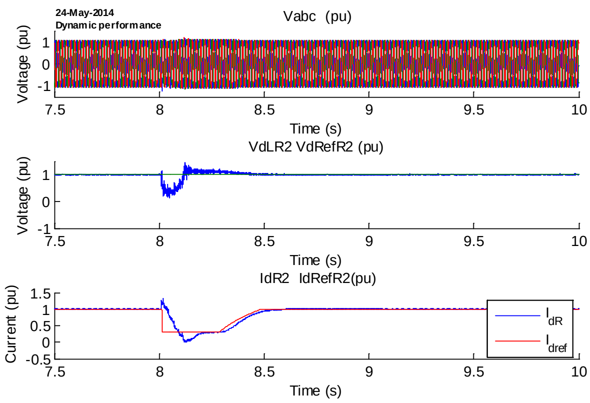
Without loss of generality, the dynamic response of 3- phase to ground (3phg) AC fault at I1 is presented in this paper. The remained AC voltage at I1 during AC fault is set to 10% of its nominal value to simulate a fault electrically close to the converter. The AC fault is simulated by a programmable three-phase voltage source module.

Two scenarios with different short circuit ratio (SCR) for the entire four AC network are included in the simulation study, i.e. SCR=10 SCR=3 respectively.

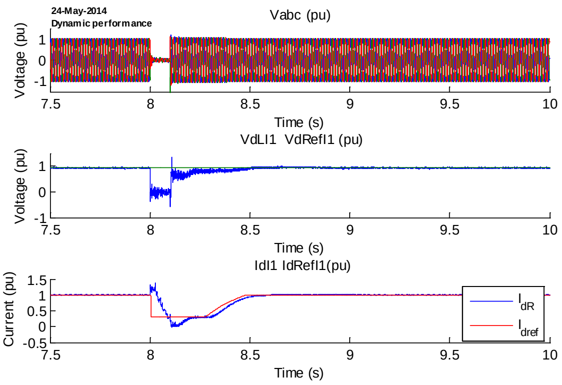
The long distances between different terminals of MTDC have an impact on the traveling time of both main circuit transients and telecommunication signals. The speed of light in an optic fiber is about 2×10^6 km/s, which means that it takes 10ms for travelling the length of 2000 km. Thus the delay time of the telecommunication signals have been accounted in the series MTDC simulation model.
The simulation results of scenario 1 (SCR=3) and scenario 2 (SCR=10) are shown in Fig. 8 and Fig. 9 respectively. The 100ms fault duration is set in order to simulate the AC line circuit breaker operation. It can be observed that the VDCOL logic works properly at each converter station. Besides, if the AC system is strong, as shown in Fig. 8, the AC fault at I1 has small impact on DC voltage of I2 and the transmission capacity of I2 is remained to some extent, depending on the minimum I_d reference value in the VDCOL function. However, when the AC system is weak, as shown in Fig. 9, although the VDCOL works properly at each converter station, the AC fault at I1 triggers subsequent commutation failure in I2, and results in the disturbance at AC gird system of I2.



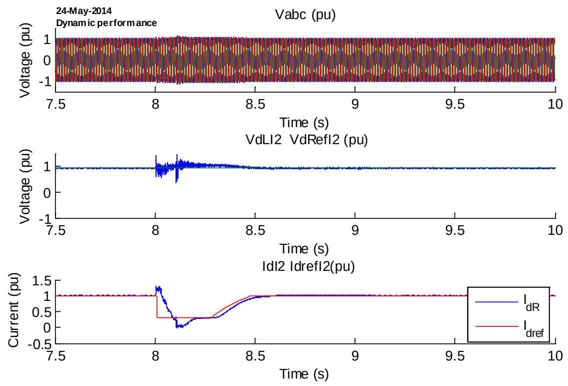
(a) AC voltage, DC voltage and DC current of R1



(b) AC voltage, DC voltage and DC current of R2

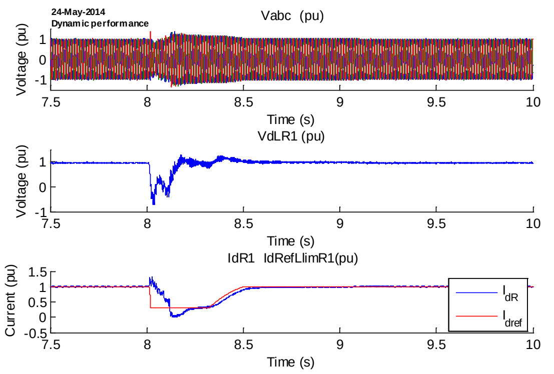


(c) AC voltage, DC voltage and DC current of I1

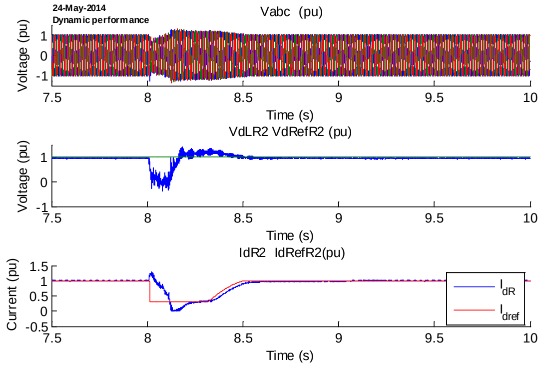


(d) AC voltage, DC voltage and DC current of I2

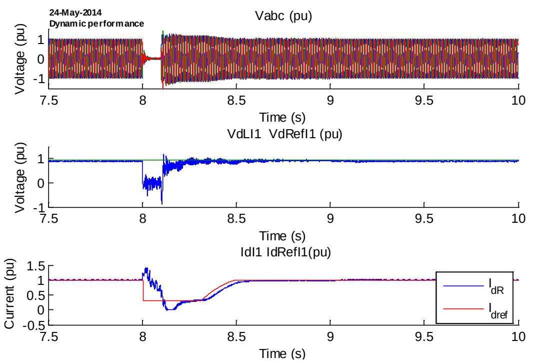
Fig. 8. 3phg AC fault at Inverter 1, 100ms duration with 10% of nominal AC voltage remained, SCR=10 for all AC systems



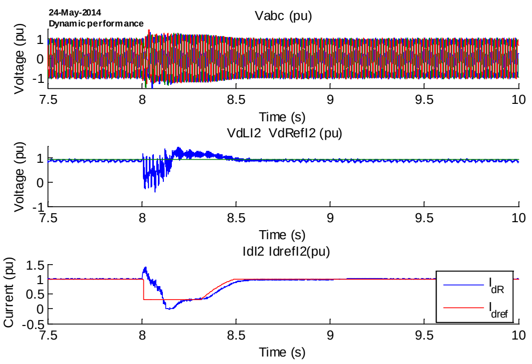
(a) AC voltage, DC voltage and DC current of R1



(b) AC voltage, DC voltage and DC current of R2



(c) AC voltage, DC voltage and DC current of I1



(d) AC voltage, DC voltage and DC current of I2

Fig. 9. 3phg AC fault at Inverter 1, 100ms duration with 10% of nominal AC voltage remained, SCR=3 for all AC systems

Conclusion

With the development of HVDC market, there is increasing attention to the MTDC technology. It has been known that series MTDC has the merits of lower converter cost as a whole; in particular, series MTDC is a competitive solution for high altitude application. In this paper, the AC fault ride through capability of series MTDC is studied, based on a +800 kV/3.2 GW monopole 4-terminal series MTDC model.

Firstly, the control algorithm of series MTDC is established. A current margin sequence is defined to realize normal DC current control by current setting terminal (CST). The VDCOL for series MTDC is proposed, which keeps the current margin sequence during both steady state and transient state.

Secondly, based on the proposed control algorithm, the dynamic performance of series MTDC during AC faults at inverter station is studied. Based on the simulation results, it can be concluded that during AC fault at one inverter station, the AC fault ride through capability of the other healthy inverter depends on the AC system strength: for strong AC system, the AC fault at one inverter has small impact on the operation of the other inverter station and the system remains power transmission capability to some extent; for weak system, the AC fault at one inverter results in the increasing of DC current and consequently it might trigger commutation failures on the healthy inverter if the same commutation margins were used.

Finally, the paper attempts to conclude that series MTDC may have another advantage of AC fault ride though capability, whereas the capability depends on the AC system strength that the healthy inverter station connects to. To improve the AC fault ride though capability for weak AC system application, new control and protections methods are expected to reduce the commutation failure possibility at the healthy inverter station.

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