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The Thyristor based Hybrid Multiterminal HVDC System

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***Abstract*—In the multiterminal high voltage dc current (MTDC) transmission system, the line commutated converter (LCC) MTDC was capable of achieving high power rating with low cost and low losses. By far, there were two types of LCC MTDC studied in the world, i.e. parallel MTDC and series MTDC. Both of these two types had respective pros and cons in terms of economic and technique. In the paper, a new kind of thyristor based hybrid MTDC system was presented, which consists of both parallel and series LCC converter stations. The structures and application scenarios were explained. The New control strategies were proposed for the hybrid MTDC system, and the control methods were illustrated. The system operation characteristics were analyzed under different situations. Finally, a simulation model was established to verify the hybrid MTDC system and the proposed control method.**

***Index Terms*— HVDC, multiterminal, thyristor, control method**

I. INTRODUCTION

THE multiterminal HVDC (MTDC) transmission system is an HVDC system in which more than two HVDC stations are interconnected with transmission lines. Based on the different technologies of converters, there are two kinds of MTDC technologies, which are voltage source converter based MTDC (VSC MTDC) and line commutated converter based MTDC (LCC MTDC). LCC MTDC can be also entitled as thyristor based MTDC.

The VSC is considered to be suitable for constructing of MTDC, due to its easy control, active power and reactive power decoupling control etc[1].

For LCC MTDC, the research had been started since as early as 1960s [2-5]. Thyristor based LCC is widely utilized in long-distance bulk-power transmission. Generally, MTDC can be arranged with different stations connected in parallel or in series.

In the parallel type MTDC, the LCC stations are connected to the same DC line and taken on the same DC voltage, but contribute respective DC current. In practice, the concept with parallel converters has been used in commercial projects as it offers much more flexibility and lower overall transmission losses [6]. By far, there are three parallel type MTDC projects commissioned. The control methods for LCC MTDC had been widely discussed [5-10].

For the series type MTDC, the LCC stations are connected with DC lines a station by a station in a string. Comparing with the parallel type MTDC, there is just only a few research activities focusing on the series type MTDC technology[10-13].

Generally speaking, compared with the series type MTDC, the parallel type MTDC has the advantages of lower power losses and richer engineering application experiences. Besides, the parallel type MTDC project is easier for expansion.

However, when the distance between LCC stations at sending end or receiving end is within certain value, the series type MTDC will has advantage of lower cost. Another potential advantage of the series type MTDC is the possibility of AC fault ride through at inverter side, if the inverters in the MTDC system are connected to electrically different AC systems or to two AC systems with weak intertie.

In this paper, an thyristor based hybrid MTDC system including partial parallel type stations and partial series type stations, is introduced which can benefit from the advantages of the two types of LCC MTDC with both parallel connection and series connection of converter stations. The topologies and application scenarios are explained with several examples. The control method for the hybrid MTDC is exhibited and the operation performance is analyzed by V-I characteristics. Finally, a simulation model is established to verify the feasibility of the hybrid MTDC system.

II. THYRISTOR BASED HYBRID MTDC SYSTEM

The hybrid MTDC system is based on thyristor converters, which comprises several rectifier stations connecting in parallel and several inverter stations connecting in series. Fig. 1 depicts an example of a simplified monopole four-terminal hybrid MTDC system. Wherein the converter stations simply drawn in the figure (R1, R2, I1, and I2) are configured by 12-pulse

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thyristor based converters or double 12-pulse thyristor based converters.

In the four-terminal hybrid MTDC system shown in Fig.1, two rectifier stations R1 and R2 are connected in parallel to supply the power from two different AC sources. Two inverter stations I1 and I2 are connected in series to feed the power to two different AC loads. The R1 and R2 take on the same DC voltage of the MTDC system, and contribute the partial DC current respectively. I1 and I2 share the DC voltage of the MTDC system together, while bearing the same DC current. L1, L2 and L3 are transmission lines between the stations of R1 and R2, R2 and I2, and I2 and I1 respectively.

The four-terminal MTDC example is a minimum compounding for the hybrid MTDC system. Based on the approach, the hybrid MTDC with more terminals configurations can be developed.

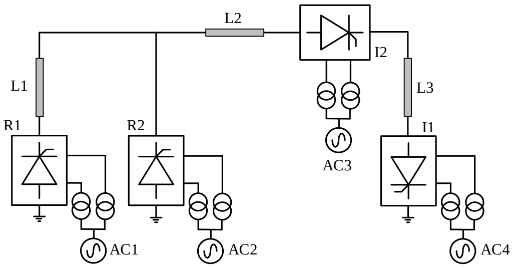


Fig. 1. The topology of thyristor based 4-terminal hybrid MTDC

In the hybrid MTDC system, the two parallel rectifiers can be used to transmit large scale wind power bundled with thermal power from respective HVDC terminals, in order to suppress fluctuant transmitted wind power. The two series connected inverters are adjacent electrically and connected to a load center, because series connection of LCC stations will be more economical than parallel inverters when the distance between inverters is short.

There is also another type of four-terminal hybrid MTDC system, as shown in Fig. 2. In this example, the multiple rectifier stations are connected in series to transmit the power, and the inverter stations are connected in parallel.

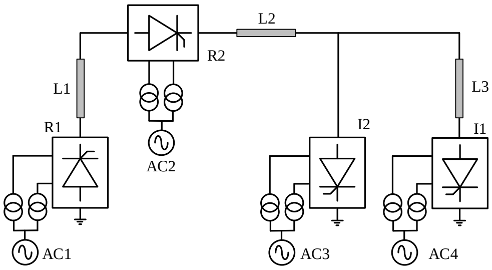


Fig. 2. The topology of thyristor based 4-termial hybrid MTDC

In the second topology, the two series rectifiers can be used for high altitude application to reduce total insulation cost: low voltage converter is laid at high altitude area, and high voltage converter is laid at low altitude area. The typical scenario of different altitude stations is hydro power transmission, for example in the Tibet area in China. The two parallel inverters feed power to two large load centers respectively.

III. CONTROL STRATEGY AND CONFIGURATION

For the hybrid MTDC systems, similar configuration exists in which several stations are connected in parallel and several stations are connected in series. Consequently, a generalized control method can be designed for the hybrid MTDC systems. In this section, a control method for the hybrid MTDC system is proposed and analyzed, based on the topology shown in Fig.1.

A. *Control strategy*

In the 4-terminal hybrid MTDC system shown in Fig.1, two control modes are designed:

1) Control mode 1: It is the major control mode for the hybrid MTDC system. Both of the two parallel rectifier stations (R1 and R2) are used to control their own DC current respectively. The two series inverter stations (I1 and I2) are both used to control DC voltage.
2) Control mode 2: It is a backup control mode for the hybrid MTDC system. One of the parallel rectifier stations and one of the series inverter stations are used to control DC current, and others two converter stations are used to control DC voltage.

For the two control modes, control mode 1 is used for normal operation. Generally, the control mode 1 can keep working well for the hybrid MTDC system even if the DC voltages of the series converter stations vary due to AC voltages fluctuate.

However, the control mode 1 cannot always make the hybrid MTDC system on good operation state for any dynamic process. For example, when one of the parallel connected converter stations has an AC voltage decreasing caused by certain AC fault, the station will deteriorate the capability of DC current control due to the limitation of minimum firing angle. The fault station needs to change its operation mode from the DC current control to the DC voltage control. While one of series converter stations has to change its operation mode from the DC voltage control to the DC current control in order to avoid more than one terminal of DC voltage control, and the control modes of other stations will not change. Finally, the control mode is shifted from Control mode 1 to Control mode 2.

The two control modes are both required in the control system of the hybrid MTDC. To realize a smooth transition between the two modes, the two series converter stations equipped with different DC current margins in their respective controllers. During the control mode transition, the inverter station with the smaller current margin, will be chosen to change its control modes from DC voltage control to DC current control. Finally, the hybrid MTDC system can complete the control transition automatically if the requirement happens.

In short, the control system of the hybrid MTDC can be equipped with two control modes for normal operation and special situation respectively. The two control modes can be fast transited automatically without telecommunication by setting different current margin at inverter stations. Thus, combining the two control modes constitute an integrated control system for the hybrid MTDC system.

B. *Control configuration*

Under the two control modes, the control configuration can be depicted in the Fig.3. In the control configuration, the control functions are designed to implement the control methods of the control modes.

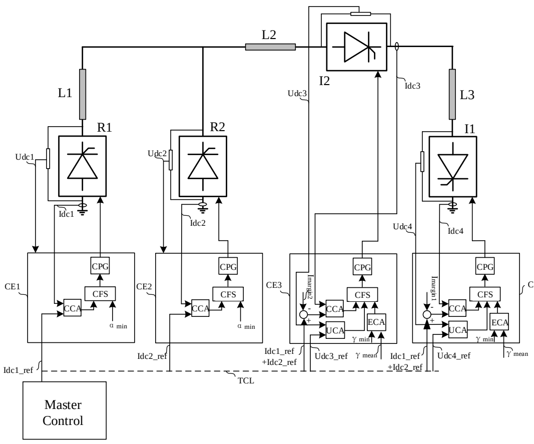


Fig. 3. The control configuration for the 4-terminal hybrid MTDC system

In the control configuration, the two rectifier stations R1 and R2 are schemed DC current control (CCA: "Current Control Amplifier" in Fig.3) for control mode 1 and fixed alpha (firing angle) control for control mode 2. The outputs of the two control function is selected by the block CFS.

The two inverter stations I1 and I2 employ DC voltage control (UCA: "Udc Control Amplifier" in Fig.3) and extinguished angle control (ECA: "Extinguished angle Control Amplifier" in Fig.3) for the control mode 1, and meanwhile employ DC current control (CCA) for the backup control mode 2. Different current margins are set up in the controllers of I1 and I2. In the control system, the margin of I2 is larger than the margin of I1. The margin values determine the selection of inverter station when changing and system capacity design.

The master controller is used to coordinate the start/stop process and power control in the system level.

IV. DYNAMIC PERFORMANCE

Based on the control strategy of the hybrid MTDC system, the operation performance can be studied. The static and dynamic performance can be analyzed and presented through V-I characteristics.

A. *Normal operation*

Under basic V-I characteristics shown in the Fig.4, the system is stable during normal operation with the control mode 1. The two rectifier stations (R1 and R2) work on the constant DC current control, and the two inverter stations (I1 and I2) work on the constant DC voltage control.

From the fig.4, the static operation point of the system is actually operated on the cross of the curves of the DC current summation of the two parallel stations and the DC voltage summation of the two series stations. The feature is similar with the system of point to point HVDC. For the each station, the parallel rectifier stations work on different current points under the same voltage of $U_{I1}+U_{I2}$, while the series inverter stations work on different voltage points under the same current of $I_{R1}+I_{R2}$.

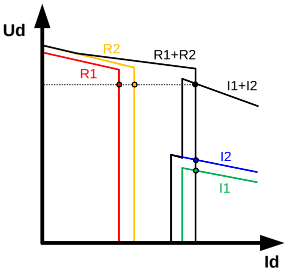


Fig. 4. The V-I characteristics in the normal operation

B. *Voltage suppression at the inverter station*

Taking inverter station I1 as example, if AC voltage at I1 is decreased due to AC fault, the DC voltage will reduce accordingly for the affection. It can be seen from the Fig.5. The overall DC current of the system doesn't change as R1 and R2 will keep current automatically by decreasing the voltage. The system can always operate normally and control mode will not be changed.

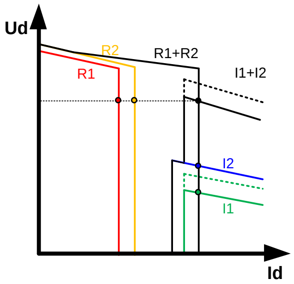


Fig. 5. The V-I characteristics under voltage drop of I1

C. *Voltage suppression at the rectifier station*

The voltage suppression control at the rectifier station, however, will be more complicated.

Taking R1 station as the example, if AC voltage at R1 is suddenly decreased, R1 is tried to keep the current by decreasing its firing angle. When the firing angle reaches its minimum limit, R1 will lose current control capability for the limitation of alpha minimum control. With the depression of R1 current, the summation of DC current will be decreased until the current reach to I1 current order, and then I1 will become one of current control terminal. The result is that R2 and I1 control respective DC currents, and at same time R1 and I2 control respective DC voltages. The control order will shift from control mode 1 to mode 2. The process can be illustrated in Fig.6.

In this example, it can be seen obviously that the original control mode cannot be maintained during AC faults at rectifier end, and the change from mode 1 to mode 2 is an automatic process without fast telecommunication.

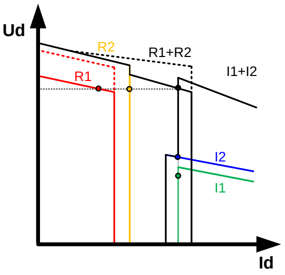


Fig. 6. The V-I characteristics under voltage drop of R1

V. SIMULATION AND ANALYSIS

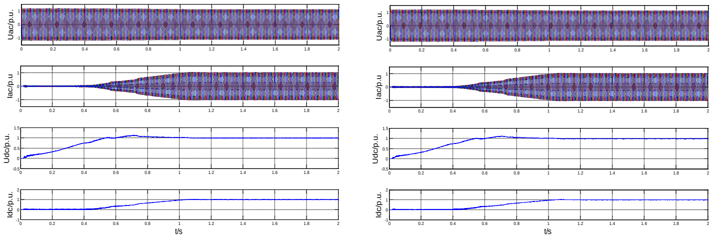
A simulation model of the monopole 4-terminal hybrid MTDC system was constructed based on the configuration in Fig.3. In the simulation model, the total transmitted power is 3200 MW. The nominal DC voltage and current of both R1 and R2 are 800 kV and 2 kA respectively. The nominal DC voltage and current of I1 and I2 are 400 kV and 4 kA respectively. The current margin of I1 and I2 are 0.1 p.u. and 0.2 p.u. respectively. More parameters can be found in the Table 1.

TABLE I
MAIN PARAMETERS OF THE SIMULATION MODEL

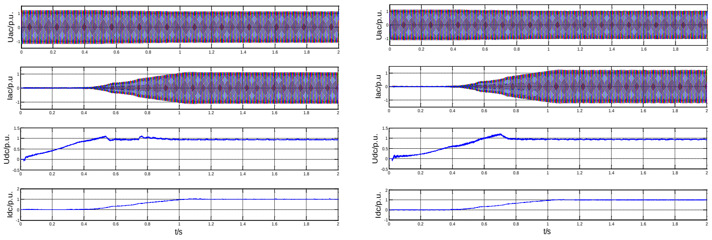
	R1	**R2**	**I1**	**I2**
Topology	Double 12-pulse	Double 12-pulse	12-pulse	12-pulse
AC source	530 kV/ 50Hz	530 kV/ 50Hz	530 kV/ 50Hz	530 kV/ 50Hz
DC voltage/ current	800 kV/ 2 kA	800 kV/ 2 kA	400 kV/ 4 kA	400 kV/ 4 kA
DC Power	1600 MW	1600 MW	1600 MW	1600 MW
Firing angle min.	5°	5°		
Extinguish angle min.			15°	15°
Current margin			0.05 p.u.	0.1 p.u.
OHL	L1	L2	L3	
Length	500 km	1000 km	300 km	

The simulation results shown in the Fig.7 displays the process from start-up to normal operation of the 4-terminal hybrid MTDC system. In the system, the master control takes responsibility for the coordination in the start-up process. Firstly, the four stations build DC voltage through their AC source respectively. Then, the master control release the DC current orders to the two rectifier stations (R1 and R2) with a restricted slope in order to the limit the start-up current for the system. The two inverter stations (I1 and I2) will increase their transmitted power with the two rectifier stations.

It's better to start up the power of two rectifier stations one by one. However, the process of the two stations is schemed at the same time in the simulation, in order to shorten the start- up process. The results of the fig. 7 illustrate that the start-up (from 0 to 1.3s) of the system is still smooth.



(a) R1 station (b) R2 station



(c) I1 station (d) I2 station

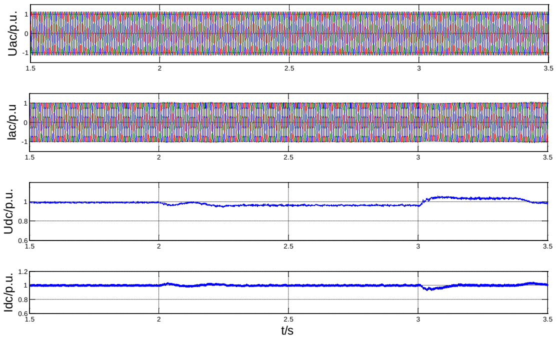
Fig. 7. The start-up process and normal operation for the hybrid MTDC system

After 1.3s, the system is running in the normal operation with the control mode 1.

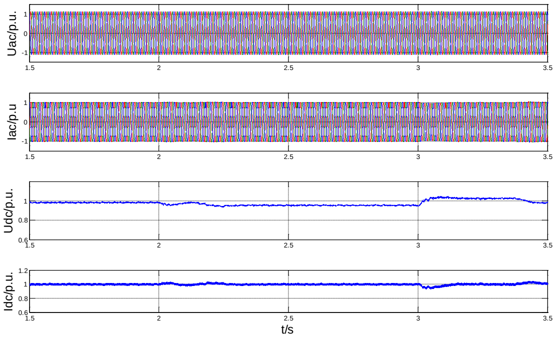
A 10% AC voltage depression is set during 2 ~ 3s at the I1 station, as shown in Fig. 8, to verify the analysis on the system robust characteristic in control mode 1 during DC voltage depression at inverter station. As shown in Fig. 8, the DC voltage of I1 station reduces due to AC voltage depression, and the DC voltages of the two rectifier stations also decrease to keep their DC currents following respective orders. However, the whole system is still in the normal operation. The system recovers to normal operation from the disturbance quickly after fault clearance at 3s. It can be seen from the waveforms of DC current in Fig.8 that the transient lasted 0.2s. At the same time, the control mode is not transited for the fault.

Note that I2 station isn't impacted during the process, which is a great advantage for the two adjacent receiving terminals in the system because the inter action of the two terminals during AC faults is small.

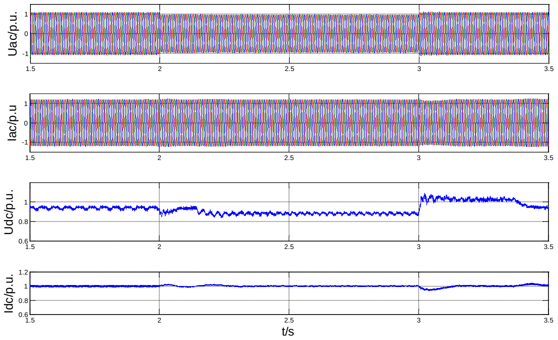
According to the previous analysis, the control mode will shift from the mode 1 to mode 2 when voltage depression happens at a rectifier station. In the simulation, the AC voltage depression at R1 station is used to illustrate this problem. In the simulation, R1 station happens a 15% AC voltage deprecation from 2s to 3s. The simulation results are shown in Fig. 9.



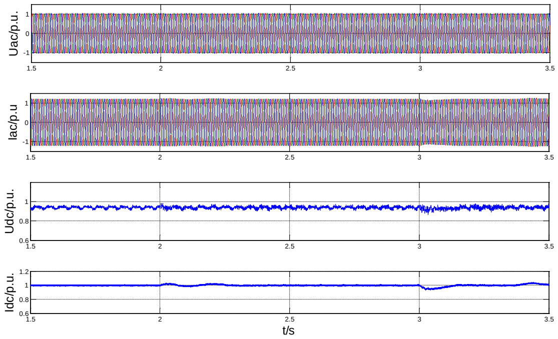
(a) R1 station



(b) R2 station



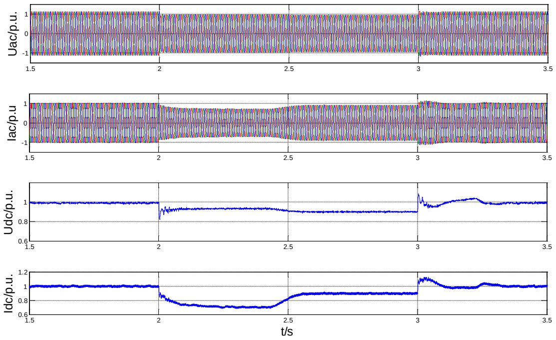
(c) I1 station



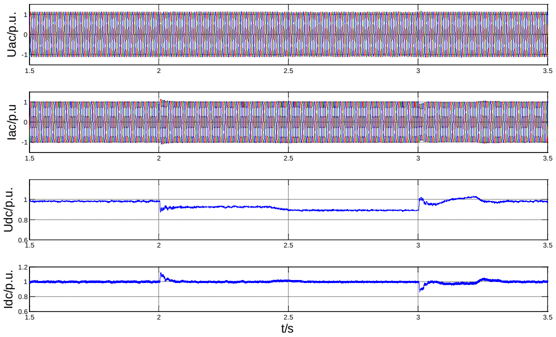
(d) I2 station

Fig. 8. AC voltage depression at I1 station

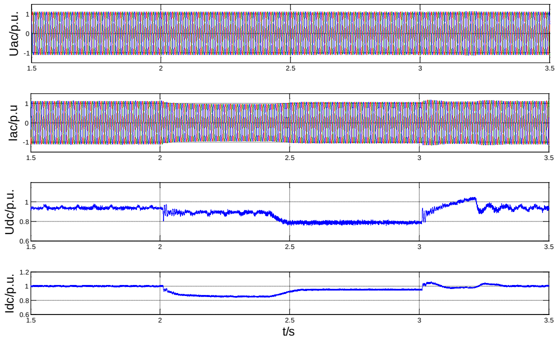
In Fig. 9, the DC current at R1 station is limited and declined a lot, due to the AC voltage depression of R1 station. Further, R1 station loses the capability of DC current control. The current via the two series stations (I1 and I2) is also decreased due to the decreasing of DC current at R1 station. If the DC current decreases further and below the current order of the inverter station with smaller current margin, the inverter station will change the operation mode from voltage control to current control. In the simulation, the DC current decreases below the current order of I1 station. The I1 station decreases its DC voltage, and controls the DC current of the two series two inverter station as shown in Fig. 9 (c). R1 is forced to control its DC voltage, as shown in Fig. 9 (a). Finally, the system control mode is shifted automatically.



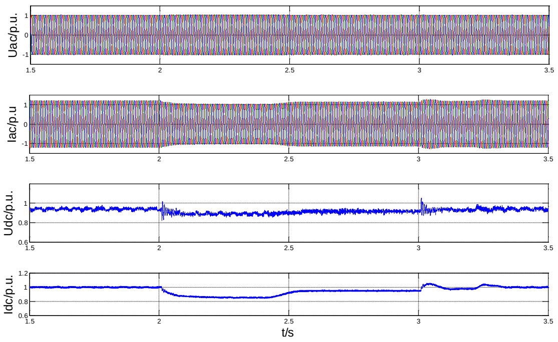
(a) R1 station



(b) R2 station



(c) I1 station



(d) I2 station

Fig.9. AC voltage depression at R1 station

In the voltage depression of R1, the transmitted power at R1, I1 and I2 are affected and decreased. However, the R2 station isn't affected, which implies that the interaction between R1 and R2 during AC fault at one rectifier is also small.

After fault clearance at 3s, the R1 station can acquire itself DC current control again, and the I1 station returns to the initial DC voltage control from the current control automatically. That means the system control mode is shifted back to control mode 1 as the dynamic performance analysis in the previous section.

VI. CONCLUSION

The thyristor based hybrid MTDC system is comprised multiple parallel connected converter stations and multiple series connected converters. Two topologies of hybrid MTDC are proposed according to the series stations at receiving end or sending end. Two main applications are presented for the two topologies.

The control strategy is proposed for the hybrid MTDC system, which includes a control mode for normal operation, and a backup mode for certain AC faults at parallel connected stations. The controller is designed based on a 4-termianl hybrid MTDC system. However, the generalized control strategy can be deduced for the other hybrid MTDC system.

The analysis of V-I characteristics and simulation results verified the control strategy. In summary, the hybrid MTDC system can work in normal operation with the first control mode even there is a voltage depression at one of series inverter stations. The two control modes can transmit automatically during the voltage depression at one of parallel rectifier stations.

Finally, based on the analysis and simulation results, it can be found that when one converter station has the limitation in power transmission due to its AC faults, there is little impact to its corresponding parallel or series connected converters.

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