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2-Terminal Hybrid HVDC

Cost Effective Alternatives for Clearing Temporary DC Line Faults

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Abstract—2-Terminal Hybrid HVDC consisting of a Line-Commutated Converter (LCC) in the sending end, and a Voltage Source Converter (VSC) in the receiving end, can be seen as a compromise between cost, loss and performance. A Hybrid system has lower cost and somewhat lower losses than a pure VSC HVDC system. Yet it is able to provide reactive power support and black start capability at the receiving end, which a pure LCC system simply cannot.

The focus of this paper is DC fault handling. Two ways of clearing DC faults are investigated and compared, namely AC breaker and Diode. Improvements to the AC breaker alternative are made, which lowers transient DC overvoltage.

Two control modes are also compared, namely LCC controlling current, and LCC controlling voltage. It is shown that both control modes are feasible, during steady state operation and also during transients.

Keywords— HVDC transmission; Hybrid power systems; Power system control

I. INTRODUCTION

2-Terminal Hybrid HVDC consisting of a Line-Commutated Converter (LCC) in the sending end, and a Voltage Source Converter (VSC) in the receiving end, can be seen as a compromise between cost, loss and performance. A Hybrid system has lower cost and somewhat lower losses than a pure VSC HVDC system. Yet it is able to provide excellent AC network performance at the receiving end, which a pure LCC system simply cannot. Typical situations where the excellent AC network performance may motivate or justify the installation of VSC HVDC are for example: HVDC multi infeed and the related stability issues [1], too high short circuit AC current due to synchronous condensers [2], too weak AC grid due to the integration of large amount of renewable energy [3].

One of the key challenges with long distance HVDC transmission is how to handle temporary DC line faults. LCC HVDC can by retarding its firing angle decrease the fault current to zero. So far there is only one VSC HVDC transmission using OHL (Over Head Lines) in commercial operation, namely the Zambezi Link [4]. It uses AC breakers to clear DC line faults, which is a very cost effective way. But the fault clearing time for that system is relatively long, since re-energization of the VSC converter is necessary. However with

modern half bridge MMC (Modular Multilevel Converter) technology, each cell will stay energized during a DC fault, thus the whole restart sequence can be made faster. This is discussed in section II.

If high performance DC fault clearing is necessary, other possible ways of clearing DC faults is using a Hybrid DC breaker [5], or full bridge MMC [6]. The main drawback with these two solutions is the increased cost. Assuming that the power only flows one way, there is yet another way of handling DC line faults, namely using a Diode at the VSC station [7]. In section III of this paper, the diode solution is introduced and compared with the AC breaker solution.

Another important aspect of a Hybrid HVDC system is the control, both in steady state and during transient operation. This is discussed in section IV. Two control modes are compared with each other, namely LCC controlling DC voltage (called Mode 1), and LCC controlling DC current (called Mode 2). It is shown in this paper that both control modes are feasible, during steady state operation and also during transients. Finally, conclusions are drawn in section V.

II. AC BREAKER FOR CLEARING TEMPORARY DC FAULTS

In this section, the state of the art for AC breaker DC fault clearing is firstly shown. Then a Hybrid HVDC system is introduced. Finally, DC fault clearing using AC breaker in the Hybrid system is tested. Some improvements are made to the existing sequence.

A. State of the art

The Zambezi Link was put into commercial operation in October 2010. It has successfully cleared many DC faults originating from for instance lightning and bush fires. The DC fault clearing sequence is as follows:

1. Block the VSC converter
2. Open the converter ACB (AC Breaker)
3. Open the NBS (Neutral Bus Switch)
4. Open the HSS (High Speed Switch)
5. Re-close the NBS
6. Re-close the converter ACB
7. De-block the VSC converter as a STATCOM

8. Re-close the HSS
9. Resume HVDC Power transmission

Since both stations in the Zambezi Link follow the same sequence, some margins are needed. As shown in [4], steps 1 to 8 takes around 900ms. An overview of the VSC converter and the related breakers and switches is shown in Figure 1.

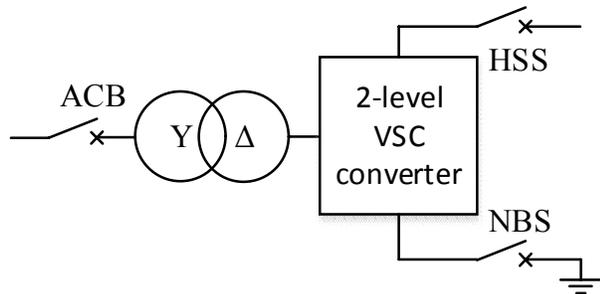


Figure 1, overview of the Zambezi Link

B. Hybrid HVDC System

In recent years, VSC HVDC has been developed rapidly. The introduction of MMC made it relatively easy to scale the voltage upwards [8]. Advances in semiconductor technology has increased the maximum attainable current [9]. It is therefore becoming practically feasible to build Hybrid HVDC with a very high capacity. The system used in this paper is therefore a ± 500 kV, 3GW bipole. The key data can be found in Table I, and a system overview is shown in Figure 2.

TABLE I. KEY SYSTEM DATA

Parameter	LCC	VSC
Nominal AC voltage (kV)	525	525
AC network short circuit capacity (MVA)	15000	15000
Frequency (Hz)	50	50
Nominal DC voltage (kV)	± 500	
Nominal DC current (A)	3000	
Length of transmission line (km)	1000	

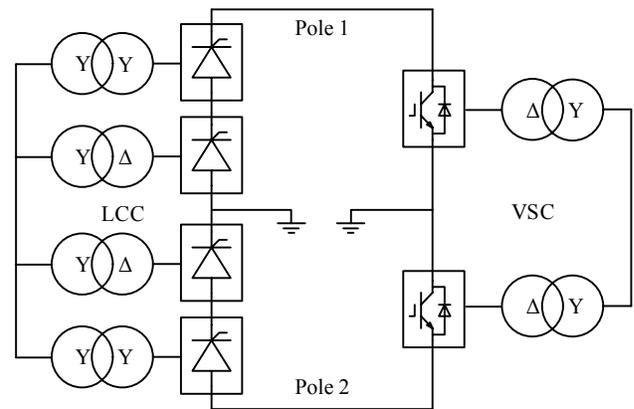


Figure 2, Overview of the tested Hybrid HVDC system

C. DC fault clearing using AC breaker in the Hybrid system

Initially, the same DC fault clearing sequence as the Zambezi Link was tested in the Hybrid system. The key issue was that significant DC overvoltage occurred at the LCC station when re-closing the HSS, up to 1.35 p.u was observed. The reason for the overvoltage is that a significant amount of charging current will be injected into the DC line at the HSS closing instant. This is a critical issue, since such a high DC voltage can easily cause a re-striking DC fault, thus permanently tripping the whole pole. In order to reduce the peak DC voltage during the sequence, some changes were necessary.

In Figure 3, the relevant equipment for the new DC fault clearing sequence is shown. The only difference compared with Figure 1, is the addition of the PRB (Pre-insertion Resistor Breaker). A PRB is a standard piece of equipment for VSC HVDC, which is used when energizing the converter from the AC side. Before energization, both the ACB and PRB are open. Then the ACB is closed. During this period of time, the inrush current is limited by the resistor. Finally when the converter capacitance has charged up to a high enough voltage level, the PRB is also closed, thus marking the end of the energization sequence.

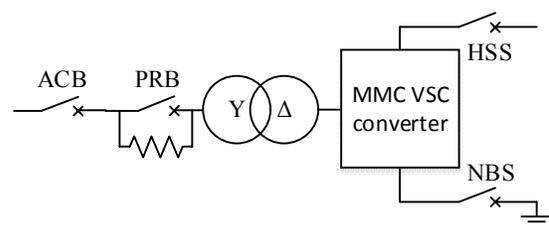


Figure 3, MMC converter, including PRB

The new DC fault clearing sequence is:

1. Block the VSC converter
2. Open the converter ACB
3. Open the NBS
4. Open the PRB
5. Open the HSS
6. Re-close the NBS
7. Re-close the HSS
8. Re-close the converter ACB
9. Re-close the PRB
10. De-block the VSC converter as a STATCOM
11. Resume HVDC Power transmission

By using the new sequence, there is virtually no DC overvoltage in the system. The reason is that the DC line charging current is limited. In Figure 4, the whole sequence is shown. The figure legend is as follows: First graph; Three converter AC voltages, in kV. Second graph; DC line voltage, in p.u. Third graph; DC line current, in p.u. Fourth graph; ACB open indication, HSS open indication, NBS open indication, PRB open indication, VSC converter de-blocked indication. All graphs from pole 1 in the VSC station.

Initially nominal power is transmitted on both poles, and the VSC converters are in AC voltage control mode. Then at 1.1s, a DC fault close to the VSC station is applied in pole 1. The VSC converter blocks almost immediately, and the ACB opens 40ms later to break the large fault current. As soon as the residual neutral bus DC current decays below 1 p.u., the NBS is opened, which happens at around 1.24s. The PRB is opened shortly after the NBS, and at around 1.28s the HSS is opened. Then at around 1.39s, the NBS is re-closed, and the HSS is re-closed at around 1.45s. The ACB is re-closed at 1.47s, with the PRB still open. As can be seen at this point, the DC voltage builds up quickly to around 0.5 p.u. The PRB is re-closed at 1.49s, thus fully energizing the VSC converter. At this point the DC voltage builds up further to around 0.8 p.u. The VSC converter is then de-blocked to STATCOM operation at 1.51s. Finally the LCC converter releases its retard command at 1.52s and HVDC power transmission is resumed. Totally the DC fault clearing sequence takes around 420ms, which is not that much longer than the typical 2-300ms used in a conventional LCC HVDC transmission.

In this sequence, the time taken to re-close the NBS after opening is around 145ms, which is shorter than usual. Normally, 300ms is specified [10]. However, based on test results of already delivered HPL B breakers, the values used in this simulation might be practically feasible.

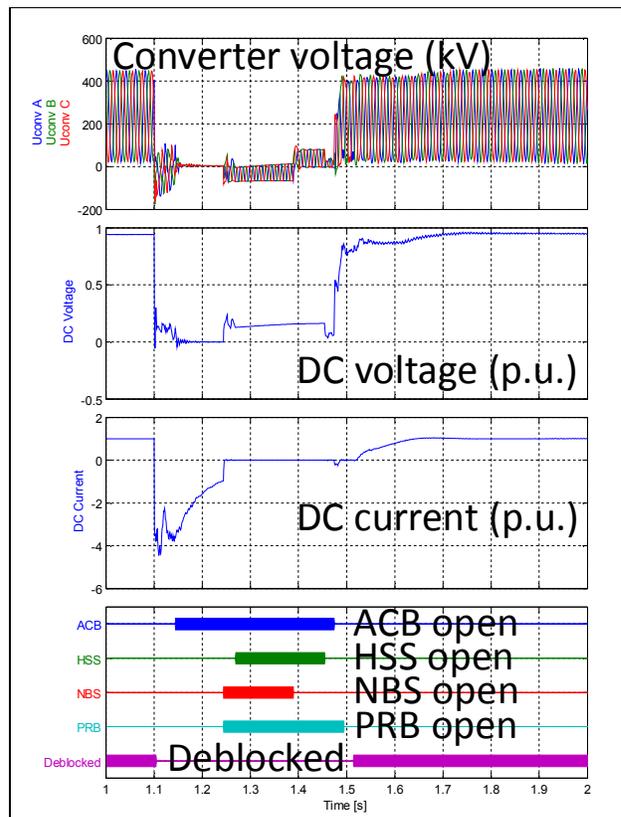


Figure 4, DC fault clearing using an AC breaker

III. DIODE FOR CLEARING TEMPORARY DC FAULTS

In this section, a diode is introduced for clearing DC faults. Simulation results shows typical performance, and the advantages and disadvantages are compared with the AC breaker alternative.

A. Diode at the VSC station

An overview is shown in Figure 5.

B. Simulation of a DC fault with diode

In Figure 6, a DC fault is shown. The figure legend is as follows: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; DC line current, in p.u. Fourth graph; Reactive power output, in MVar. All graphs from pole 1 in the VSC station.

As will be discussed in more detail in the next section, two different control modes are used. Mode 1 is in green color, while Mode 2 is in blue color. As can be seen, there is no major difference between the two control modes for DC faults.

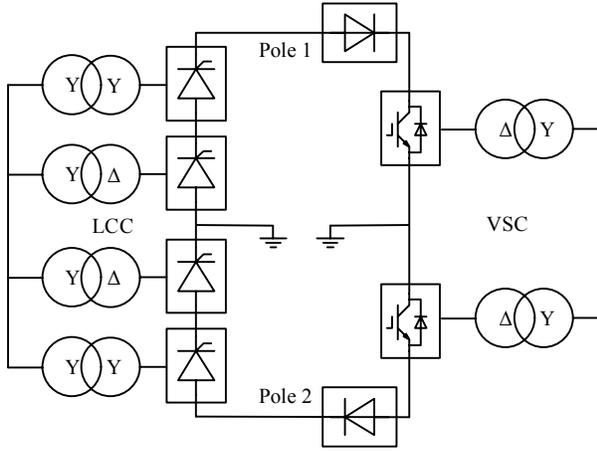


Figure 5, Hybrid HVDC system with diode

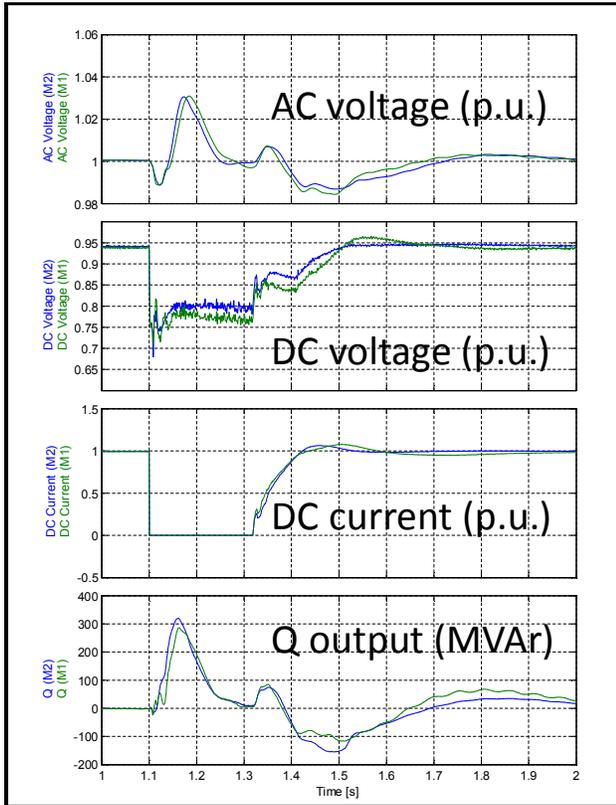


Figure 6, DC fault clearing using a diode

Initially nominal power is transmitted on both poles, and the VSC converters are in AC voltage control mode. Then at 1.1s, a DC fault close to the VSC station is applied in pole 1. The LCC converter stops the fault current by issuing a retard order. Although the active power flow stops almost immediately, the VSC converter continues to provide reactive power support to the AC network. After a DC line de-ionization time of 200ms, the LCC converter resumes HVDC power transmission.

C. Comparison of the two DC fault clearing alternatives

The key data is shown in Table II.

TABLE II. COMPARISON OF ACB AND DIODE

	<i>ACB</i>	<i>Diode</i>
DC fault clearing time (ms)	420	200
Reactive power support during DC fault (yes/no)	no	yes
Cost	low	medium
Additional losses (%)	N/A	~0.05%

The diode alternative provides DC fault clearing as fast as a conventional LCC system, and can also provide reactive power support at all times.

With regards to cost, the ACB alternative is more attractive. The reason is that the only new equipment is the HSS, which is relatively inexpensive. The diode will naturally be more costly, since a relatively large semiconductor valve is needed. As a rule of thumb, the diode will cost around one third of a corresponding 12-pulse LCC thyristor valve.

In terms of losses, the ACB alternative practically adds no more losses. The diode loss figure given in Table II, is for nominal power transmission. So in this example 3GW bipole system, the two diode valves adds around 1.5 MW extra losses.

IV. COMPARISON OF CONTROL MODES

In this section, two control modes are compared with each other, namely LCC controlling voltage (called Mode 1), and LCC controlling current (called Mode 2). It is shown that both control modes are feasible, during steady state operation and also during transients.

A. Steady state control

For a 2-Terminal HVDC transmission, one station needs to control the DC current, and the other station needs to control the DC voltage. For a typical LCC HVDC transmission, Mode 2 is used. However, Mode 1 is used in for instance the Haenam-Jeju HVDC system [11]. For a typical VSC HVDC system there is no general preference. However in many cases it is more beneficial for the whole system, if the converter that is connected to the strongest AC network controls the DC voltage.

If there is a sudden and large AC voltage dip at the DC current controlling station, it might temporarily be impossible to fulfill the control objective, until the tap changer has stepped up the converter valve voltage. This is known as a mode shift. A basic comparison is shown in Table III.

TABLE III. BASIC COMPARISON OF CONTROL MODES

	Mode 1	Mode 2
LCC control mode	DC Voltage	DC Current
VSC control mode	DC Current	DC Voltage
Will the DC current increase or decrease at a temporary mode shift?	Increase	Decrease
Is operation without interstation telecommunication possible?	Yes, telecommunication is actually not needed	Yes, by measuring the DC current

B. Transient control

In steady state operation, there will be no difference in transmitted power, regardless of control mode. However during transients, there might be differences. In order to compare the two control modes further, AC faults are applied at both the LCC and VSC terminals, and the performance during and after the fault is compared. Initially nominal power is transmitted on both poles, and the VSC converters are in AC voltage control mode.

In Figure 7, a solid three-phase AC fault with around 5% remaining voltage is applied at the LCC terminal. The figure legend is as follows: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; DC line current, in p.u. Fourth graph; Alpha order, in electrical degrees. Mode 1 is in green color, while Mode 2 is in blue color. All graphs from pole 1 in the LCC station.

At 1.1s, the AC fault is applied at the LCC converter terminal. Since the AC fault is very solid, no power can be transmitted during the fault. In order to minimize potential DC overvoltage at AC fault clearing, the LCC increases its alpha order to 35 degrees. At 1.2s, the AC fault is cleared, and fault recovery starts. For this fault case, there is no major difference between the two control modes. No major overvoltage nor overcurrent is observed, and the recovery to nominal power is done rapidly, taking less than 100ms.

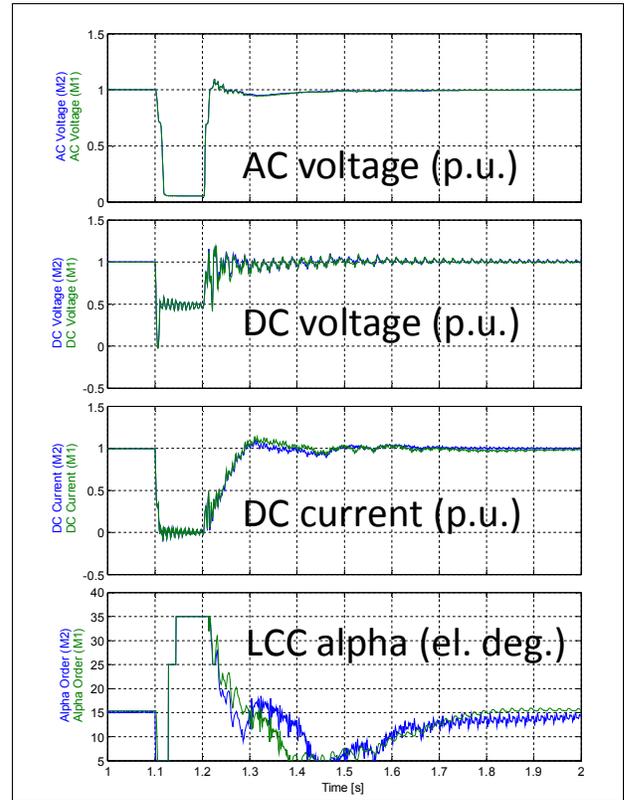


Figure 7, Solid three-phase AC fault at the LCC terminal

In Figure 8, a solid three-phase AC fault with around 5% remaining voltage is applied at the VSC terminal. The figure legend is as follows: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; DC line current, in p.u. Fourth graph; Alpha order, in electrical degrees. Mode 1 is in green color, while Mode 2 is in blue color. The first graph is from pole 1 in the VSC station, all other graphs are from pole 1 in the LCC station.

At 1.1s, the AC fault is applied at the VSC converter terminal. Since the AC fault is very solid, no power can be transmitted during the fault. Due to the energy stored in the long DC line inductance, the DC voltage will rise rapidly at the VSC station, since the energy then gets transferred into the VSC cell capacitance. In order to minimize the DC overvoltage, the LCC increases its alpha order. At 1.2s, the AC fault is cleared, and fault recovery starts. For this fault case, there is no major difference between the two control modes, although Mode 1 will react quicker to the DC overvoltage. It takes some time after AC fault clearance for the VSC converter to start to inject active power into the AC network again. Once active power flows and the DC voltage is brought down, the LCC can start to drive DC current again. The recovery to nominal power is fairly quick, taking less than 200ms.

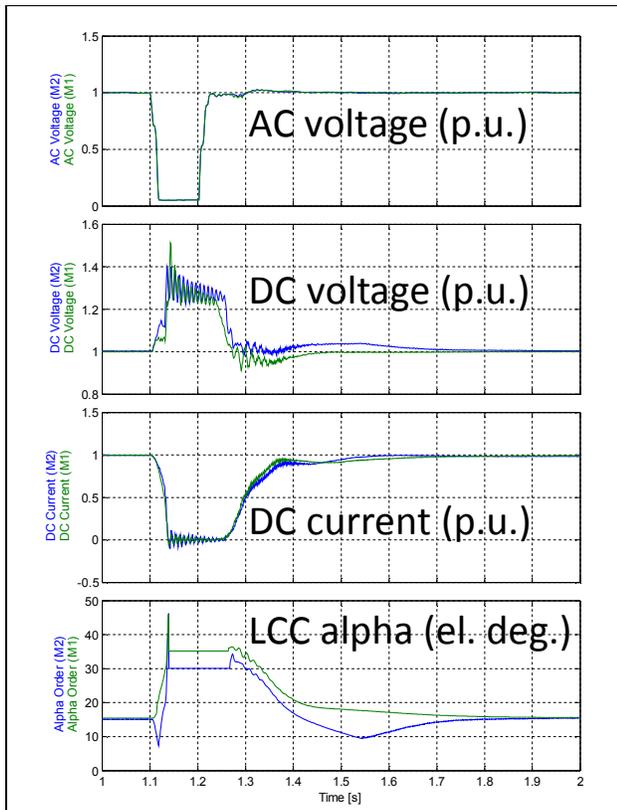


Figure 8, Solid three-phase AC fault at the VSC terminal

V. CONCLUSIONS

In this paper, two cost effective alternatives for clearing temporary DC line faults in a Hybrid HVDC system was introduced. Both alternatives are feasible, and has their own advantages and disadvantages.

The AC breaker alternative has the lowest cost, and adds no more losses to the system. By optimizing the switching sequence for a Hybrid HVDC system, a total DC fault clearing time of 420ms is achieved.

The diode alternative provides excellent and instant DC fault clearing. Reactive power support from the VSC converter

to the AC grid is available at all times. The system can resume active power transmission as fast as a conventional LCC system, in this paper a total time of 200ms is used. The main drawback is increased cost, and slightly higher losses. The additional losses due to the diode are around 0.05%, or 1.5 MW for the example 3GW bipole system.

For the tested system, there is no major differences between control Mode 1 and Mode 2. Both are found feasible, both in steady state and during transients. For a three-phase solid AC fault at the VSC station, there is significant DC overvoltage, due to the energy stored in the long DC line

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