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Dynamic and steady state performance of a 2-terminal Hybrid HVDC transmission

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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, is 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 can 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 optimizing dynamic performance. A novel control method called CDVOL (Current Dependent Voltage Order Limiter) was developed and applied at the VSC. By dynamically lowering the DC voltage reference at the VSC, the whole HVDC transmission can recover to the pre-fault DC power level significantly faster.

Two control modes are also compared, namely LCC controlling DC current, and LCC controlling DC voltage. It is shown that both control modes are feasible, during steady state operation and also during transients. An optimization is possible when LCC is controlling DC voltage, which lowers losses, cost and the overall LCC station footprint.

***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, is 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 can 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].

When mixing LCC and VSC technology in a Hybrid HVDC transmission, there are many things to consider. One such thing is the dynamic performance. An LCC rectifier can rapidly decrease its DC voltage down to zero by increasing its firing angle. However, it is quite limited in how much it can increase the DC voltage. With typical design the DC voltage increase is limited to around 3%. A VSC inverter equipped with Half Bridge is the complete opposite: Rapid DC voltage decrease is quite limited, but the DC voltage can be increased significantly by lowering the modulation index. Based on these differences, a novel control method called CDVOL (Current Dependent Voltage Order Limiter) was developed and applied at the VSC. By dynamically lowering the DC voltage reference at the VSC, the whole HVDC transmission can recover to the pre-fault DC power level significantly faster.

Another thing to consider in a Hybrid HVDC system is steady state control. One station needs to control the DC current (Mode 1), while the other station needs to control the DC voltage (Mode 2). In this paper it is shown that both ways of controlling the system are feasible, during steady state operation and during transients. An optimization (Mode 3) is possible when LCC is controlling DC voltage, which lowers losses, cost and the overall LCC station footprint.

Yet another thing to consider in a Hybrid HVDC system is DC fault handling. LCC inherently has an ability to stop fault current, which VSC does not. 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. There are other alternative ways that DC faults can be cleared, by for instance using a Hybrid DC breaker [5], or full bridge MMC [6]. Considering that in many HVDC applications the power is transferred in only one direction, half bridge MMC together with a diode valve for blocking DC fault current turns out to be the most cost-effective solution [7]. Since one of the major reasons to use a Hybrid HVDC system is overall system cost-effectiveness, the diode alternative is used in this paper.

This paper has the following layout: In section II, the CDVOL control function is introduced, and the improvements in fault recovery is demonstrated with time domain simulations. In section III, two different steady state control modes are compared with each other. An optimization is possible when LCC is controlling DC voltage. Conclusions are drawn in section IV.

II. CDVOL for Improved Dynamic Performance

In this section, the CDVOL function is introduced, and its effectiveness is demonstrated using time domain simulations.

A. *Differences in dynamic performance between LCC and VSC converters*

The key to having good dynamic performance in any type of HVDC system, is good cooperation between the converters. For a Hybrid system, this becomes even more important since the converters are of different types. An overview of how the DC voltage can be rapidly controlled is shown in TABLE I.

TABLE I. COMPARISON OF RAPID DC VOLTAGE CONTROL ABILITY

	LCC (rectifier)	***VSC with Half Bridge (inverter)***
Ability to rapidly increase the DC voltage	Typically limited, a normal design only allows for around 3%	Can increase the DC voltage significantly, by lowering the modulation index
Ability to rapidly decrease the DC voltage	Can rapidly be decreased down to zero, or even change polarity	Typically limited, the modulation index cannot be increased too high

For recovery after fault clearance, the ability to rapidly increase the DC voltage is the most important factor. Hence, the LCC converter will place the basic limitation in this system. If the VSC converter puts up too high DC voltage for the LCC, then the DC current will not build up quickly, ultimately leading to a relatively slow active power recovery.

B. *System used for all testing in this paper*

An overview of the system used for all testing is shown in Figure 1. Key data is shown in TABLE II.

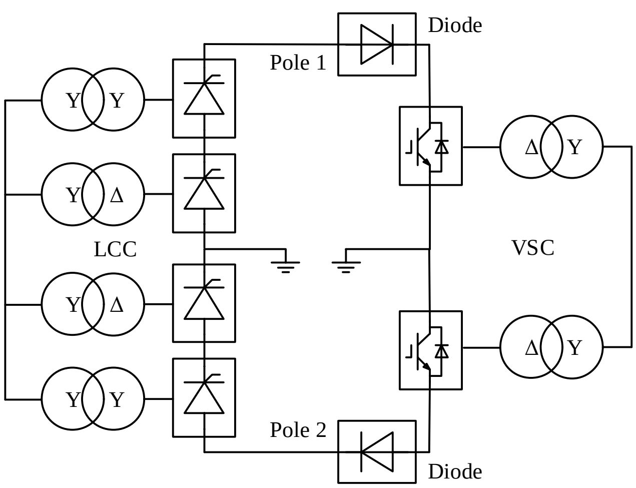

Figure 1, overview of the tested system

TABLE II. 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	
Reduced DC voltage (kV)	±400	
Nominal DC current (A)	3000	
Length of transmission line (km)	1000	

Since this is an OHL HVDC transmission, it is capable of rapidly reducing the DC voltage. The reduced DC voltage level is set to 80%, or 400 kV. To achieve reduced DC voltage, no special precautions are necessary for the LCC system. However, for the VSC system a lower than normal modulation index is used. The modulation index is chosen so that the VSC converter will be close to its upper modulation index limitation at the instant it enters reduced DC voltage. Shortly after entering reduced DC voltage, the VSC converter transformer tap changer will start to bring down the modulation index to a lower value again.

Hence, the VSC converter will have some ability to rapidly decrease the DC voltage. This is then used in the CDVOL.

C. *CDVOL function*

A core control functionality in LCC HVDC is the VDCOL (Voltage Dependent Current Order Limiter). It rapidly lowers the DC current order when the measured DC voltage dips. When the DC voltage starts to build up again, the DC current order is increased in a controlled manner.

For the VSC converter in the tested Hybrid system, a CDVOL was developed. It rapidly lowers the DC voltage order when the measured DC current dips. When the DC current starts to build up again, the DC voltage order is increased in a controlled manner. Due to the lower counter DC voltage from the VSC converter, the LCC converter can start to drive DC current sooner. Thus, the whole active power recovery becomes significantly faster. An overview of the CDVOL function is shown in Figure 2.

To verify the CDVOL, several tests were made. Time domain simulations are shown in Figure 3, Figure 4 and Figure 5. Curves in blue color shows the results with CDVOL, and curves in green color shows the results without. The figure legend is the same in all simulations and are as follows: Top curve shows DC voltage at the VSC station; Middle curve shows DC current at the VSC station. Bottom curve shows DC power at the LCC station. All quantities are in p.u.

The results are summarized in TABLE III. The CDVOL improves the dynamic performance significantly for post-fault recovery. The different steady state control modes are mentioned already in this section, just to show that the CDVOL works well in all different conditions. The steady state control modes will be discussed further in section III.

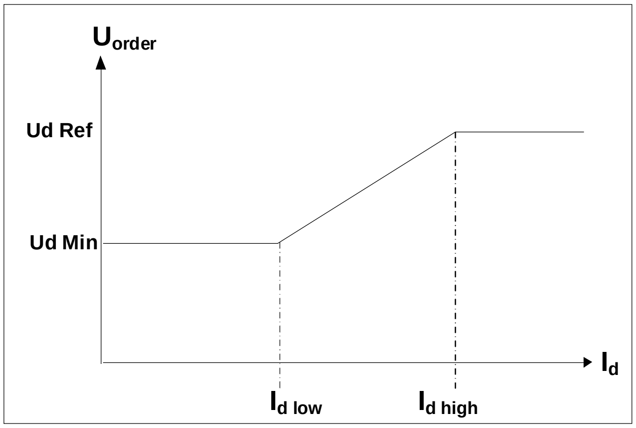

Figure 2, CDVOL function overview

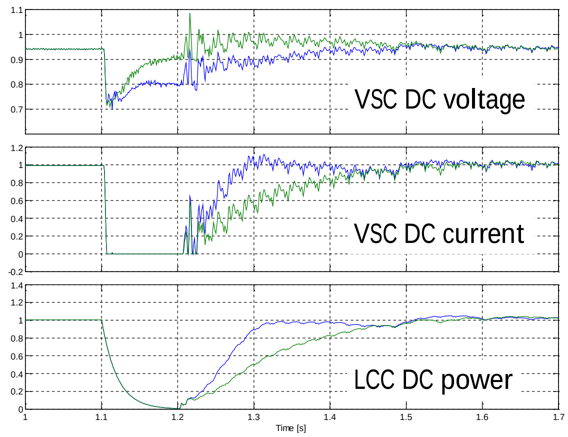

Figure 3, LCC 3-phase to ground AC fault, Mode 2

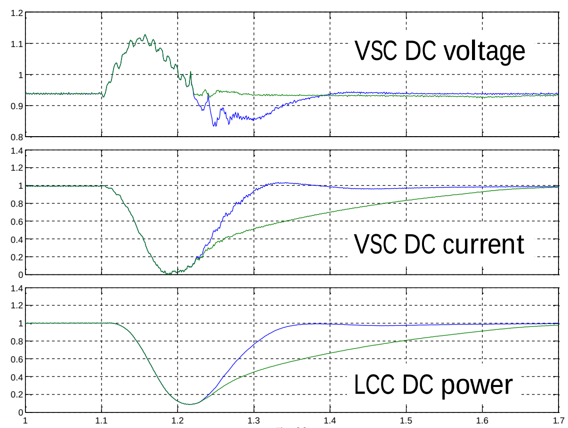

Figure 4, VSC 1-phase to ground AC fault, Mode 1

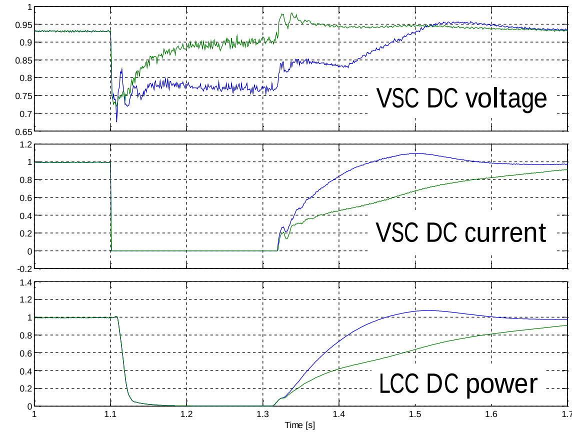

Figure 5, DC Line fault, Mode 3

TABLE III. CDVOL INFLUNCE ON RECOVERY TIME

	LCC 3-phase to ground AC fault	*VSC 1-phase to ground AC fault*	*DC line fault*
Recovery to 90% of prefault DC power at the LCC with/without CDVOL (ms)	100/230	120/390	100/380
Steady state control mode	Mode 2	Mode 1	Mode 3

III. STEADY STATE CONTROL METHODS

In this section two different ways of controlling the HVDC system are discussed, namely rectifier controlling DC voltage (called Mode 1), and rectifier controlling DC current (called Mode 2). An optimization of Mode 1 was made, which both lowers steady state losses and the overall LCC station footprint.

A. Comparison between Mode 1 and Mode 2

In a point-to-point HVDC system one station needs to control the DC current, while the other station needs to control the DC voltage. For a typical pure LCC HVDC transmission, Mode 2 is used. For a typical pure VSC HVDC system there is no general preference, but in many cases the converter that is connected to the strongest AC network controls the DC voltage. This is because a stronger AC network can easier handle rapid changes in active power flow.

A basic comparison of advantages and disadvantages between the two control modes are made in TABLE IV. A mode shift means that the AC voltage drops very suddenly at the DC current controlling converter, so that the other converter temporarily needs to take over DC current control.

TABLE IV. COMPARISON OF CONTROL MODES

	Mode 1 (LCC controls DC voltage)	*Mode 2 (LCC controls DC current)*
Main advantage	Telecommunication not really needed	Decreased DC current at mode shift
Main disadvantage	Increased DC current at mode shift, which might cause slight over-dimensioning of the VSC	System works better with telecommunication, since DC current order needs to be coordinated between

	Mode 1 (LCC controls DC voltage)	*Mode 2 (LCC controls DC current)*
	valve	stations

B. Optimization based on Mode 1

To lower the cost, footprint and losses of the whole LCC station, some further steady state optimization was possible based on Mode 1. Instead of using a firing angle at a typical 15±2.5°, it is possible to bring down the firing angle to the minimum allowed of 5° and just use the tap changer to regulate the DC voltage [8]. This optimization is called Mode 3.

Operation with Mode 3 brings significant advantages. A comparison is made in TABLE V.

TABLE V. COMPARISON BETWEEN MODE 3 AND MODE 1

	Mode 3 (5° firing angle)	*Mode 1 (15° firing angle)*
Bipolar reactive power consumption (MVAr)	1320	1640
Number of AC filters and shunt capacitors	9	11
Apparent power through the converter transformers (MVA)	3278	3419
Total Harmonic Distortion in transformer valve currents (%)	18.9	21.2

To get a better comparison between the three steady state control modes, recovery after a 3-phase to ground low impedance AC fault at the LCC is shown in Figure 6. Out of all tested cases, this is the post-fault recovery that shows the biggest difference. Voltage and power are in p.u, and firing angle is in electrical degrees. Mode 1 is in green color, Mode 2 is in blue color and Mode 3 is in red color. Both Mode 1 and 2 has some control margin left since the steady state firing angle is higher. Somewhat simplified, an LCC rectifier has a control margin that is cosine (5°) – cosine (steady state firing angle), or around 3% in this case. Therefore, the firing angle is pushed down to 5° at around 1.45s, which in turn transmits some additional DC power. In Mode 3 there is no control margin, hence the DC active power recovery will basically follow the AC voltage amplitude recovery.

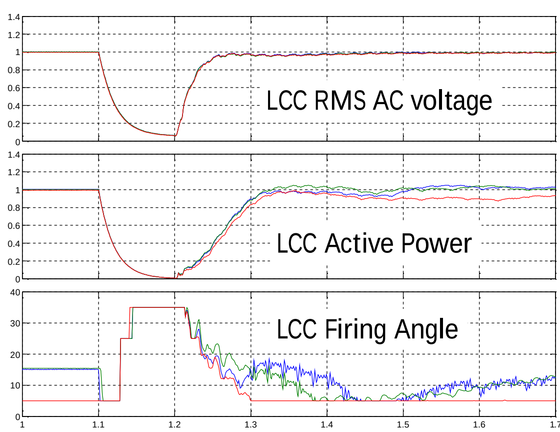

Figure 6, comparison of the three control modes

IV. CONCLUSIONS

For recovery after fault clearance, the ability to rapidly increase the DC voltage is the most important factor. Hence, the LCC converter will place the basic limitation in this system. To improve the dynamic performance, a new function called CDVOL was developed. It rapidly lowers the DC voltage order when the measured DC current dips. When the DC current starts to build up again, the DC voltage order is increased in a controlled manner. Due to the lower counter DC voltage from the VSC converter, the LCC converter can start to drive DC current sooner. Thus, the whole active power recovery becomes significantly faster.

Two control modes were also compared, namely LCC controlling DC current, and LCC controlling DC voltage. It was shown that both control modes are feasible, during steady state operation and also during transients. By using the minimum allowed firing angle of 5° together with transformer tap changer to perform DC voltage control with the LCC, significant optimization of the whole LCC converter station is possible, namely: lower losses, cost and footprint.

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