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A cost effective hybrid HVDC transmission system with high performance in DC line fault handling

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SUMMARY

This paper is about 2-terminal hybrid HVDC, with a Classical LCC converter in the sending end, and a VSC converter in the receiving end. Due to recent advancements in VSC technology, the rated bipolar capacity is 3GW, ±500 kV.

A key challenge with OHL (Over Head Lines), is that temporary DC faults must be handled. 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 is a very cost effective solution. The diode valve enables the VSC converter to provide continuous reactive power support to its local AC grid, and also enables very fast active power recovery.

Two ways of controlling the HVDC system is compared with each other, namely LCC controlling DC voltage, and LCC controlling DC current. Optimizations are made, which lowers footprint, cost and losses at the LCC station. It is shown through time domain simulation that both ways of controlling are feasible, in steady state as well as during transients. The key issue with transients is a solid three-phase AC fault at the VSC station, which causes overvoltage at the VSC station. The overvoltage is manageable with improved LCC controls.

KEYWORDS

Hybrid HVDC, LCC HVDC, VSC HVDC, Diode Valve, UHVDC, Series Connected Converters.

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1. INTRODUCTION

In recent years, Voltage Source Converter (VSC) HVDC has rapidly increased both its maximum voltage and current rating. The introduction of Modular Multilevel Converter (MMC) made it relatively easy to scale the voltage upwards [1]. The increase in maximum attainable current comes mostly from advances in semiconductor technology [2]. It is therefore becoming practically feasible to build Hybrid HVDC, consisting of traditional Line-Commutated Converter (LCC) HVDC in one station, and VSC HVDC in the other station. An overview of the system tested in this paper is shown in Figure 1, and the key data is listed in Table 1.

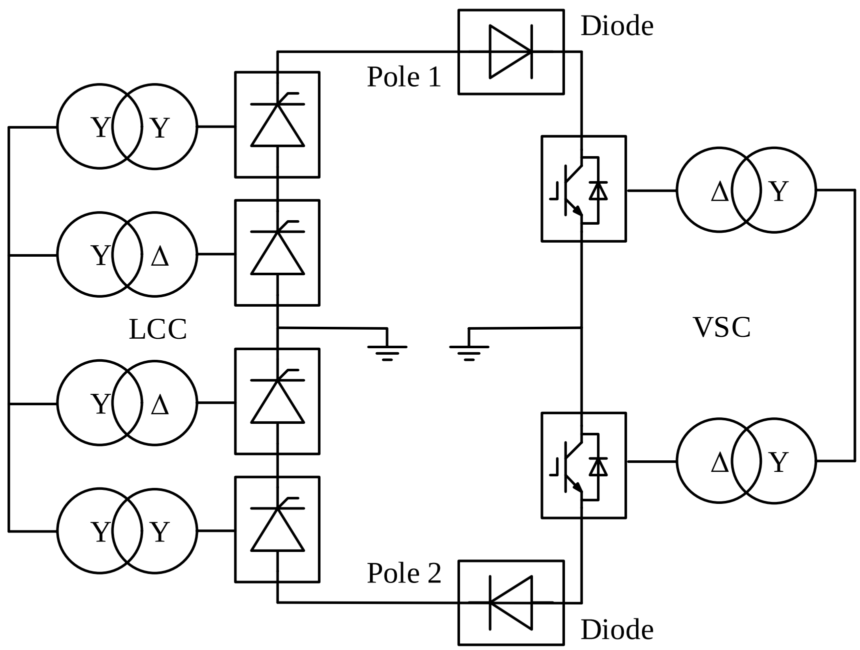

Figure 1 – Overview of the tested hybrid HVDC system, including Diode

Table 1 – key data of the tested hybrid HVDC system

Parameter	LCC	VSC
Nominal AC voltage (kV)	525	525
AC frequency (Hz)	50	50
Nominal DC voltage (kV)	±500	
Nominal DC current (A)	3000	
DC line length (km)	1000	

LCC based HVDC converters which have the advantages of low cost and low losses are widely used in HVDC applications, and they also have the capability of controlling DC fault current. The disadvantage is that commutation failures could occur during an AC voltage dip, especially during inverter operation. Due to large penetration of HVDC transmission systems in a bulk AC grid, one commutation failure could trigger commutation failures in other HVDC inverters. As a consequence, a cascaded HVDC system trip event could occur, which could potentially lead to unacceptable power system disturbances.

VSC based HVDC converters have no commutation failures, and they can also support a weak AC grid by controlling reactive power independent of active power. Although there are some challenges in handing DC fault in addition to higher cost and losses, the greatly improved AC network performance that the VSC offers over a traditional LCC converter may still motivate or justify the installation of a VSC HVDC converter in a number of situations, for example: HVDC multi infeed and the related stability issues [3], too high short circuit AC current due to synchronous condensers [4], and too weak AC grid due to the integration of large amount of renewable energy [5].

So far there is only one VSC HVDC transmission using OHL in commercial operation, namely the Zambezi Link [6]. It uses both AC breakers as well as mechanical resonant DC breakers to clear DC line faults. There is a short interruption on the reactive power support to the connected AC grid due to the AC breaker opening. If faster active power recovery and/or continuous reactive power support during the DC fault clearing is necessary, there are several other options, namely: Hybrid DC breaker + half bridge MMC [7];Full Bridge MMC [8], which will have significantly higher cost compared with the existing solutions.

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 [9]. This paper examines the diode solution and the related system requirements in detail, both in steady state and in transient operation. In section two of this paper, different steady state control modes are compared with each other. In the third section, dynamic performance during and after temporary AC and DC faults is shown and discussed. The key problem is low impedance AC faults at the VSC station, which in turn causes a high DC voltage.

2. STEADY STATE CONTROL

For this type of HVDC system, one station needs to control the DC current, while the other station needs to control the DC voltage. Hence two control modes are possible, namely rectifier controlling DC voltage (called Mode 1), and rectifier controlling DC current (called Mode 2). For a typical 100% LCC HVDC transmission, Mode 2 is used. For a typical 100% 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 2. 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 2 – Advantages and disadvantages between the two 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 valve	System works better with telecommunication, since DC current order needs to be coordinated between stations

In Figure 2, a mode shift when operating at nominal power in Mode 2 is shown. At 0.1s, the AC voltage at the LCC station is stepped down from 1.0 to ~0.91 p.u. and the LCC tries to keep the DC current at the ordered value, by reducing its firing angle to the minimum allowed 5°. However, this is not enough to satisfy the current order, so the backup DC current controller at the VSC activates. In a very similar manner to a normal 100% LCC transmission, a current margin of 0.1 p.u. is used. Therefore, the transmitted DC current is equal to “order - current margin”, or around 0.9 p.u. in this case. Finally at 1.1s, the AC voltage is stepped up to 1.0 p.u again, and the LCC takes back DC current control. Both control mode transitions at 0.1s and 1.1s are smooth and stable.

The figure legend is: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; Measured and ordered DC current, in p.u. Fourth graph; Alpha order, in electrical degrees. All graphs from pole 1 in the LCC station.

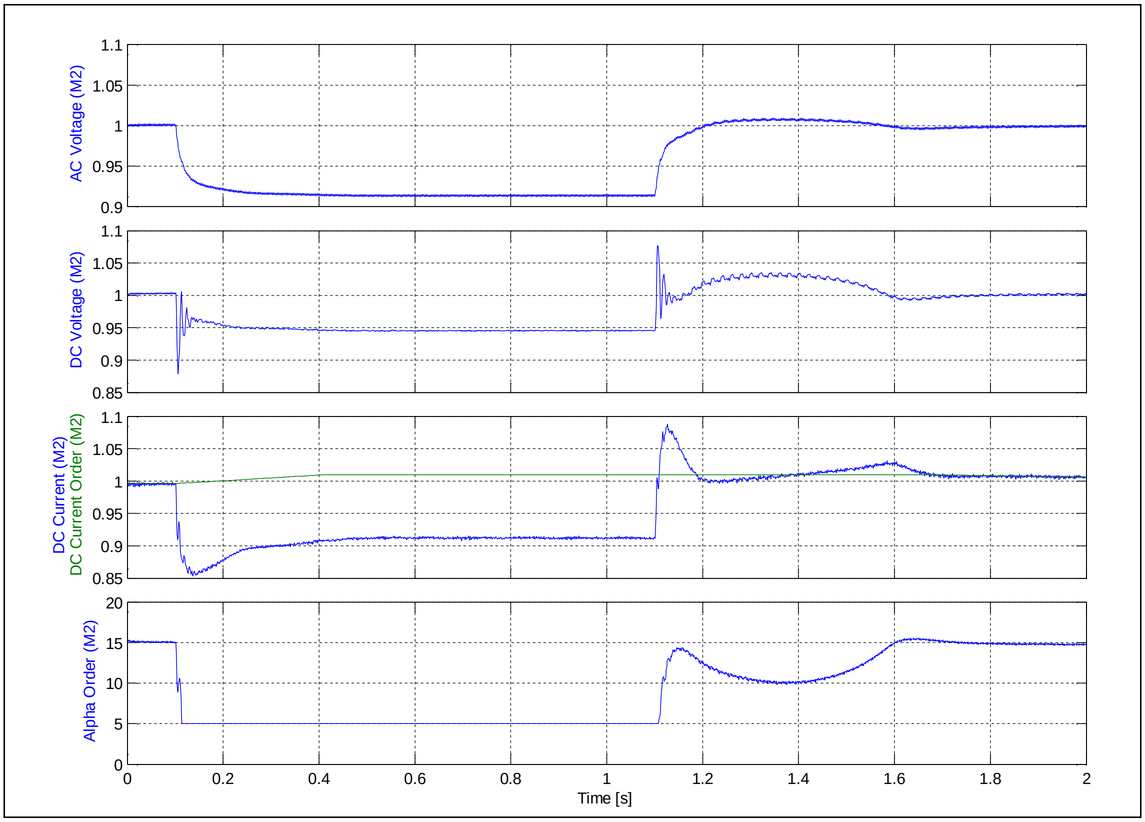

Figure 2 – AC voltage drop at the LCC station, resulting in mode shift.

In order to lower the cost, footprint and losses of the whole hybrid DC transmission system, some further steady state optimization was possible:

- Initially in Mode 1, DC voltage control was implemented with a LCC firing angle of 15±2.5°, which is identical to how DC current control is implemented in Mode 2
- However in Mode 1, it is possible to use the minimum allowed firing angle of 5°, and instead use the tap changer to regulate the DC voltage

The key impact this had to the LCC station in the tested system is summarized in Table 3.

Table 3 – Comparison between 5° and 15° firing angle

Parameter	**5° firing angle**	**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

Hence operating the LCC with 5° in steady state is very attractive:

- Smaller station footprint and lower cost, since less shunt capacitors are needed
- Lower apparent power rating of the converter transformers, which saves cost
- Lower overall losses (mostly transformer), due to lower harmonics
- AC and DC filter optimizations might be possible, due to lower harmonics

For convenience, Mode 1 with 5° firing angle is called Mode 3 for the rest of this paper. As will be shown in the next chapter, the dynamic performance of Mode 3 is almost identical to Mode 1 and Mode 2. This is because the thyristors are still fully controllable during transients.

3. TRANSIENT PERFORMANCE DURING AC AND DC FAULTS

In this chapter, transient performance is evaluated. Solid three-phase AC faults are applied at both the LCC and VSC station, and DC faults are also tested. Some changes were made to both the LCC and VSC controls, to improve the overall performance.

3.1 Three-phase to ground AC fault at the LCC station

In Figure 3, a solid three-phase to ground AC fault is applied at 1.1s at the LCC station. Since the remaining AC voltage is very low, no power can be transmitted from the AC network to the LCC converter during the fault. In order to decrease the DC voltage at the instant when the AC fault is cleared, the firing angle alpha is increased to 35°. The AC fault is then cleared at 1.2s, and active power recovery starts. The VSC converter is undisturbed, and therefore has a fairly high DC voltage at the moment of AC fault clearance. The LCC converter uses a conventional VDCOL (Voltage Dependent Current Order Limiter) to ensure a stable and fast recovery. Recovery to 90% of pre-fault active power at the LCC is done within 90ms for all three control modes.

The figure legend is: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; Measured DC current, in p.u. Fourth graph; Alpha order, in electrical degrees. Mode 1 is in blue color, Mode 2 is in green color, and Mode 3 is in red color. All graphs from pole 1 in the LCC station.

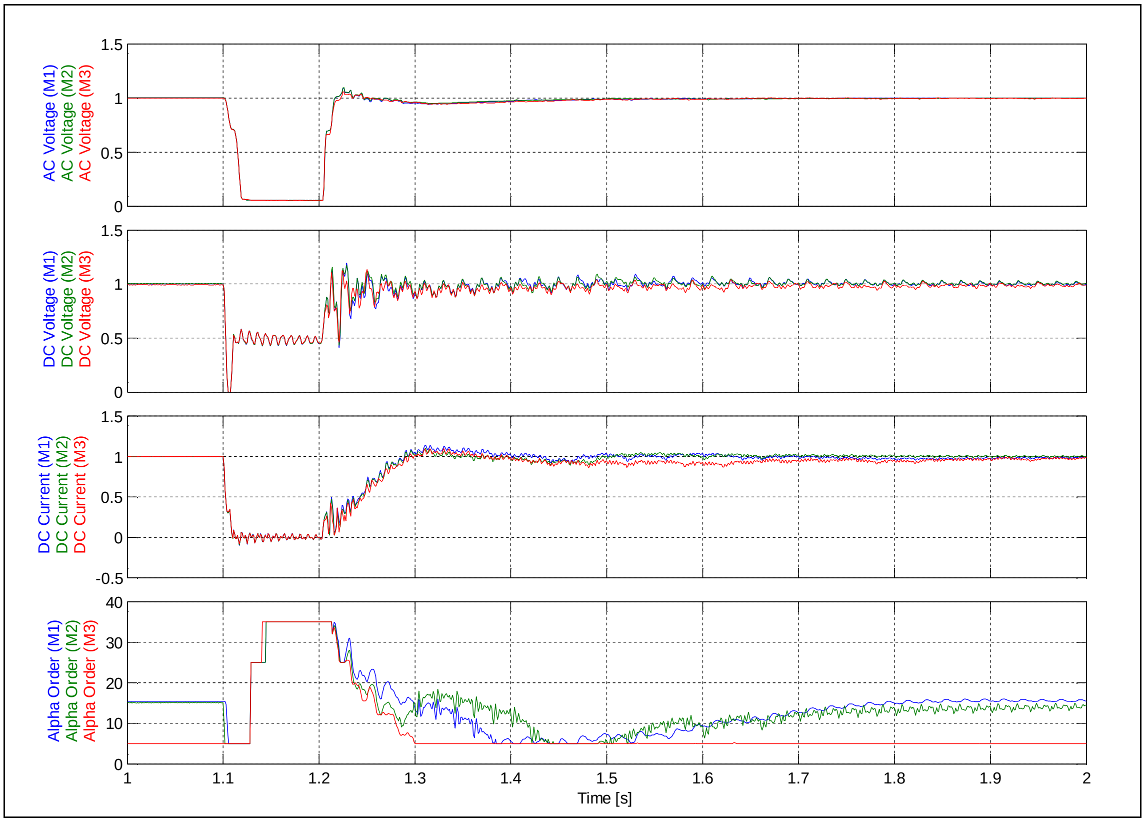

Figure 3 – Three-phase to ground AC fault at the LCC station.

3.2 Three-phase to ground AC fault at the VSC station

In Figure 4, a solid three-phase to ground AC fault is applied at 1.1s at the VSC station. Since the remaining AC voltage is very low, almost no active power can be transmitted from the VSC converter to the AC network. Instead the energy flows into the VSC cell capacitance, which rapidly builds up high cell voltages. This is very critical, since there is a risk that the whole transmission must make a protective stop, since operation with too high cell voltages can destroy the whole VSC valve.

Therefore the LCC converter needs to act quickly, in order to reduce the overvoltage at the VSC station. When a sudden increase in DC voltage is detected, a high gain DC voltage controller is activated and increases the firing angle rapidly. However with a high gain, the DC voltage controller will easily wind-up, which will then slow down the recovery once the AC fault is cleared at the VSC station. Therefore an upper limit of 50° is used.

The AC fault is then cleared at 1.2s, and active power recovery starts. The VSC starts injecting active power into the AC network, which lowers the cell overvoltage. Attention must however be paid to the cell voltages again, which might dip to very low levels if the first stage of active power recovery is made too quickly. This is due to the fact that the LCC is not capable of providing active power at this moment. The DC voltage is reduced down to nominal levels at roughly 1.28s, and the second stage of active power recovery starts when DC current flows again. Recovery to 90% of pre-fault active power at the LCC is done within 200ms for all three control modes.

The figure legend is: First graph; RMS AC voltage, in p.u. Second graph; DC line voltage, in p.u. Third graph; Measured DC current, in p.u. Fourth graph; Alpha order, in electrical degrees. Fifth graph; Maximum VSC cell voltage, in p.u. Sixth graph; Active power from the VSC converter to the AC grid, in p.u. Mode 1 is in blue color, Mode 2 is in green color, and Mode 3 is in red color. Graphs 2-4 from pole 1 in the LCC station, all others from pole 1 in the VSC station.

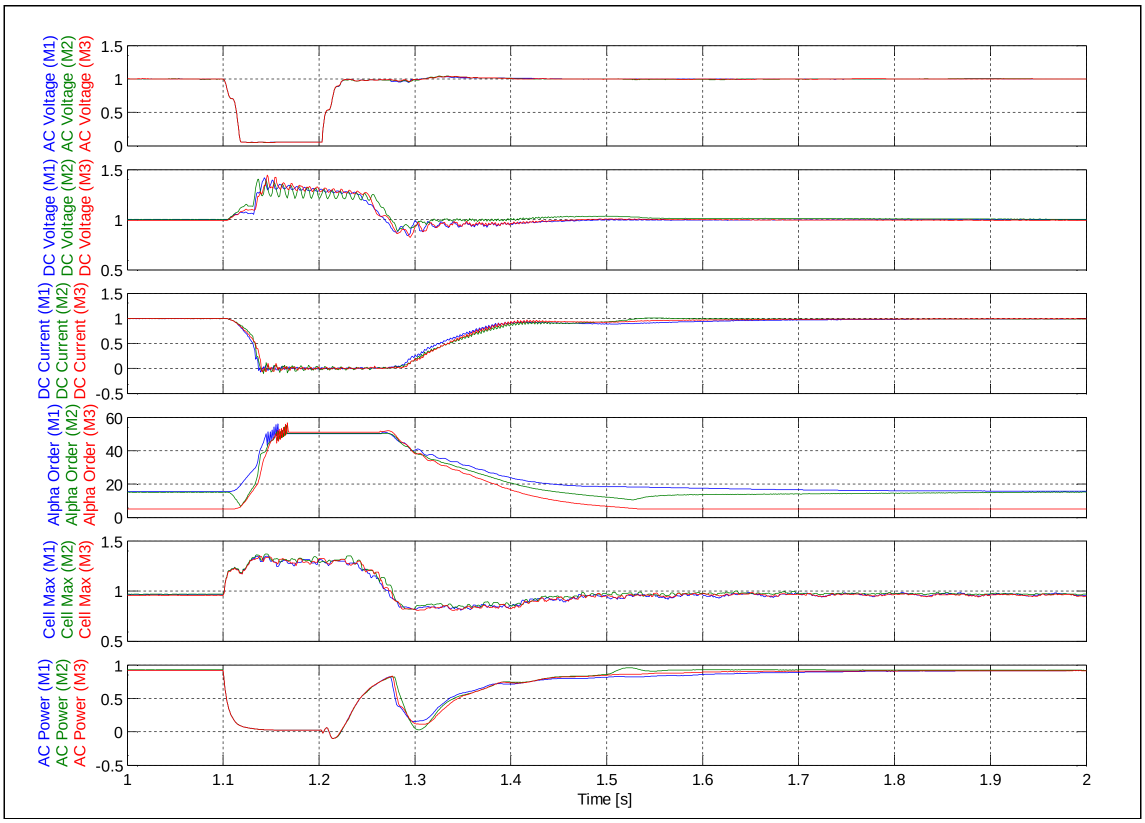

Figure 4 – Three-phase to ground AC fault at the VSC station.

3.3 DC fault close to the VSC station

In Figure 5, a DC fault is applied in pole 1 close to the VSC station at 1.1s. Since a diode valve is used, the fault just looks like a sudden stop of active power transmission for the VSC. The VSC can therefore give continuous reactive power support to the AC network during the whole fault and recovery sequence. In the tested case, AC voltage control with a setting of 1.0 p.u. is used.

The LCC will however see a sharp reduction in DC voltage and a sharp increase in DC current, and will therefore issue a protective retard order. The firing angle is rapidly increased to 164°, which changes polarity of the LCC converter and effectively stops the fault current. After a line de-ionization time of 200ms, the LCC restarts power transmission again. Recovery to 90% of pre-fault active power at the LCC is done within 100ms for all three control modes.

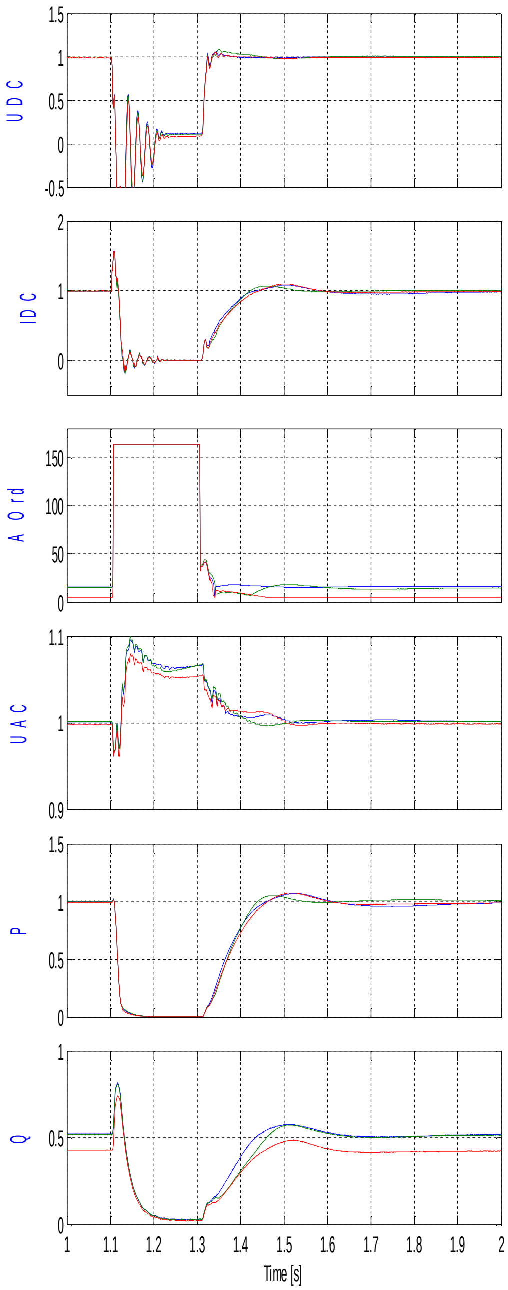

Figure 5a – DC fault, LCC response

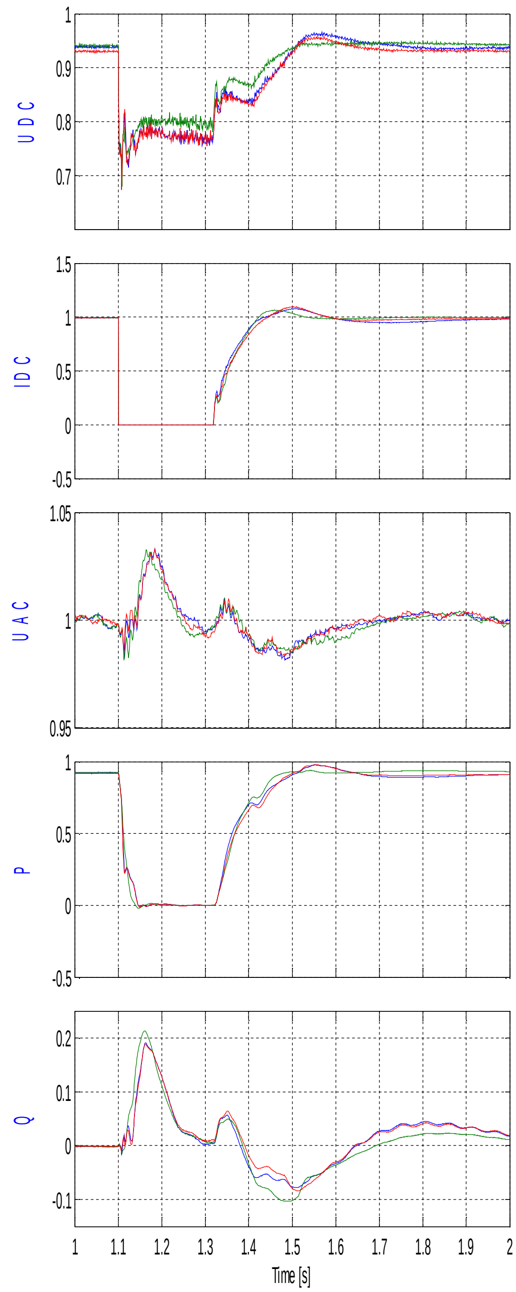

Figure 5b – DC fault, VSC response

The LCC figure legend is: DC line voltage, in p.u. Second graph; Measured DC current, in p.u. Third graph; Alpha order, in electrical degrees. Fourth graph; RMS AC voltage, in p.u. Fifth graph; Active power from the AC grid to the LCC converter, in p.u. Sixth graph; Reactive power from the AC grid to the LCC converter, in p.u.
The VSC figure legend is: DC line voltage, in p.u. Second graph; Measured DC current, in p.u. Third graph; RMS AC voltage, in p.u. Fourth graph; Active power from the VSC converter to the AC grid, in p.u. Fifth graph; Reactive power from the VSC converter to the AC grid, in p.u.
Mode 1 is in blue color, Mode 2 is in green color, and Mode 3 is in red color.

5. CONCLUSIONS

In this paper, it is shown that a diode valve enables high performance DC fault handling in a Hybrid HVDC system. The VSC at the receiving end can provide continuous reactive power support to its AC network. By optimizing the overall control of the system, the LCC station gets a smaller footprint, lower cost, and lower losses.

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