Novel solutions for LCC HVDC fault ride through

Mats Andersson, Rong Cai, Hailian Xie
Corporate Research, Power and Control, ABB (China) Ltd.

***Abstract*—LCC HVDC has always been and will always be susceptible to commutation failures, due to the physical properties of the thyristor. Typically the key input for predicting when a commutation failure is likely to happen at the inverter are the AC voltages [1]. In this paper, a novel commutation failure prediction based on DC currents and DC voltages is introduced. It is proven by simulation that correct predictions are possible for two distinct cases, namely a sudden increase in rectifier AC voltage, and also during the recovery after a DC line fault in a bipolar transmission.**

However, even with an improved prediction, it will never be possible to avoid commutation failures, which will cause a temporary stop to the HVDC transmission. Since the transmission needs to stop for a while, the rectifier AC network will have a surplus of both active and reactive power. This surplus will cause an increase in AC voltage amplitude and/or frequency. In order to handle this temporary surplus, a DC Chopper is introduced at the rectifier. The Chopper combined with the LCC converter thus provides controllable active power consumption. If the Chopper resistance is made sufficiently variable, the reactive power consumption from the LCC converter will roughly equal the pre-disturbance consumption. In one sentence: By using a Chopper, the overall impact to the rectifier AC network is very small.

***Index Terms*—Commutation failure prediction, DC Chopper, LCC HVDC, Weak AC network.**

I. INTRODUCTION

In order for a thyristor to turn off successfully, a negative voltage must be applied for a long enough time, in order to drain the stored charge [2]. If all charge has not been drained before the voltage becomes positive, the thyristor will automatically come into conduction again. This is in commonly known as a commutation failure, since inside the 6-pulse Graetz bridge the DC current is not successfully commutated to the next valve. The consequence of this happening at an HVDC inverter station is particularly undesirable, since it causes a temporary stop to the HVDC transmission. A lot of research has already been put into predicting commutation failures. The most commonly used approach is to detect deviations in the inverter AC voltages, and then rapidly increase the inverter extinction angle [1]. In section II of this paper, a novel commutation failure prediction based on DC currents and DC voltages is introduced. Two typical cases are taken into consideration, namely a sudden increase in rectifier AC voltage, and also during the recovery after a DC line fault in a bipolar transmission. Time domain simulations shows the effectiveness of the proposed commutation failure prediction.

In section III, focus is placed on rectifier AC network stability, during a temporary stop of the HVDC transmission. The reason for the stop could be an inverter AC fault, or a DC fault. Since no active power can be transmitted, there will be an active power surplus in the rectifier AC network. Since LCC HVDC requires a large amount of AC filters and shunt capacitors to be connected, there will also be a reactive power surplus. This dual surplus will cause an increase in AC voltage amplitude and/or frequency. In order to handle this temporary surplus, a DC Chopper is introduced at the rectifier. By rapidly connecting a resistor on the DC side and then burning controllable active power using the LCC converter, the active power surplus in the rectifier AC network can effectively be dealt with. If the Chopper resistance is made sufficiently variable, the reactive power consumption from the LCC converter will roughly equal the pre-disturbance consumption. Hence both the active and reactive power surplus can be minimized at the same time. This has a positive effect on the rectifier AC network stability, especially if it is a weak network.

II. NOVEL COMMUTATION FAILURE PREDICTION

In this section, state of the art for commutation failure prediction is firstly reviewed. Then a novel commutation failure prediction based on DC current and voltage measurements is introduced. Two scenarios are considered, namely a sudden increase in rectifier AC voltage, and also during the recovery after a DC line fault in a bipolar transmission.

A. State of the art for commutation failure prediction

In order to avoid commutation failures, the currently used solutions has AC voltage measurements as the key input. The most common cause for a commutation failure is indeed a temporary AC voltage dip at the inverter. The detection principles consists of two key parts. The first part adds the three AC voltage measurements together, thus it can detect a sudden zero sequence component. The other part does a αβ-transformation of the three phases, and creates a steady state reference value by applying a low-pass filter. If the instantaneous input is much lower than the steady state reference value, AC faults without a zero sequence can also be detected. Once a detection has been made by either part, a rapid contribution is made to the gamma reference. This causes an earlier firing of the inverter, and depending on circumstances, a commutation failure might be avoided.

However, it is not only inverter AC voltage dips that may cause inverter commutation failures, therefore focus was put on how to also deal with rapidly increasing DC current.

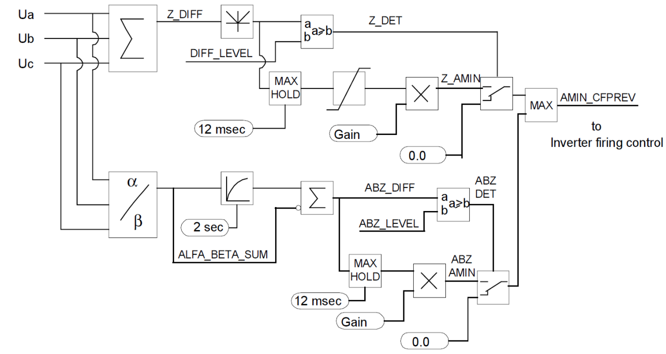

Figure 1, commutation failure prediction, copied from [1]

B. Novel commutation failure detection method #1

As an AC network gets weaker, temporary overvoltage will also be higher. If a HVDC rectifier is connected to a weak AC network, a temporary AC overvoltage can cause a commutation failure at the inverter station. The reason is that the suddenly increasing AC voltage causes a sudden increase in DC current. At the inverter station, the sudden increase in DC current causes a longer overlap, which with an unchanged firing angle causes a smaller gamma.

Based on this scenario, a novel detection method was developed. If both the measured DC current and DC voltage suddenly rises at the inverter, a rapid contribution is made to the gamma reference. A simplified overview is shown in Figure 2.

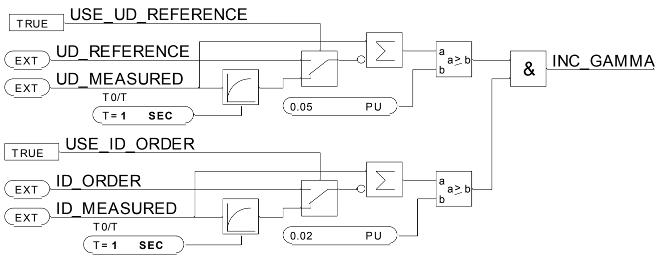

Figure 2, novel commutation failure prediction #1

Based on the test system presented in Figure 3 and Table II-1, a case which causes very high and sudden AC overvoltage at the rectifier was tested, namely disconnection of the supporting AC network, called AC Grid 2.

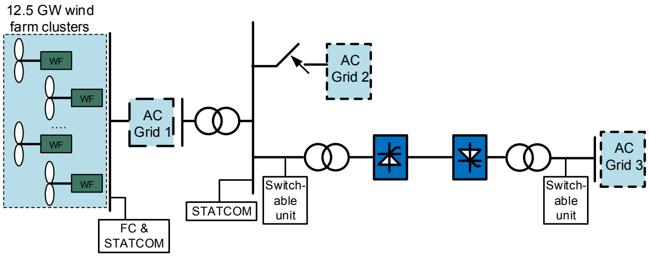

Figure 3, test system

Table II-1

Name	*Value*	*Unit*
Nominal DC voltage	±800	kV
Nominal DC current	5.0	kA
Number of 6-pulse groups/pole	4	-
Nominal AC voltage level S1/S2	750/500	kV
Nominal AC Short Circuit Ratio S1/S2	3/5	-
Nominal AC voltage frequency	50	Hz
DC line length	2300	km
DC line resistance	8.6	Ω

As can be seen in the time domain simulation in Figure 4, a commutation failure can be avoided at the inverter by a rapid increase in the gamma reference.

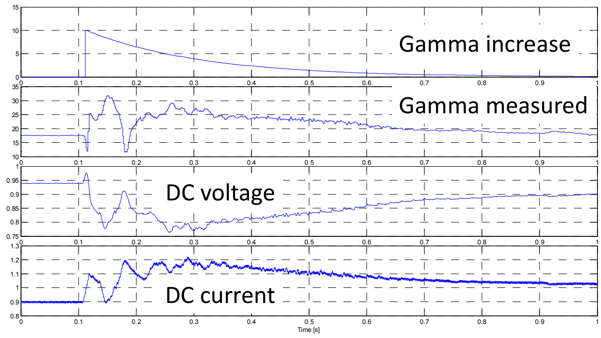

Figure 4, gamma increase at rectifier AC overvoltage

C. Novel commutation failure detection method #2

Today's bipolar UHVDC transmissions are getting extremely long and compared to 800 kV, the most recent level of 1100 kV becomes economically attractive at distances of over 3000 km [3]. Two DC conductors placed side-by-side with each other for thousands of kilometers are naturally going to form a mutual inductance. The effects that this mutual inductance has on the HVDC system is mostly going to appear during a DC line fault, since at that moment the current flow in the two poles are very different. During a normal DC fault clearance period, short time overload of the healthy pole is often used since it lowers the impact to both the rectifier and inverter AC networks. After the de-ionization period of the faulty line, it is time to restart the faulty pole. Until the faulty pole has recovered successfully, it is very important to not have any disturbances to the healthy pole, since otherwise there will be a temporary bipolar stop of power transmission.

It was observed in the test system that the healthy pole can quite easily suffer from a commutation failure shortly after the faulty pole restarts. This is due to the mutual inductance between the DC lines, in combination with the fairly rapid recovery of the faulty pole. One option could be to recover the faulty pole much slower, but since this is generally speaking undesirable a novel commutation failure prediction was designed instead. In order to make a fast and reliable detection mechanism that is not dependent on interstation telecommunication, the key principle is based on local measurements: The healthy pole monitors the DC current in the faulty pole. As soon as there is DC current flowing again, the healthy pole rapidly increases its gamma. A simplified overview is shown in Figure 5, and a time domain simulation comparing the recovery before (in blue color) and after using the novel commutation failure prediction (in green color) is shown in Figure 6.

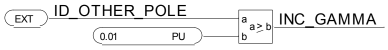

Figure 5, novel commutation failure prediction #2

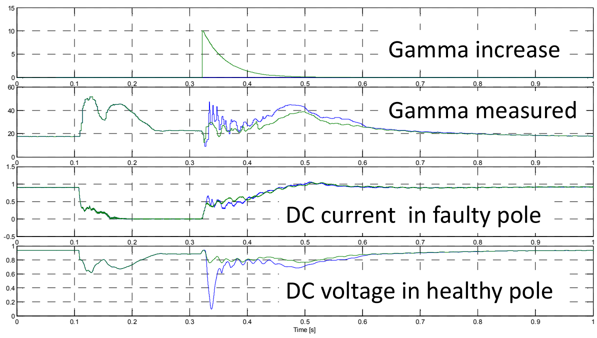

Figure 6, recovery after a DC line fault

III. Rectifier DC Chopper Concept

In this section, state of the art for DC Choppers is firstly reviewed. Then based on the previously described ±800 kV bipolar UHVDC test system, a novel DC Chopper concept is introduced. This has a positive effect on the rectifier AC network stability, especially if it is a weak network.

A. State of the art for DC Choppers

In VSC HVDC, DC choppers are commonly used. A typical usage of a DC Chopper is for offshore wind integration, where the onshore DC Chopper can temporarily burn the active power produced by the offshore windfarm. This way the offshore AC network does not have to deal with a sudden and large active power surplus, should the onshore station not be able to inject power into its AC grid [4]. The onshore placement of the Chopper is purely an economical choice, there is practically nothing preventing placing a Chopper offshore. This is because offshore systems are cable based, hence there is no need to consider temporary DC faults. DC cable faults are not temporary, and in addition they are very costly to repair. Based on this, the whole power transmission must trip immediately should there be a DC fault.

There is currently one commercial OHL (Over Head Line) VSC HVDC transmission in operation, namely the Caprivi Link [5]. It clears temporary DC faults by opening the AC breakers, and then resumes transmission by re-closing them again. Caprivi Link is equipped with a DC Chopper at the inverter station. However, this DC Chopper cannot help the very weak local rectifier AC network during a DC fault, since the DC line will be disconnected.

B. DC Chopper at the rectifier

Traditionally, LCC HVDC rectifiers have been connected to fairly strong AC networks, such as a hydro power plant or a coal power plant. With increasing penetration of renewable energy such as wind power, the rectifier AC networks are getting considerably weaker. One example of this is the Jiuquan – Hunan UHVDC transmission, which transmits a mix of coal power and wind power [6]. If there is a temporary disturbance to the transmission, such as an inverter AC fault or DC line fault, there will be a large active power surplus in the rectifier AC network. Since LCC HVDC requires a large amount of AC filters and shunt capacitors to be connected, there will also be a large reactive power surplus. This dual surplus will cause an increase in AC voltage amplitude and/or frequency. In order to handle this temporary surplus, a DC Chopper is introduced at the rectifier. A simplified system overview is shown in Figure 7. It should be noticed that the only new equipment is the Chopper switch and the Chopper resistance, everything else is already existing.

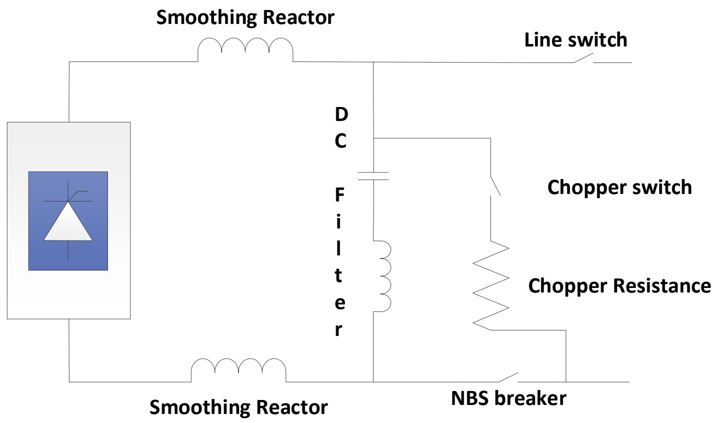

Figure 7, rectifier including DC Chopper

The flow chart in Figure 8 assumes that both the Line switch and the Chopper switch has an ability to commutate DC current, breaking DC current is not an absolute requirement.

C. Hardware consideration for the DC Chopper

As can be seen in Figure 7, both the Line switch and Chopper switch will be exposed to the full pole voltage. In addition, the Line switch will need to handle continuous nominal DC current. Although there is a lot of research going on regarding fast disconnectors in the VSC HVDC field [7],[8] there are currently no fast disconnectors available that could handle the extreme UHVDC conditions. Therefore focus was placed using mechanical breakers outfitted with resonant LC circuits, i.e. traditional mechanical DC breakers. According to data sheet [9], opening and closing times are 33 and 65 ms for a typical 800 kV breaker (HPL800B4). Depending on application requirements, the closing time might be a bit long. Therefore the Chopper switch could possibly be built as a normally closed mechanical breaker with a normally open thyristor valve in series, as shown in Figure 9.

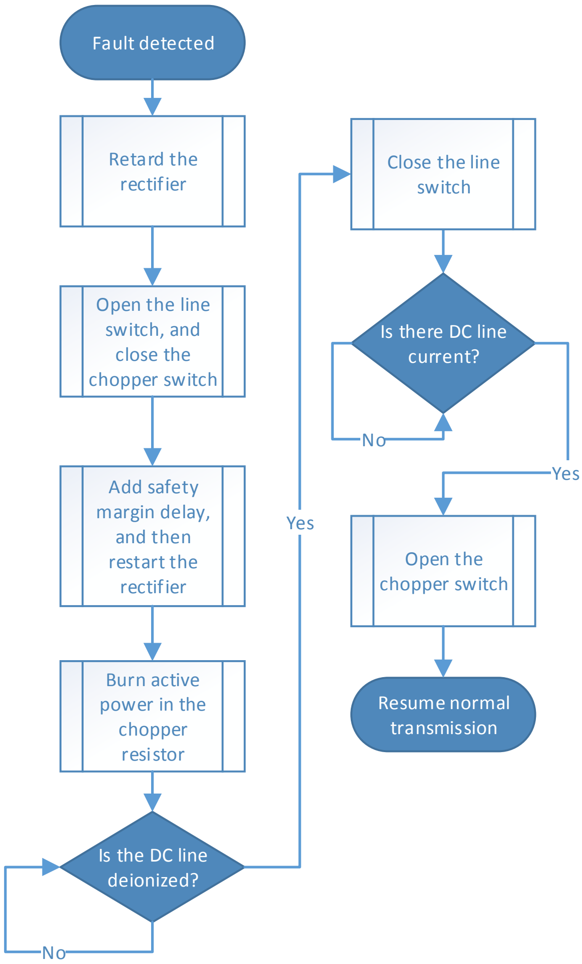

Figure 8, DC Chopper flow chart

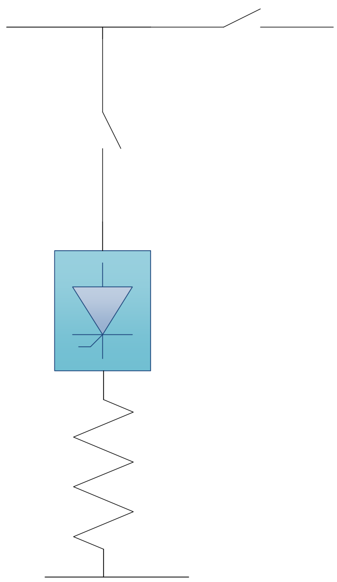

Figure 9, mechanical breaker and thyristor valve in series

D. Time domain simulation of the DC Chopper

In order to verify the DC Chopper concept, the previously described test system was used again. In addition, it was assumed that traditional mechanical DC breakers were used as both line and Chopper switches.

As can be seen in Figure 10, a solid three-phase-to-ground fault was applied at the inverter AC network at 0.1s. The rectifier acts according to the flowchart in Figure 8, and both poles start to burn active power in their respective DC Choppers at around ~0.17s. It is clearly shown in Figure 10 that the rectifier AC system quickly restores pre-disturbance values as soon as the DC lines have been disconnected and the DC Choppers have been connected. The AC fault clears at the inverter station at 0.25s, but since the DC lines are temporarily disconnected there is no influence to the rectifier AC network at this point. At around ~0.37s, the first pole resumes power transmission. When it has recovered to full power, the second pole resumes power transmission at around ~0.57s. By letting the two poles restore power transmission with some time separation, there will be a continuous draw of active power and consumption of reactive power.

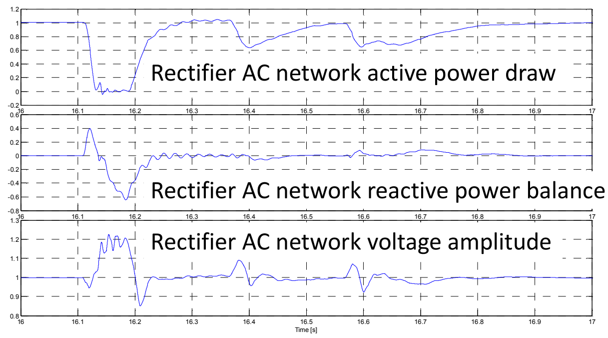

Figure 10, simulation of the DC Chopper

IV. CONCLUSIONS

In this paper, a novel commutation failure prediction based on DC currents and DC voltages was introduced. Two typical cases were taken into consideration, namely a sudden increase in rectifier AC voltage, and also during the recovery after a DC line fault in a bipolar transmission. Time domain simulations shows the effectiveness of the proposed commutation failure prediction.

When a temporary stop to the DC transmission happens, like an inverter AC fault or a DC fault, there will be a large surplus of both active and reactive power. In order to handle this temporary surplus, a DC Chopper was introduced at the rectifier. By rapidly connecting a resistor on the DC side and then burning controllable active power using the LCC converter, the active power surplus in the rectifier AC network can effectively be dealt with. If the Chopper resistance is made sufficiently variable, the reactive power consumption from the LCC converter will roughly equal the pre-disturbance consumption. Hence both the active and reactive power surplus can be minimized at the same time.

REFERENCES

[1] Lidong Zhang, Lars Döfnäs, "A Novel method to mitigate commutation failures in HVDC systems", PowerCon 2002, Kunming, China, October 13 - 17, 2002

[2] Ned Mohan et. al. "Power Electronics, Converters, Applications and Design", Second Edition, 1995, Chapter 23, Thyristors

[3] Yu Jun, "New LCC-HVDC technology and its applications in SGCC", International High Voltage Direct Current 2015 Conference, Seoul, Korea, October 18-22, 2015
[4] Ying Jiang-Häfner, Rolf Ottersten, "HVDC with Voltage Source Converters - A Desirable Solution for Connecting Renewable Energies", Large-scale integration of wind power into power systems, Bremen, Germany, Oct 14-15, 2009
[5] T. Magg, M. Manchen, E. Krige, J. Wasborg, J. Sundin, "Connecting networks with VSC HVDC in Africa: Caprivi Link Interconnector", IEEE PES PowerAfrica 2012 Conference and Exposition, Johannesburg, South Africa, 9 - 13 July 2012
[6] ZHONG Sheng, HUANG Juanjuan, LI Taijun, Tian Xin, XIA Yi, FAN Xuefeng, SONG Wenqin, "±800 kV UHVDC Planning Operation Curve from Jiuquan to Hunan", Electric Power Construction, Vol. 36, No. 9, September 2015
[7] Per Skarby, Ueli Steiger, "Ultra-fast Disconnecting Switch for a Hybrid HVDC Breaker – a technical breakthrough", CIGRE Canada, September 9-13, 2013
[8] Chen Chen, "Simulation, design and experimental validation of a passive magnetic damper for ultra-fast actuators", M.Sc. Thesis, KTH, Stockholm, 2014
[9] ABB, "Live Tank Circuit Breakers Buyer's Guide", available online

Mats Andersson was born in Hudiksvall, Sweden, in 1978. He received the B.Sc. degree in electrical engineering from Mälardalens University, Ludvika, Sweden in 2001. After graduation to present date he has held various positions in ABB, all related to HVDC. Currently he is a principal scientist at ABB Corporate Research Center in Beijing, China. His main fields of interest are HVDC, power electronics and power systems, with a focus on integration of renewable energy.

CONTACT INFORMATION

Mats Andersson is with ABB Corporate Research Center, Universal Plaza, 10 Jiuxianqiao Lu, Chaoyang District, Beijing, 100015, China (phone number: +86 10-6423-1345, fax number: +86 10-6423-1649, e-mail: mats.andersson@cn.abb.com).