A Novel Method to Mitigate Commutation Failures in HVDC Systems

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Abstract: **In this paper we show a method to mitigate commutation failures in HVDC systems due to voltage dips from ac systems. The abc-αβ transformation is used for three-phase fault detection, and the zero-sequence voltage, which is obtained by the addition of the three-phase voltages, is used for single-phase fault detection. Both detection methods are based on instantaneous values, which ensure fast reaction of the control system when ac faults occur. After detecting the fault, an additional angle is deducted from the firing order at the inverter station, which in practice enlarges the commutation margin. The test results show that this method is very effective in reducing the risk of commutation failures.**

Index Terms—**Commutation failures, voltage dips, power system faults, HVDC transmission.**

I. Introduction

Commutation failures following ac system disturbances may occur in HVDC systems, especially in the inverter station. The sensitivity of an HVDC inverter to commutation failures for depends on the specific main circuit design and on the control system. It is reported that commutation failures may happen during an ac system disturbance, where the voltage reduction is only as small as 10% [2]. Repeated commutation failures generally cause overcurrent in the valves and also delay the restart time of the HVDC system after the fault clears. In a severe situation it might also cause the protection system to block the valves.

Commutation failures happen if the commutation of current from one valve to another has not been completed before the commutating voltage reverses across the ongoing valve. This results in a short circuit across the valve group. The basic reason for commutation failures is that the extinction angle during system disturbance is too small. The ac system fault affects the commutation margin by voltage magnitude reduction, increased overlap due to higher dc current, and phase angle shifts. One solution to mitigate commutation failure is to have a larger commutation margin in normal operation. But a large commutation margin also means higher reactive power consumption, which is often not justified by economic considerations. Another solution is to advance the firing instant immediately after the control system detects the ac system disturbance. The problem of this solution is that the control system is often too slow to react to such a disturbance. Thanks to ABB's new developed MACH2™ system for HVDC, the control system is able to react quickly to the ac disturbance. This makes the second solution a feasible way to mitigate commutation failures.

II. COMMUTATION FAILURES IN HVDC SYSTEMS

The basic module of an HVDC converter is the three-phase, full-wave bridge circuit shown in Fig. 1. The circuit is known as Graetz Bridge. Although several alternative configurations are possible, the Graetz Bridge has been universally used for HVDC converters as it provides better utilization of the converter transformer and a lower voltage across the valve when not conducting [7].

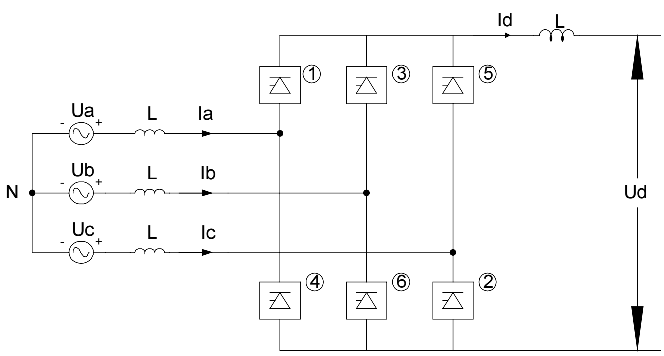

Fig. 1. Equivalent circuit for three-phase full-wave bridge converter

The Graetz Bridge can be used for transporting power in two directions, rectifier mode and inverter mode. This is achieved by applying different firing angles to the valves. When the firing angle is less than 90 degrees, the dc current flows from the positive polarity of the dc circuit, so that power flows from the ac side to the dc side; When the firing angle is greater than 90 degrees, the dc voltage U_d changes polarity, so that the dc current flows from the negative polarity of the dc circuit, and the power flows from the dc side to the ac side. An HVDC system is essentially made up of two Graetz Bridge, which are connected at the dc side, one in rectifier mode and the other in inverter mode.

Fig. 2 illustrates the angle relationships and angle definitions for a rectifier and an inverter. In both cases, current is being commutated from valve 1 to valve 3.

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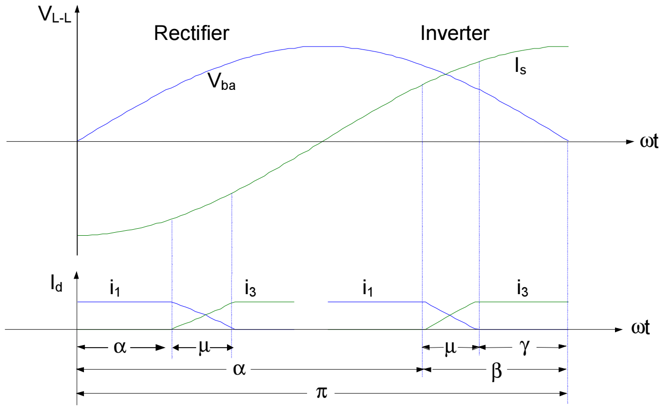

Fig. 2. The angle relationships and angle definitions for both rectifier and inverter

Since a converter transformer has inductance, the transformer current cannot change instantly. The finite rate of change of current means that the transfer of current from one valve to another requires a finite commutation time. The volt-time area A, which is shown in Fig. 3, Fig.4 and Fig.5, is required for the commutation. The volt-time area A is related to the commutating current. The higher the commutating current, the larger the volt-time area A will be.

Typical full load values of μ are in the range 20^0 to 50^0 under normal steady-state operation. A phenomenon in thyristor valves is that the internal stored charges produced during a forward conduction interval must be removed before the valve can establish a forward voltage blocking capability. This time is known as the de-ionisation time of the valve, and the time from the instant when the valve current goes to zero to the time that the line-to-line voltage is zero is defined as the extinction angle (γ). If a thyristor becomes positively biased before complete de-ionisation occurs, this thyristor will regain current.

Commutation failures in HVDC systems are mainly caused by voltage dips due to ac system faults [1]. As indicated in [1], voltage dips may cause both voltage magnitude reduction and phase-angle shift. Voltage dips may affect the commutation in three ways:

1). Voltage magnitude reduction

Commutating ac line-to-line voltage decreases because of a voltage dip, as shown in Fig. 3. Since the voltage magnitude has decreased, but the commutation area still remain the same, so the end of commutation will be delayed and the extinction angle will change from γ to γ'.

2). Phase-angle shift

The classification of three-phase voltage dips in [3] shows that the phase-angle of the line-to-line voltage may shift either backward or forward during voltage dips. The backward phase-angle shift affects the commutating process negatively. If we assume that the firing instant does not change, although the volt-time area remains the same, the final extinction angle will be reduced from γ to γ'. Fig. 4 illustrates how a voltage dip with backward phase-angle shift affects the commutation margin.

3). Increased dc current.

The dc current increases on the initiation of the fault at the inverter. Since the volt-time area increases with the increased dc current, a relatively larger overlap μ will be needed to complete the commutation. This will in the end reduce γ to γ' in Fig. 5.

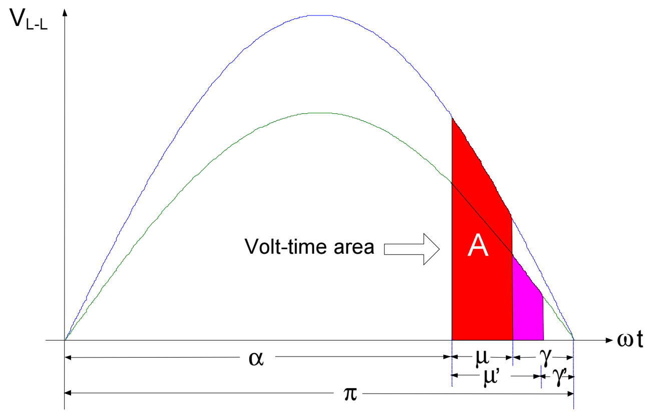

Fig. 3. Reduced commutation margin due to suppressed voltage magnitude

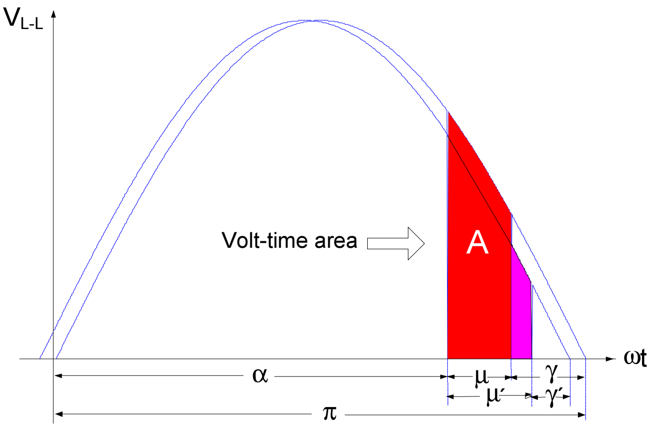

Fig. 4. Reduced commutation margin due to backward phase-angle shift

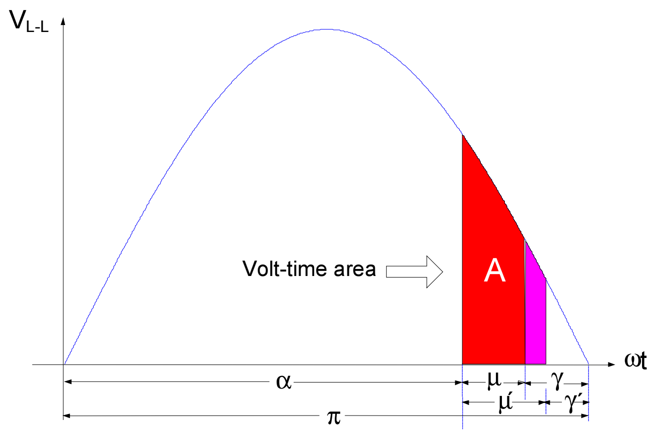

Fig. 5. Reduced commutation margin due to increased dc current

All the above influences from voltage dips reduce the extinction angle γ to a smaller γ'. If γ' is smaller than a certain value (5-8 degrees), the previously conducting valve will regain current, and will end up with a commutation failure.

Fig. 6 gives an example plot with the dc voltage, valve current and the Valve 1 (V1) voltage when a commutation failure occurs. Fig. 6 shows that a disturbance on U_{ab} occurs during the commutation between V1 and V3. This reduces the volt-time area A. Because V1 does not get the reverse voltage that is needed to switch off the current, V1 continues to conduct and the valve current of V3 goes down to zero again. When the next commutation occurs between V2 and V4, V1 and V4 conduct at the same time. From Fig. 6, we can see that the commutation failure actually creates a short circuit on the dc side.

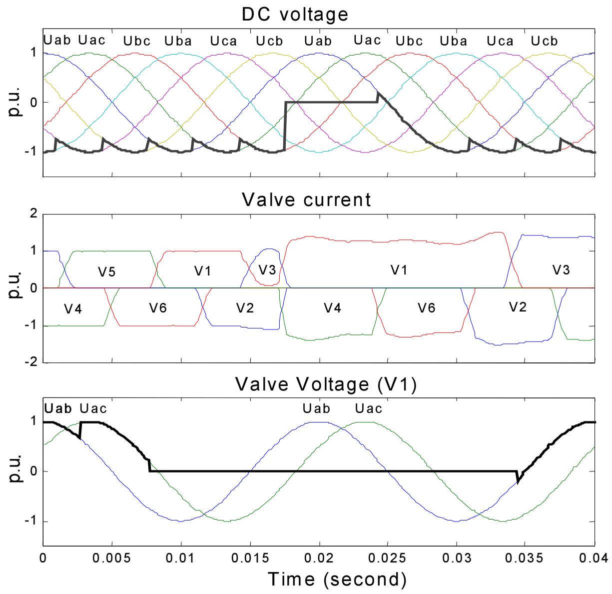

Fig. 6. DC voltage, valve current, and valve voltage during a commutation failure

III. THE PROPOSED MITIGATION METHOD

As shown in Fig. 3, Fig. 4, and Fig. 5, too small an extinction angle γ due to voltage dips in ac systems is the basic reason of commutation failures. To be able to keep a big enough γ, the control system should give an advanced firing instant on detection of the ac system disturbance.

The block diagram in Fig. 7 shows how this function is designed. This control function includes two parallel parts. One is based on zero-sequence detection to detect single-phase faults, and the other one is based on abc-$\alpha\beta$ transformation to detect three-phase faults. This control module is called CFPREV (Commutation Failure Prevention).

Single-phase faults are the most frequently-occurring unbalanced faults experienced by the HVDC converter. The three-phase voltages at the converter bus usually contain zero-sequence voltage during this type of fault. Z_DIFF is obtained simply by adding up three-phase instantaneous voltage as shown in (1)

$$U_o = U_a + U_b + U_c \tag{1}$$

A MAX_HOLD function with is used to convert the sinusoidal wave shape into a dc quantity. The MAX_HOLD function is so designed that it holds the maximum value it detects and maintains it for certain time (12 ms in this case, slightly more than half the period of a sinusoidal wave), if no bigger value is detected. If Z_DIFF is greater than a pre-defined level, the signal Z_AMIN from MAX_HOLD will be the angle that will be deducted from the final firing angle.

Another part is based on abc-$\alpha\beta$ transformation to detect three-phase faults. The idea of abc-$\alpha\beta$ transformation is to use one rotating vector to represent three-phase voltages [8]. (2) and (3) give the expressions of U_α and U_β used in CFPREV

$$U_\alpha = \frac{2}{3}U_a - \frac{1}{3}(U_a + U_b) \tag{2}$$

$$U_\beta = \frac{\sqrt{3}}{3}(U_b - U_c) \tag{3}$$

U_α and U_β correspond to the projection of the vector $U_{\alpha\beta}$ on to the α-axis and the β-axis in the $\alpha\beta$-plane. The transformation of symmetrical three-phase quantities gives a vector in the $\alpha\beta$-plane that rotates with the angular velocity ω.

The signal ALPHA_BETA_SUM in Fig.7 is calculated by (4), which equals to the magnitude of the rotating vector.

$$\left|U_{\alpha\beta}\right| = \sqrt{U_\alpha{}^2 + U_\beta{}^2} \tag{4}$$

ALPHA_BETA_SUM is a dc quantity if the three phases of the converter bus voltage are symmetrical. When a fault occurs in the ac system, ALPHA_BETA_SUM is compared to a filtered ALPHA_BETA_SUM with a relatively large time constant, that is used as the pre-fault voltage. If the difference between those two values is greater than a pre-defined level, the control module determines that a voltage dip has occurred at the inverter bus. A MAX_HOLD function is also used on ALPHA_BETA_SUM although this signal is assumed to be a dc quantity during a balanced three-phase fault. One reason is that ALPHA_BETA_SUM usually has a transient oscillation immediately after fault initiation; MAX_HOLD gives a smoother dc quantity. Another reason is that this part can be used as a backup for unbalanced faults where no zero-sequence voltage is present in the three-phase, such as phase-to-phase faults. During an unbalanced fault, ALPHA_BETA_SUM is an oscillating value due to the negative sequence. However, MAX_HOLD will transform it into a dc quantity.

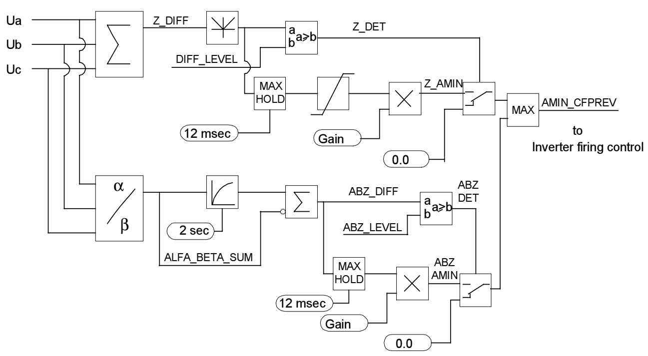

Fig. 7. Commutation Failure Prevention Control Module (CFPREV)

Although the above two parts of the control module deal with different fault conditions, they might be activated at the same time. In such a situation, the maximum value of Z_AMIN and ABZ_AMIN will be chosen as the final output of the entire control module. The output AMIN_CFPREV value will be deducted from the final inverter firing control, advancing the firing instant and leaving a bigger commutation margin. CFPREV is put at the highest level of the DSP controller. It is executed in a 70-microsecond step, which corresponds to 1.26^0 in a 50 Hz system. This makes sure that the control system has a fast reaction to the voltage dips.

IV. SIMULATION AND TEST RESULTS

The proposed commutation failure mitigation function CFPREV was tested and implemented for the first time in The Three Gorges – Changzhou ±500 kV DC transmission project. This project is the first of two 3000 MW HVDC links to transmit power from the Three Gorges hydro-electric generation complex on the Yangtze River in Central China to the Shanghai area in Eastern China. The dc link spans 890 km from Longquan to Zhengping on China's east coast.

A. Simulation setup

A simulation model, as shown in Fig. 8, has been developed on PSCAD/EMTDC to study the effect of CFPREV in mitigating commutation failures.

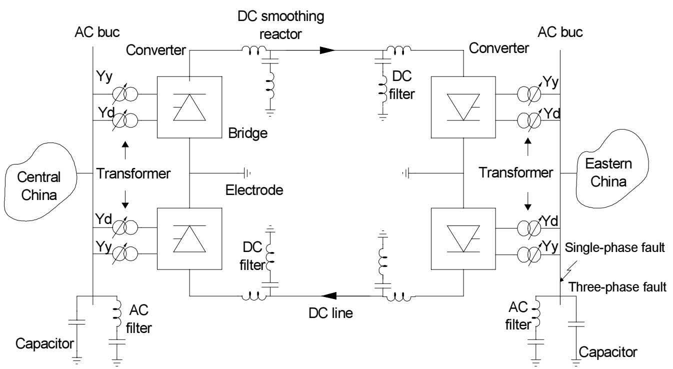

Fig. 8. The simulation model of Three Gorges HVDC transmission in PSCAD/EMTDC .

The main circuit representation of the Three Gorges HVDC transmission system includes the following:

- The four 12-pulse converter bridges with representation of converter transformers.
- Smoothing reactors
- AC filters, shunt banks, reactors
- HVDC transmission line
- DC filters
- Electrodes

The main controls and protections used in the study are based on the same control as will be used in the real plant.

B. Fault tests

To test the effect of the commutation failure prevention module (CFPREV), simulation tests were performed to induce commutation failures during single-phase faults and three-phase faults on the Eastern China side. The fault is applied at the inverter bus. A fault inductance is connected at the fault location as shown in Fig. 8. By adjusting the fault inductance, voltage dips with different remaining voltages are applied at the inverter bus.

Fig. 9 shows the inverter bus voltages, Z_DIFF, AMIN_CFPREV during a single-phase fault with 20% remaining voltage at the faulted phase. When the fault is applied at 0.05 second, the voltage at the faulted phase drops immediately. The zero-sequence voltage comes up because the three phases are no longer symmetrical. As we have noticed, the zero-sequence voltage is a sinusoidal curve, whose magnitude depends on how high the remaining voltage is at the faulted phase. The MAX_HOLD item maintains the maximum value of Z_DIFF for 12 ms, which converts the sinusoidal curve to a flat curve. The signal AMIN_CFPREV is the final output from CFPREV to the main control system at the inverter station. The contribution AMIN_CFPREV of CFPREV is deducted from the final inverter firing angle.

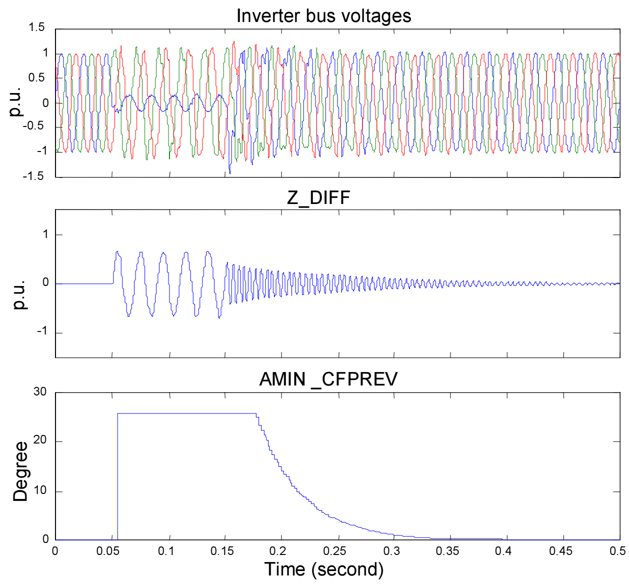

Fig. 9. Inverter bus voltages, Z_DIFF, and CFPREV during a single-phase fault at the inverter bus.

Fig.10 shows inverter bus voltages, ALPHA_BETA_SUM, AMIN_CFPREV during a three-phase balanced fault with 20% remaining voltage at all three phases. When the fault is applied at 0.05 second, the voltages at all three phases drop immediately. The ALPHA_BETA_SUM signal drops to a level that depends on the remaining fault voltages. Note that ALPHA_BETA_SUM is the magnitude of the ac voltage vector. It is a dc quantity if the three-phase voltages are symmetrical. AMIN_CFPREV is deducted from the final firing angle in the same way as for the single-phase fault.

It should be noted that the ALPHA_BETA_SUM also drops during a single-phase fault. The maximum value of the contribution from Z_SUM and ALPHA_BETA_SUM will be used as the final contribution to the inverter firing angle.

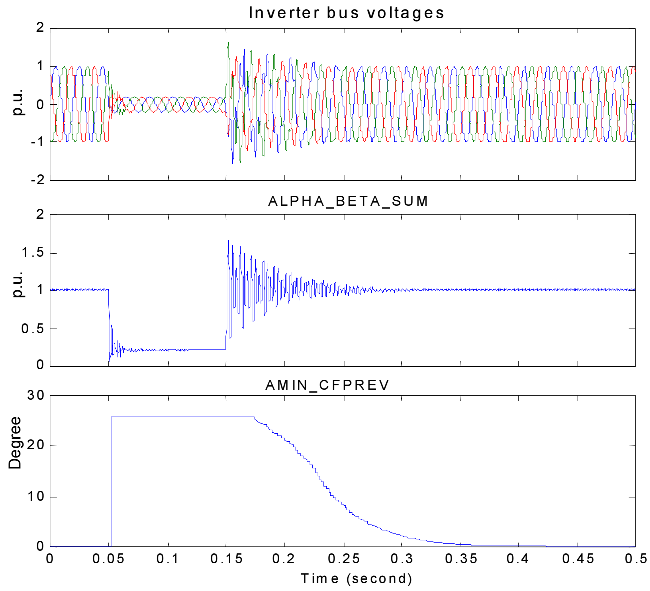

Fig. 10. Inverter bus voltages, AB_SUM, and AMIN_CFPREV during a three-phase fault at the inverter bus.

C. Test results

Table I gives the single-phase fault test results. From these, the improvement of commutation failure sensitivities due to the use of CFPREV can be evaluated. The fault inductance varies between 0.0 H to 0.36 H, giving a single-phase fault where the remaining voltage at the faulted phase varies between 0.0 p.u. to 0.91 p.u. The fault is applied at different time instants between 0.1 to 0.118 second with a 0.002 s step after the snapshot is made to test the fault time dependency of commutation failure sensitivity. The gray parts indicate commutation failures when CFFPREV is not applied, while the darker part indicates commutation failures when CFPREV is applied. Table I shows the great improvement due to the use of CFPREV. For some time instants, the inverter valve can avoid commutation failures for the faulted phase dropping down to 20% remaining voltage. However, for some time instants such as 0.106 s and 0.116 s, CFPREV has no effect at all. This happens when the voltage dip occurs after commutation on that valve has already started. Commutation failures cannot be prevented by CFPREV in such a situation.

Table II shows the test results for three-phase faults. The results show very limited improvement of commutation failure sensitivity by CFPREV. The reason is that all the three-phase voltages are affected during a three-phase fault. Consequently, the chances of the voltage dip occurring after commutation of the valve has started are quite high. CFPREV has no effect for most of the fault time instants.

TABLE I
IMPROVEMENT OF COMMUTATION FAILURE SENSITIVITY DURING SINGLE-PHASE FAULTS BY APPLYING CFPREV

L (H)	V	Z_DIF F	Fault time (from 10 seconds snapshot)									
			0.10	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116	0.118
0.36	0.91	0.10										
0.34	0.91	0.11										
0.32	0.90	0.11										
0.30	0.88	0.12										
0.28	0.87	0.12										
0.26	0.86	0.12										
0.24	0.86	0.13										
0.22	0.85	0.13										
0.20	0.84	0.14										
0.18	0.83	0.14										
0.16	0.82	0.15										
0.14	0.81	0.17										
0.12	0.75	0.18										
0.10	0.71	0.22										
0.08	0.68	0.23										
0.06	0.57	0.27										
0.04	0.47	0.36										
0.03	0.44	0.43										
0.02	0.37	0.48										
0.01	0.19	0.56										
0.0	0	0.78										

No Commutation Failure
Commutation Failure without CFPREV
Commutation Failure with CFPREV

TABLE II
IMPROVEMENT OF COMMUTATION FAILURE SENSITIVITY DURING THREE-PHASE FAULTS BY APPLYING CFPREV

L (H)	V	AB_S UM	Fault time (from 10 seconds snapshot)									
			0.10	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116	0.118
0.36	0.93	0.93										
0.34	0.91	0.92										
0.32	0.91	0.92										
0.30	0.90	0.91										
0.28	0.89	0.91										
0.26	0.88	0.91										
0.24	0.87	0.90										
0.22	0.86	0.88										
0.20	0.85	0.87										
0.18	0.84	0.87										
0.16	0.85	0.85										
0.14	0.82	0.84										
0.12	0.81	0.82										
0.10	0.77	0.80										
0.08	0.77	0.77										
0.06	0.76	0.77										
0.04	0.61	0.60										
0.03	0.52	0.54										
0.02	0.43	0.44										
0.01	0.27	0.27										
0.0	0.0	0.0										

No Commutation Failure
Commutation Failure without CFPREV
Commutation Failure with CFPREV

However, if we look at the statistics on multi-valve and repeated commutation failure sensitivities in Table III and Table IV, the improvement is obvious. If CFPREV is not applied, multi-valve and repeated commutation failures already occur when the remaining voltage is lower than 90% of the pre-fault voltage. After CFPREV is applied, multi-valve commutation failure sensitivity is reduced to 50%-70% remaining voltage, while repeated commutation failure sensitivity is reduced to 40%-50% remaining voltage. In HVDC systems, repeated commutation failures greatly increase the current through the valve. The valve protection systems usually block the valves if the commutation failure has repeated a certain number of times. CFPREV reduces such risks.

TABLE III
IMPROVEMENT OF MULTI-VALVE COMMUTATION FAILURE SENSITIVITY DURING THREE-PHASE FAULTS BY APPLYING CFPREV

L (H)	V	AB_SUM	Fault time (from 10 seconds snapshot)									
			0.10	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116	0.118
0.36	0.93	0.93										
0.34	0.91	0.92										
0.32	0.91	0.92										
0.30	0.90	0.91										
0.28	0.89	0.91										
0.26	0.88	0.91										
0.24	0.87	0.90										
0.22	0.86	0.88										
0.20	0.85	0.87										
0.18	0.84	0.87										
0.16	0.85	0.85										
0.14	0.82	0.84										
0.12	0.81	0.82										
0.10	0.77	0.80										
0.08	0.77	0.77										
0.06	0.76	0.77										
0.04	0.61	0.60										
0.03	0.52	0.54										
0.02	0.43	0.44										
0.01	0.27	0.27										
0.0	0.0	0.0										

No Multi-valve Commutation Failure
Multi-valve Commutation Failure without CFPREV
Multi-valve Commutation Failure with CFPREV

TABLE IV
IMPROVEMENT OF REPEATED COMMUTATION FAILURE SENSITIVITY DURING THREE-PHASE FAULTS BY APPLYING CFPREV

L (H)	V	AB_SUM	Fault time (from 10 seconds snapshot)									
			0.10	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116	0.118
0.36	0.93	0.93										
0.34	0.91	0.92										
0.32	0.91	0.92										
0.30	0.90	0.91										
0.28	0.89	0.91										
0.26	0.88	0.91										
0.24	0.87	0.90										
0.22	0.86	0.88										
0.20	0.85	0.87										
0.18	0.84	0.87										
0.16	0.85	0.85										
0.14	0.82	0.84										
0.12	0.81	0.82										
0.10	0.77	0.80										
0.08	0.77	0.77										
0.06	0.76	0.77										
0.04	0.61	0.60										
0.03	0.52	0.54										
0.02	0.43	0.44										
0.01	0.27	0.27										
0.0	0.0	0.0										

No Repeated Commutation Failure
Repeated Commutation Failure without CFPREV
Repeated Commutation Failure with CFPREV

V. CONCLUSIONS

In this paper we have presented a method to mitigate commutation failures in HVDC systems. It has been shown by the simulation model that this method is very effective in reducing the possibility of commutation failures from single-phase faults. For three-phase faults, although the effect of the method is very limited in preventing the first commutation failure after the fault initiation, it greatly reduces the risk of multi-valve and repeated commutation failures.

This method has been tested and implemented for the first time in the Three Gorges-Changzhou ±500 kV HVDC project. The Dynamic Performance Study and Factory System Test all show that this method helps to mitigate commutation failures during ac system faults, without adverse effects.

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VII. BIOGRAPHIES

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Lars Dofnas graduated as an electrical engineer from the Vasa Institute of Technology in Vasa, Finland in 1979. He joined ASEA/ABB in the same year, working with control systems for HVDC transmission systems. For more than 20 years he has been involved with development and commissioning of HVDC systems, and presently holds a position as specialist for control systems at ABB Utilities, Power Systems.