Reduction of Commutation Failure Frequency in HVDC Transmission Systems by means of an Improved Solid-State Fault Current Limiter

Sohrab Mirsaedi
School of Electrical Engineering
Beijing Jiaotong University
Beijing, China
msohrab@bjtu.edu.cn

Hanzhang Liu
School of Electrical Engineering
Beijing Jiaotong University
Beijing, China
16292009@bjtu.edu.cn

Jinghan He
School of Electrical Engineering
Beijing Jiaotong University
Beijing, China
jhhe@bjtu.edu.cn

Dimitrios Tzelepis
Department of Electronic and
Electrical Engineering
University of Strathclyde
Glasgow, UK
dimitrios.tzelepis@strath.ac.uk

Dalila Mat Said
Faculty of Electrical Engineering
Universiti Teknologi Malaysia (UTM)
Johor, Malaysia
dalila@utm.my

Abstract—In the recent decade, High Voltage Direct Current (HVDC) technology has become the preferred option for bulk power transmission due to its numerous advantages such as lower losses and less space requirements compared to High Voltage Alternating Current (HVAC) transmission. However, in order to accelerate the widespread adoption of HVDC systems, some of their technical challenges such as commutation failure need to be resolved. In this study, a Fully Controllable Solid-State Fault Current Limiter (FCSSFCL) is proposed, which is designed based on both fault severity (fault resistance) and fault initiation time. It inserts an adequate number of resistors in the fault current path so that the commutation failure is prevented. The salient feature of the proposed FCSSFCL is that it is fully controllable, and hence it prevents additional power losses in the inverter AC system. The importance of the proposed FCSSFCL becomes more evident in a power system, wherein the inverter supplies more than one AC system. In such a network, insertion of a large resistance by the FCL during a non-severe fault at one of the inverter AC systems leads to the unnecessary reduction of power flow in other non-faulted AC systems. In order to validate the efficacy of the proposed FCSSFCL, several simulations have been performed under different fault types. The simulation results indicate that the proposed approach can effectively reduce the commutation failure frequency.

Keywords—HVDC transmission, line-commutated converters, commutation failure, solid-state fault current limiters.

I. INTRODUCTION

Nowadays, HVDC technology is considered as a suitable alternative for bulk power transmission over long distances. It offers several advantages in comparison with traditional HVAC system such as asynchronous interconnection, reduction in line losses, and improvement of network stability [1]. Line-Commutated Converters (LCC) and Voltage Source Converters (VSC) are two dominant types of HVDC converters [2]. Even though the VSC is a more modern technology and is used for more diverse applications, the efficiency and transmission capability of LCCs are still higher than VSCs. In VSCs, Insulated gate bipolar transistor (IGBT) switches are used

which have superior controllability, while the switching of LCCs is performed by thyristors with only turn-off capability. Therefore, LCCs are vulnerable to commutation failure which is mainly caused by the voltage drop at the inverter AC system [3].

Commutation failure is an adverse dynamic event which may lead to some serious transient phenomena such as temporary interruption of HVDC transmission power, increased stress on the network equipment, overheating of the converter valves, and malfunction of the protection system. If commutation failure is not inhibited and continuously repeats, the converter is forcibly blocked which leads to a large-scale blackout at the inverter AC system [4]. As a result, to propose a countermeasure for effective commutation failure prevention is of great importance. The existing commutation failure strategies can be categorized into two groups, i.e. improvement of HVDC control system performance, and addition of extra devices [5].

For the first group, the main idea is to swiftly detect the inverter AC fault and decrease the firing angle order applied to the inverter thyristors so that the commutation margin becomes larger and the commutation failure is prevented. In references [6]–[14], various strategies have been proposed which are different in terms of fault detection type, accuracy in calculation of the reduced commutation margin, and the speed of response to commutation failure. Nevertheless, such strategies are not appropriate options for dealing with severe commutation failures. In fact, the main purpose of these approaches is to reduce the number or impact of commutation failures.

In order to remedy the challenges of strategies based on improvement of HVDC control system, the methods in the second group propose installation of extra devices at the inverter side. In [15], [16], adoption of Superconducting Fault Current Limiter (SFCL) is suggested as an effective way for commutation failure prevention. The function of SFCLs is to inhibit the excessive voltage drop at the inverter AC bus through inserting a large impedance in the fault current path. However, the main drawback of the SFCLs is that they are not able to insert a desired

impedance, since they function based on a quenching characteristic, wherein the current level at which the quench occurs is dependent on the operating temperature, and the amount and type of superconductor.

In this paper, based on further research and simulation, a Fully Controllable Superconducting Fault Current Limiter (FCSSFCL) is proposed which prevents the commutation failure by inserting a suitable resistance in the fault current path through a multi-switch circuit. The main advantage of the presented FCSSFCL is that the number of inserted resistances can be selected according to the severity of the fault which prevents the additional power losses in the inverter AC system.

The remainder of this paper is organized as follows: In Section II, the mechanism of commutation failure is introduced; in Section III, the proposed commutation failure prevention approach is presented; Section IV discusses the obtained simulation results; and finally, Section V concludes the paper.

II. MECHANISM OF COMMUTATION FAILURE

The most frequently used structure for line-commutated converters is shown in Fig. 1 which is referred to as Graetz bridge. As can be seen from the figure, it includes six thyristor valves which are numbered based on their firing sequence. Since each valve conducts for 120 degrees, such structure is termed as 6-pulse converter. Line commutated converters can be used for transmission of power from AC to DC side (rectification) or from DC to AC side (inversion) by applying different firing angles to the valves. As mentioned before, thyristor switches have no turn-off capability. As a result, for successful turn-off of these valves, a negative anode-cathode voltage needs to be applied across the valves which is provided by the inverter AC voltage. When a fault happens at the inverter AC side, a voltage drop appears at the inverter bus and the switching valves cannot be turned off. Such a phenomenon is termed as commutation failure which is a frequent event in line-commutated HVDC systems.

Fig. 1. Structure of a 6-pulse line-commutated converter.

Fig. 2 illustrates the commutation process between valves T_1 and T_3 of the converter shown in Fig.1. As can be seen from the figure, the conduction of the valve T_1 cannot be transferred to valve T_3 instantaneously due to the equivalent inductance of the inverter AC system L_c and takes for a certain time which corresponds to the overlap area A_{μ} . The voltage equation for the loop including valves T_1 and T_3 can be written as:

$$\overbrace{\sqrt{2}V_{LL} \sin \omega t}^{V_{ba}} = L_c \omega \frac{di_{T3}}{d\omega t} - L_c \omega \frac{d(i_d - i_{T3})}{d\omega t} \quad (1)$$

where V_{ba} is the voltage across valves T_1 and T_3 which is termed as commutation voltage. In this equation, since the DC current is constant, $dI_d/d\omega t = 0$. Integrating from both sides of (1) results in:

$$\overbrace{\int_{\alpha_i}^{\pi - \gamma_i} \sqrt{2}V_{LL} \sin \omega t}^{A_{\mu i}} = 2\omega L_c \int_0^{I_d} di_{T3} \quad (2)$$

From this equation, it can be concluded that:

$$A_{\mu i} \propto I_d \quad (3)$$

In case a fault occurs at the inverter AC side, the commutating voltage of the affected phases will decrease in magnitude. For example, in case a symmetrical three-phase fault takes place, the magnitude of all phase voltages decreases, and hence a voltage drop happens on commutation voltage V_{ba} . Such an AC voltage reduction leads to the decrease of the DC voltage. However, since the transmitted power in an HVDC system is controlled to be constant, the DC voltage drop leads to the sudden increase of the DC current which is proportional to $A_{\mu i}$ according to (3). Therefore, according to Fig. 2, both decrease of V_{ba} and increase of $A_{\mu i}$ will result in a severe reduction of commutation margin ($A_{\gamma i}$). Consequently, valve T_1 will not be able to receive adequate negative anode-cathode voltage, and hence cannot be turned off. In the next switching sequence, T_4 also turns on. This means that both valves T_1 and T_4 which belong to one converter valve conduct at the same time and a short circuit occurs on the HVDC line. If such a phenomenon repeats several times, the converter is shut down after about 500 ms which results in a large blackout at the inverter AC system.

It should be stressed that since the commutation margin in the inverter side is much smaller than the rectifier side, the risk of commutation failure for the inverter is much higher. As a result, the majority of commutation failure strategies are designed for the inverter side.

In addition to AC faults, an internal malfunction of the converter firing control system or an action of the protection function may lead to commutation failure. In such circumstances, no firing pulses are applied to the valves, and hence no power is transmitted from DC to AC side. However, in this research, only commutation failures caused by AC faults are investigated.

III. PROPOSED COMMUTATION FAILURE PREVENTION APPROACH

A. Design of the Proposed FCSSFCL

Fig. 3 depicts the flow chart for the design of the proposed FCSSFCL. As mentioned before, fault current limiters can effectively inhibit commutation failure through inserting suitable impedance in the fault current path. When a fault occurs at the inverter AC system, the inverter AC voltage is reduced depending on the fault severity and the fault initiation time. Also, since the fault leads to the enlargement of $A_{\mu i}$, the DC current increases. Therefore, commutation failure phenomenon can be recognized through changes of both AC voltage and DC current. However, since the speed of response is one of the most important factors in the commutation failure elimination

Fig. 2. Commutation process between valves T_1 and T_3 of the converter shown in Fig.1

Fig. 3. Flow chart for the design of the proposed FCSSFCL.

TABLE I. DIFFERENCE BETWEEN CHANGE RATE OF THE DC CURRENT AND AC VOLTAGE DURING A TYPICAL INVERTER AC FAULT FOR FIVE VARIOUS FAULT INITIATION TIMES

$R_f [\Omega]$	Fault Initiation Time [s]				
	1.000	1.002	1.004	1.006	1.008
75			$\Delta V_{ac} = 10.72 \text{ kV}$ $\Delta t_v = 0.032 \text{ s}$ $\Delta I_d = 0.38 \text{ kA}$ $\Delta t_l = 0.009 \text{ s}$		
65		$\Delta V_{ac} = 9.24 \text{ kV}$ $\Delta t_v = 0.034 \text{ s}$ $\Delta I_d = 0.34 \text{ kA}$ $\Delta t_l = 0.011 \text{ s}$	$\Delta V_{ac} = 14.43 \text{ kV}$ $\Delta t_v = 0.034 \text{ s}$ $\Delta I_d = 0.50 \text{ kA}$ $\Delta t_l = 0.010 \text{ s}$		
55	$\Delta V_{ac} = 10.45 \text{ kV}$ $\Delta t_v = 0.036 \text{ s}$ $\Delta I_d = 0.35 \text{ kA}$ $\Delta t_l = 0.015 \text{ s}$	$\Delta V_{ac} = 12.90 \text{ kV}$ $\Delta t_v = 0.034 \text{ s}$ $\Delta I_d = 0.46 \text{ kA}$ $\Delta t_l = 0.009 \text{ s}$	$\Delta V_{ac} = 18.52 \text{ kV}$ $\Delta t_v = 0.031 \text{ s}$ $\Delta I_d = 1.90 \text{ kA}$ $\Delta t_l = 0.010 \text{ s}$	$\Delta V_{ac} = 10.62 \text{ kV}$ $\Delta t_v = 0.030 \text{ s}$ $\Delta I_d = 0.37 \text{ kA}$ $\Delta t_l = 0.008 \text{ s}$	
45	$\Delta V_{ac} = 13.63 \text{ kV}$ $\Delta t_v = 0.036 \text{ s}$ $\Delta I_d = 0.46 \text{ kA}$ $\Delta t_l = 0.014 \text{ s}$	$\Delta V_{ac} = 19.00 \text{ kV}$ $\Delta t_v = 0.029 \text{ s}$ $\Delta I_d = 1.88 \text{ kA}$ $\Delta t_l = 0.009 \text{ s}$	$\Delta V_{ac} = 19.36 \text{ kV}$ $\Delta t_v = 0.031 \text{ s}$ $\Delta I_d = 1.90 \text{ kA}$ $\Delta t_l = 0.010 \text{ s}$	$\Delta V_{ac} = 13.33 \text{ kV}$ $\Delta t_v = 0.030 \text{ s}$ $\Delta I_d = 0.45 \text{ kA}$ $\Delta t_l = 0.008 \text{ s}$	
35	$\Delta V_{ac} = 19.70 \text{ kV}$ $\Delta t_v = 0.030 \text{ s}$ $\Delta I_d = 1.93 \text{ kA}$ $\Delta t_l = 0.014 \text{ s}$	$\Delta V_{ac} = 20.46 \text{ kV}$ $\Delta t_v = 0.029 \text{ s}$ $\Delta I_d = 1.92 \text{ kA}$ $\Delta t_l = 0.011 \text{ s}$	$\Delta V_{ac} = 20.26 \text{ kV}$ $\Delta t_v = 0.031 \text{ s}$ $\Delta I_d = 1.98 \text{ kA}$ $\Delta t_l = 0.011 \text{ s}$	$\Delta V_{ac} = 22.70 \text{ kV}$ $\Delta t_v = 0.030 \text{ s}$ $\Delta I_d = 1.94 \text{ kA}$ $\Delta t_l = 0.010 \text{ s}$	$\Delta V_{ac} = 13.02 \text{ kV}$ $\Delta t_v = 0.039 \text{ s}$ $\Delta I_d = 0.44 \text{ kA}$ $\Delta t_l = 0.015 \text{ s}$

strategies, in this study only DC current is used which has a higher change rate compared to the AC voltage.

The difference between change rate of the DC current and AC voltage during a typical inverter AC fault for five various fault initiation times is shown in Table I. In this table, ΔI_d is the difference between the maximum value of I_d after a commutation failure and the value of I_d in the normal conditions, and Δt_f is the corresponding time to reach this maximum value. Similarly, ΔV_{ac} and Δt_v are used to show the rate of AC voltage changes. In order to design a controllable resistance for the FCSSFCL, the first step is to find the relationship between DC current changes and the minimum resistance required for prevention of commutation failure. Fig. 4 indicates the simulation results for the determination of minimum FCSSFCL resistance R_{min} which prevents the commutation failure under different fault resistances and fault initiation times. The obtained data from Fig. 4 can be classified into three ranges, as shown in Table II.

Fig. 4. Simulation results for the determination of minimum FCSSFCL resistance which prevents the commutation failure under different fault resistances and fault initiation times.

TABLE II. CLASSIFICATION OF THE OBTAINED DATA FROM FIG. 4

Ranges	Range of ΔI_d [kA]	Range of R_{min} [Ω]	Number of cases
Range1	0.32-0.9	1-80	33
Range2	1.88-2.01	18-50	22
Range3	2.02-2.21	60-805	11

B. Structure of the Proposed FCSSFCL

As discussed in Section I, the main demerit of SFCLs is that they are not able to insert a desired impedance, since they function based on a quenching characteristic, wherein the current level at which the quench occurs is dependent on the operating temperature, and the amount and type of superconductor. To obviate this challenge, in this study, a Fully Controllable Solid-State Fault Current Limiter (FCSSFCL) is proposed which the process of its design was explained in Section III.A. Fig. 5 demonstrates the schematic diagram of the proposed FCSSFCL in a hybrid AC/DC grid which includes two receiving AC systems. The five main parts of the proposed FCSSFCL are as follows:

1) A three-phase transformer with the turns ratio of α in series with the receiving AC system. The main purpose

of using this transformer is to isolate the FCSSFCL from the main network and reduce the current at a suitable level for the power electronic devices.

2) A three-phase diode bridge rectifier.

3) Three series modules, each of which contains a Self Turn-off Switch (STS) in parallel with a resistor, R_d . These modules are used for limiting the fault current under different ranges.

4) FCSSFCL control system, which is the most important part of the strategy. It determines the number of resistors required to be included in the circuit by applying suitable firing pulses to the STSs.

5) A small reactor (L_d) which is required to prevent severe di/dt on the STS. Since the value of L_d is small, it is usually equipped with air core to prevent its saturation.

Fig. 5. Schematic diagram of the proposed FCSSFCL.

Table III shows the suitable ranges of ΔI_d and the value of resistors R_{d1} , R_{d2} , and R_{d3} for the design of the FCSSFCL which are determined according to the obtained data in Table II.

TABLE III. SUITABLE RANGES OF ΔI_d AND RESISTANCES FOR THE DESIGN OF FCSSFCL.

R_d	Range of ΔI_d [kA]	Resistance [Ω]
R_{d1}	0.3-0.9	80
R_{d2}	1.88-2.01	420
R_{d3}	more than 2.02	305

During the normal operation of the FCSSFCL, all STSs are on, and hence R_{d1} , R_{d2} , and R_{d3} are all bypassed. As a result, the small reactor L_d is fully charged and acts as a short-circuit. If the small voltage drop on the semiconductor device is ignored, then the total voltage across the diode bridge is approximately zero. Therefore, the impact of existence of the proposed FCSSFCL can be neglected under normal conditions.

Fig. 6. Structure of the FCSSFCL control system.

Fig. 7. Structure of STS synchronizer.

When a fault occurs at point F, FCSSFCL control system detects it through measuring the difference between pre-fault and fault currents, ΔI_d . Subsequently, it inserts the adequate number of resistors according to the measured value of ΔI_d , so that the commutation failure is inhibited.

The structure of the FCSSFCL control system is shown in Fig. 6. As can be seen from the figure, if ΔI_d is between 0.3 and 0.9 kA, a pulse will be delivered to the gate of STS_1 and only R_{d1} is inserted into the circuit. However, if ΔI_d is in the range of 1.8 to 2.01 kA, the gates of both

STS_1 and STS_2 receive a pulse signal and both R_{d1} and R_{d2} are inserted. In case ΔI_d is greater than 2.02 kA, then all switches are triggered, and hence all of the three resistors are put in the FCSSFCL circuit. Also, in order to prevent the malfunction of the FCSSFCL during the initial HVDC fluctuations, a minimum activation time is considered. The FCSSFCL control system also includes an STS synchronizer which is used for the cases, in which more than one resistor is required. Fig. 7 shows the structure of the STS synchronizer. The function of STS synchronizer is to coordinate the firing pulses applied to the switches so that they are triggered at the same time. It shall be noted that for the design of the control system, a monostable multivibrator is also required which its task is to create a pulse with a desirable duration once it receives a trigger signal.

IV. SIMULATION RESULTS

In order to validate the effectiveness of the proposed FCSSFCL, several simulations have been conducted using PSCAD/EMTDC software. The single-line of the test network is shown in Fig. 8. As can be seen, it includes a mono-polar 500 kV and 1000 MW HVDC link with 12-pulse converters on both rectifier and inverter sides. The test network also includes shunt capacitors, smoothing reactors, low-pass and high-pass filters in both sides of the HVDC line. The detailed parameters of the test network are listed in Table IV.

TABLE IV. PARAMETERS OF THE TEST NETWORK

Parameter [Unit]	Rectifier	Inverter
AC system frequency [Hz]	50	50
Bus line-to-line voltage [kV]	345	230
Nominal firing angle [deg]	5	-
Nominal extinction angle [deg]	-	15
Turn-off time of thyristor [μ s]	30	30

Because of the fact that the AC voltage is sinusoidal, the performance of the proposed FCSSFCL does not only depend on the fault type and fault resistance, but also on the fault initiation time. The results obtained from the simulation of various types of faults are indicated in Tables V to VIII. In each of the tables, the effectiveness of the proposed FCSSFCL for ten fault initiation times ranged from 1 to 1.018 s is evaluated. The results are reported from the highest fault impedance which leads to the commutation failure. In Tables V to VIII, white cells denote the cases, in which no failed commutation is observed even without applying the FCSSFCL. Also, the gray cells show the cases, in which the inverter is faced with commutation failure, but the FCSSFCL can effectively prevent it. However, the cells which are specified with black color denote the cases, wherein commutation failure occurs but the proposed FCSSFCL is not able to prevent it even by inserting all of the resistors in the circuit. With regard to the obtained results, it can be concluded that the proposed strategy is highly effective in most of the simulation cases.

V. CONCLUSION

In this paper, a fully controllable solid-state fault current limiter for the prevention of commutation failure in LCC-HVDC system is proposed. The proposed FCSSFCL

TABLE VIII. IMPROVEMENT OF COMMUTATION FAILURE PREVENTION DURING THREE-PHASE FAULT

R_f [Ω]	Fault Initiation Time [s]									
	1.000	1.002	1.004	1.006	1.008	1.010	1.012	1.014	1.016	1.018
135										
120										
105										
90										
75										
$R_f < 60$										

detects the inverter AC fault occurrence through measuring the difference between pre-fault and fault currents, and adds an adequate number of resistors to the circuit to prevent commutation failure. Compared to other commutation failure inhibition techniques, the proposed FCSSFCL is fully controllable, and hence it prevents additional power losses in the inverter AC system. To verify the effectiveness of the proposed approach, several simulations have been undertaken using PSCAD/EMTDC software. The obtained results indicate that the proposed FCSSFCL is able to effectively prevent commutation failure and increase the reliability of the inverter AC system.

ACKNOWLEDGMENT

This work was supported in part by the National Key Research and Development Plan of China (2018YFB0904602), and in part by the Fundamental Research Funds for the Central Universities (2019RC051).

REFERENCES

- [1] B. Hu, K. Xie, and H. M. Tai, "Optimal reliability allocation of 800 kV ultra HVDC transmission systems," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1174–1184, Jun. 2018.
- [2] Y. Ma, H. Li, G. Wang, and J. Wu, "Fault analysis and traveling-wave-based protection scheme for double-circuit LCC-HVDC transmission lines with shared towers," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1479–1488, Jun. 2018.
- [3] S. F. Huang, H. M. Shen, B. Fei, and O. Li, "Effect of commutation failure on the distance protection and the countermeasures," *IET Gener., Transmiss. Distribution*, vol. 9, no. 9, pp. 838–844, Jun. 2015.
- [4] Y. Xue, X. P. Zhang, and C. Yang, "AC filterless flexible LCC HVDC with reduced voltage rating of controllable capacitors," *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 5507–5518, Sep. 2018.
- [5] J. Chen, Q. Wang, and X. Zhu, "Evaluation of commutation failure risk for HVDC caused by harmonic voltage," in *2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2)*, 2019, pp. 248–252.
- [6] S. Tamai, H. Naitoh, F. Ishiguro, M. Sato, K. Yamaji, and N. Honjo, "Fast and predictive HVDC extinction angle control," *IEEE Transactions on Power Systems*, vol. 12, no. 3, pp. 1268–1275, Aug 1997.
- [7] C. V. Thio, J. B. Davies, and K. L. Kent, "Commutation failures in HVDC transmission systems," *IEEE Transactions on Power Delivery*, vol. 11, no. 2, pp. 946–957, Apr 1996.
- [8] S. Mirsaedi and X. Dong, "An enhanced strategy to inhibit commutation failure in line-commutated converters," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 340–349, Jan 2020.
- [9] C. Guo, Y. Liu, C. Zhao, X. Wei, and W. Xu, "Power component fault detection method and improved current order limiter control for commutation failure mitigation in HVDC," *IEEE Transactions on Power Delivery*, vol. 30, no. 3, pp. 1585–1593, June 2015.
- [10] J. Bauman and M. Kazerani, "Commutation failure reduction in HVDC systems using adaptive fuzzy logic controller," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 1995–2002, Nov 2007.
- [11] Y. Z. Sun, L. Peng, F. Ma, G. J. Li, and P. F. Lv, "Design a fuzzy controller to minimize the effect of HVDC commutation failure on power system," *IEEE Transactions on Power Systems*, vol. 23, no. 1, pp. 100–107, Feb 2008.
- [12] A. Hansen and H. Havemann, "Decreasing the commutation failure frequency in HVDC transmission systems," *IEEE Transactions on Power Delivery*, vol. 15, no. 3, pp. 1022–1026, July 2000.
- [13] S. Mirsaedi, X. Dong, D. Tzelepis, D. M. Said, A. Dysko, and C. Booth, "A predictive control strategy for mitigation of commutation failure in LCC-based HVDC systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 160–172, Jan 2019.
- [14] W. Yao, C. Liu, J. Fang, X. Ai, J. Wen, and S. Cheng, "Probabilistic analysis of commutation failure in LCC-HVDC system considering the CFPREV and the initial fault voltage angle," *IEEE Transactions on Power Delivery*, pp. 1–1, 2019.
- [15] H. Lee, G. T. Son, J. Yoo, and J. Park, "Effect of a SFCL on commutation failure in a HVDC system," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 5 600 104–5 600 104, June 2013.
- [16] L. Chen, H. Pan, C. Deng, F. Zheng, Z. Li, and F. Guo, "Study on the application of a flux-coupling-type superconducting fault current limiter for decreasing HVDC commutation failure," *Canadian Journal of Electrical and Computer Engineering*, vol. 38, no. 1, pp. 10–19, winter 2015.