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Original scientific paper

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METHODS TO PREVENT COMMUTATION FAILURES IN HVDC SYSTEMS

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Abstract: Commutation failure (CF) is the main fault type in HVDC (High voltage direct current) system with line commuted converter. So, Commutation faults are the main disadvantages of line commutated converter HVDC systems. There are some situations that cause the fault in these types of faults that occur in thyristor valve compartments. These situations can be seen in the magnitude of the commutation voltage, phase angle reversal and sudden changes, a sudden change in DC currents or failure of ignition controls. To mitigate CFs, considerable researches have been done either in modelling or control methods. However, with the operation of more and more large-capacity HVDC projects, the coupling characteristics between HVDC and power grid are more complex. The existing reviews tend to focus only on the CFs of a single HVDC itself. Also, in the event of any commutation fault, the system can be put back into operation after the fault is completely eliminated. However, if the valve ignition circuits are designed to be blocked at a pre-set low voltage and the blockage is lifted under normal voltage conditions, they can be partially protected in the event of a commutation fault. Otherwise, the fault process can be prolonged. This paper provides more systematic overview of CFs also the influences of the occurring moment on the commutation process are observe quantitatively to predict and prevent commutation failures effectively. Then, according to the critical fault voltage and extinction angle CFs reactance is calculation and presented based by formulations. The concept of the commutation failure domain and security domain is determined to estimate the probability of commutation failures. Furthermore, the direct current and RMS voltage calculation methods under asymmetrical faults are presented and direct current is predicted rather than real time measured and the RMS voltage under asymmetrical faults can be calculated instantaneously. In particular, the advantages and limits of various CFs prevention methods are analyzed and compared in order to reveal the latest research result.

Keywords: AC, CF, HVDC, RMS, SCFL, UPVC, VDCOL, SCMVA, ESCR

INTRODUCTION

High voltage direct current (HVDC) has been widely used in the field of long-distance transmission and asynchronous power grid interconnection because of its long transmission distance, large transmission capacity and low transmission loss [1,2]. Also line commutated converter- based high voltage direct current (LLC-HVDC) technology has been advantaged such as lower transmission loses and bulk power. To further reduce transmission loss and increase transmission capacity the number of HVDC transmission projects has increased rapidly [3]. However, commutation failure is one of the most common inverter failures in the HVDC systems. Commutation Failure (CF) can directly cause a sudden increase in DC current and a sharp decrease in DC voltage. It is precisely because of the larger transmission capacity of HVDC, the risk of DC pole blocking is increased due to the CFs of its converter station [4,5]. DC block fault will cause power surplus at the sending end and power shortage at the receiving end, thus causing the interlocking unit to be disconnect, load shaking the other failures [6,7]. It brings about significant threats to system security and stability therefore it is a vital to investigate the mechanism of commutation failures and the measures to enhance the immunity against commutation failures. Commutation failure is an inherent feature of semi-controlled DC commutation valves (such as thyristors) consisting of thyristors. The semi –controlled valve can only control its conduction and cannot control its breaking. When switching from one valve another, the inductance of the commutation loop prevents the valve current from abruptly changing, which takes a period of time to complete.

Many scholars proposed various detection methods, which can be classified into two categories. One way is to detect commutation failures by measuring electrical quantities and comparing them with threshold values. The other way measured electrical quantities can be extinction angle [8,9], commutating voltage [10,11], the voltage–time area [12,13], and the current characteristics [14].

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Measuring methods can be highly accurate, while they are conservative and not rapid enough. The other methods calculate the electrical quantities instead of measuring and forecasting commutation failures.

In another study to date, CF prevention and mitigation methods fall into three categories: (i) improving primary equipment, including valves, converters and converter transformers; (ii) improving control strategies by CF prediction and parameter optimization and (iii) creating system-level coordination strategies involving several HVDC converters and receiving AC systems. However, a CF can be triggered by many factors occurring in the entire power grid. Although many attempts were made considering subsets of influential factors, they still failed to exactly identify various CF patterns and avoid all of CFs.

1. COMMUTATION FAILURE PROCESS AND ANALYSIS FOR HVDC

The universal configuration of the LCC-HVDC system is the Graetz bridge. It includes six thyristor valves, and each valve connects one of the three phases in the AC system with one of the positive/negative DC terminals. The Graetz bridge can transfer the power flexibly between AC and DC systems by adjusting the firing angle of thyristor valves. The configuration of the Graetz bridge in the inverter mode it is consists of six thyristors assembled in form of three phase legs. Each phase legs contains two thyristors; the center points are connected to a three-phase power supply this is shown in Figure 1.

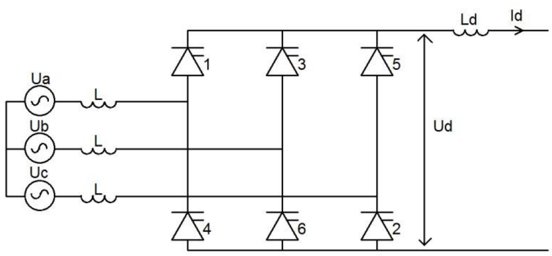

Figure 1: The basic three phase six pulse converter [15].

In Figure 1, the thyristor valves are 1 to 6, L is the total commutation inductance per phase seen by the valves, Ua,b,c are the source voltages of the AC network, Ud and Id are the DC voltage and direct current respectively. Ld is a large DC inductance to ensure that the ripples in the direct current are significantly reduced.

Valve 1 is fired during an interval when is forward biased such that is conducting current. An alternating two phase (Uab) voltages can appear across valve 3 when (Uab) is negative cycle when a firing pulse provided valve 3 can be a negative voltage across it can't conduct current. Valve 3 is forward biased if line voltage switches to positive cycle. If it fired it will conduct current and consequently, then valve 1 across a negative current its terminals. The incoming thyristors valves causes the applications of line voltage to the outgoing valve which reverse biases the outgoing valve.

The duration between receiving forward voltage and starts of calculations is usually expressed in angular measure and is referred to as firing or delay angle. Generally, delay angle ranges from 0-180 degree. When delay angle lies between 0-90 degree converter operate rectifier. On the other hand, delay angle lies between 90-180 degree converter operate inverter. However, the minimum delay angle 5 degree for operate rectifier and for inverter operation range 110-165 degree.

The commutation is referred to as overlap time or angle of overlap, it is measured in degrees or radians and denoted by μ[14]. When valve 1 and valve 2 are conducting direct current is to be commutated from valve 1 to valve 3 in the top row of Figure 1. As long as voltage difference Ua-Ub is positive the commutation can create. The commutation voltage is described as the reverse voltage. If the valve had not been fired, which at constant direct current would have occurred across thyristor valve. During the commutation process, the converter bridge can be represented with an equivalent circuit shown in Figure 2. Valves 1 and 3 are both conducting in the top row while valve 2 in the bottom row continues to conduct as before. The commutating voltage drives a commutating current i through valve 1 and 3, this commutation current will increase thereby increasing the current flowing through valve 3 while decreasing the current through valve 1[15].

The commutation process is complete when the commutation current has increased and is equal to the direct current Id. This is illustrated in Figure 3. where Uba is the commutation voltage, i is the commutation current, i1 and i3 are the currents flowing through valve 1 and valve 3 respectively and area A is the inverter commutation margin.

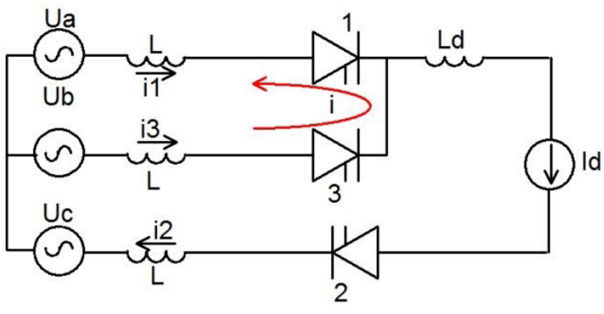

Figure 2: Commutation process circuit [15].

In the rectifier, valve 3 is fired at $\alpha 1$ and the commutation of current from valve 1 to valve 3 takes $\mu 1$. The remaining area, $\gamma 1$, is more than sufficient for successful commutation therefore commutation failures rarely occur in the rectifier. In the inverter, valve 3 is fired at α and the commutation of current from valve 1 to valve 3 takes μ. The remaining voltage-time area A (commutation area) can be greatly reduced in the event of disturbances in the AC network.

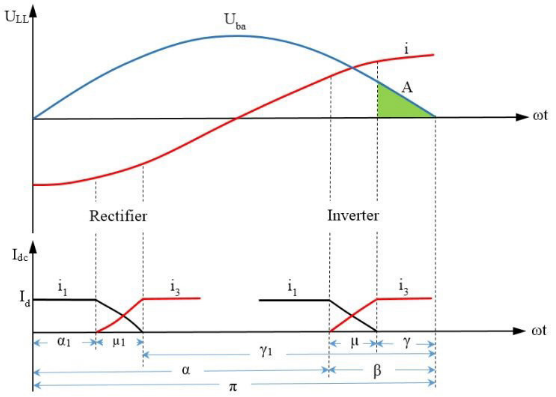

Figure 3: CF's process and angle [15].

Where delay angle (α), which corresponds to the time when valve 3 is fired after the commutation voltage has turned positive. u (μ) is the overlap angle, the angle corresponding to the time when both valves 1 and 3 are conducting. Gamma (γ) is extinction angle or commutation margin, the angle corresponding to the time between when valve 1 is extinguished and when the commutation voltage goes through its zero crossing and during steady state operation the between angles relationship is expressed, $\alpha + \mu + \gamma = 180^{o}$

A reverse voltage needs to be applied across a thyristor valve for a certain duration. This is required to remove the charges stored during the conduction process such that the valve can withstand a voltage in the forward direction [16].

The commutation process in DC engineering, when the AC bus of the converter station is the access point of the AC filter, the commutation reactance can refer to the sum of the leakage reactance of the converter transformer and the valve reactance (also called anode reactance). Generally, the valve reactance can be ignored, so the leakage reactance X_T of the commutation transformer can be used as the commutation reactance. The following is the commutation reactance value (Ω) obtained from the short-circuit impedance value (%) of the commutation transformer.

The resistance voltage drop percentage of the commutator is U_r :

$$U_r = \frac{P_k}{P_r} \times 100, \% \tag{1}$$

The percentage of reactance drop is:

$$U_x = \sqrt{U_z^2 - U_r^2}, \% \tag{2}$$

Among them P_k is the load loss at the rated capacity of converter W, P_r is the rated capacity of the converter VA, Uz is the short circuit impedance at threated capacity of the converter, %.

The percentage of short-circuit reactance voltage drop for each phase winding is:

$$U_x = \frac{X_p I_p}{U_p} \times 100, \% \tag{3}$$

Therefore, the equivalent reactance of phase winding can be obtained as:

$$X_p = \frac{U_x U_p}{100 \times I_p}, \Omega \tag{4}$$

Among them U_p is rated phase voltage of the winding V; I_p is the rated phase current of the winding A.

When the valve side winding is a Y junction, the commutation reactance (2XT) is the reactance value (Ω) of the two phase windings in series (Figure 4).

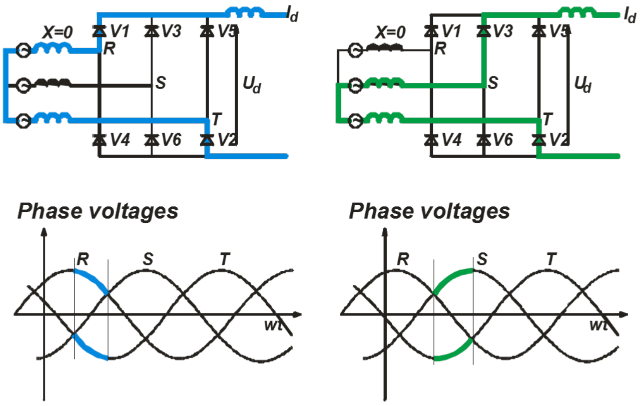

Figure 4: Commutation reactance

$$2X_T = 2X_p = 2 \times \frac{U_x U_p}{100 \times I_p} = 2 \times \frac{U_x}{100} \times \frac{\frac{U_l}{\sqrt{3}}}{I_l} = \frac{2}{\sqrt{3}} \times \frac{U_x}{100} \times \frac{U_l}{I_l}, \Omega \tag{5}$$

Among them; U_l is the rated line voltage of the converter variable valve side V; I_l is rated line current of the converter variable valve side A. When the valve side winding is D-junction, the commutation reactance (2XT) is the reactance value (Ω) of the two-phase winding is series and then other-phase winding in parallel.

$$2X_T = \frac{2X_p * X_p}{2X_p + X_p} = \frac{2X_p}{3} = \frac{2}{3} \times \frac{U_x U_p}{100 \times I_p} = \frac{2}{3} \times \frac{U_x}{100} \times \frac{U_l}{\frac{I_l}{\sqrt{3}}} = \frac{2}{\sqrt{3}} \times \frac{U_x}{100} \times \frac{U_l}{I_l}, \Omega \tag{6}$$

Therefore, regardless of whether the valve side winding is a Y junction or a D junction, the commutation reactance ($2X_T$) can be calculated by the following formula:

$$2X_T = \frac{2}{\sqrt{3}} \times \frac{U_x}{100} \times \frac{U_l}{I_l}, \Omega \tag{7}$$

Generally, the commutation reactance (theoretical calculated value) of the commutation transformation can be obtained from the formulas (1), (2) and (7).

If the converter capacity is large, U_r can be ignored. At this time $U_x \approx U_z$.

Then formula (5) can be:

$$2X_T = \frac{2}{\sqrt{3}} \times \frac{U_z}{100} \times \frac{U_l}{I_l}, \Omega \qquad (8)$$

For example, for 400/85 kV a converter transformer if calculate CF's reactance value of valve hole;

U_z=15,88 % , U_l=85/√3 kV, I_l=2500 A

$X_T \approx$0,036 Ω.

1.1. Simulation model

HVDC model configuration Dig silent model shown Fig.5. The simulation model consist of two converter station with each converter station is composed of two poles. One station was operated in rectifier mode the other station was operated in inverter mode. AC filter and smoothing reactors are connected and the filters were tuned to suppress the AC harmonics. All the other parameters were given in Table I.

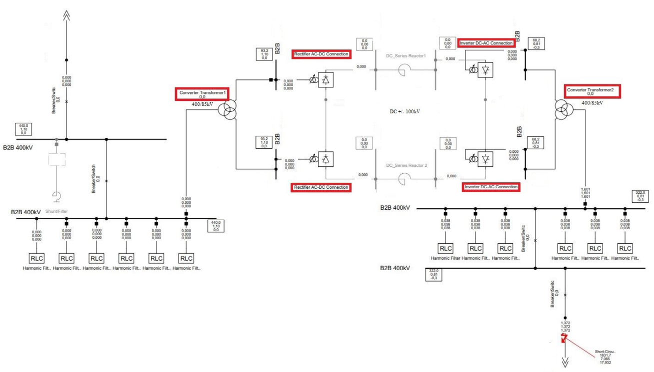

Figure 5: The simulation model.

This model is connected to two different grids with AC overhead lines the rectifier AC network was modelled by a source and inverter AC network was modelled by another source.

B2B-F1 lines were shown to the Figure 5 has been selected AC fault location in inverter side, according to fault was determined to term as winter and spring. Term of winter short circuit current 1543 A and term of spring short circuit current 1631,7 A. Similarly, the safe portable PDC power and short circuit currents of the connect lines calculated as a result of faults on the lines were shown in Table II.

The network short circuit was calculated according to $P_{DC}=(SCMVA-S_{filter})/ESCR$. PDC represents the safe DC power MW, S_{filter} was represent the filter power Mvar and $SCMA$ was represent the network short circuit power MVA.Calculated value $ESCR \geq 2{,}5$.

Table I: Simulation model parameters.

	Rectifier	Inverter	Unit
Continuous rating power	500	500	MW
Rated direct voltage	±100	±100	kV
Rated direct current	2500	2500	A
Ideal no-load direct voltage	114,43	114,43	kV
Base power	360	360	Mvar
Valve AC base voltage	84,73	84,73	kV
Commutation reactance	0,036	0,036	Ohm
Firing angle (α)			Degre
Rated	15	N/A	°C
Maximum	15+2,5	N/A	°C
Minumum	15-2,5	N/A	°C
Extinction angle (β)			Degre
Rated	N/A	18	°C
Maximum	N/A	18+1	°C
Minumum	N/A	18–1	°C

Table II: Related AC lines faults PDC and CF's situations.

Fiders	B2B Converter Center			
	Case 1- Winter		Case 2- Spring	
	SCMVA	SAFE PDC MW	SCMVA	SAFE PDC MW
B2B-F1	1543,0	473,6	1631,7	508,7
F1-F2	1381,9	408,8	1453,6	437,4
F1-F3	1384,5	409,8	1459,3	439,7
F1-F4	1472,9	445,2	1552,8	477,1
F2-F5	2036,3	670,5	2254,1	757,6
*Assuming that the B2B center connected to 360 Mvar filter.				
*F1,F2,F3,F4,F5 are connected lines to grid of inverter side.				

According to the Tab.2 the minimum safe DC power required for the operation of the B2B center was 408.8 MW. Under this value it can create CF's.Therefore a possible commutation failure situation should be prevented by paying attention to the connected lines F1,F2,F3,F4,F5 . These lines has been selected according to grid weak or strong connected situations.

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2. PREVENTION OF COMMUTATION FAILURES

Commutation failure is an adverse dynamic event that occurs when a converter valve that is supposed to turn off continues to conduct. Hence, the current is not transferred to the next valve in the firing sequence. Its occurrence causes a temporary interruption of transmitted power and stresses the converter equipment [17]. Furthermore, it can result in significant direct current increase and thus lead to additional heating of the converter valves. Consequently, shortening their lifespan [18]. Most commutation failures are caused by voltage disturbances due to AC system faults and they can never be completely avoided [19].

The methods can be divided into four categories (I) optimize protection and control characteristic; (II) Install auxiliary equipment; (III) coordinate DC power; (IV) modify converter structure. All the above methods can be used in traditional HVDC system. HVDC Systems have high voltage level, large transmission capacity, and special structure such as multi-infeed or hierarchical infeed structure. In order to adapt the characteristics of HVDC, the above four methods need to be improved.

2.1. Optimize protection and control characteristics

Optimizing protection and control characteristics is the most common method to mitigate CFs of HVDC. It is not limited by the withstand voltage level and transmission capacity of HVDC, which has a good economy. It can be divided into predictive control of CF, The Voltage-Dependent Current Order (VDCOL- Voltage control function) and other control methods based on commutation failure related parameters.

2.2. Install auxiliary equipment

In HVDC systems, common auxiliary equipment includes reactive power compensation device, superconducting fault current limiter (SCFL), unified power flow controller (UPFC). Due to the existence of multi-infeed structure and hierarchical structure in HVDC systems, how to coordinate the auxiliary equipment among DC subsystems to maximize its benefits has become the focus of research.

2.3. Coordinate DC power

In HVDC, especially due to large transmission capacity of DC lines, reasonable use of DC power of each DC line and coordination with each other can effectively alleviate CFs. It assumed that the extinction angle γ is kept constant due to the control effect of constant extinction angle, then the reactive power consumed by DC decrease with the decrease of transmission active power can be reduced to reduce the DC reactive power demand and improve the system recovery characteristics after the fault. At the same time due to high-power DC transportation, the DC current Id is at a high level and the extinction angle is small in the commutation process, so the risk of CFs is high. The relations ship between DC transmission power and arc extinction angle can be deduced [20]. It can be seen that the decrease of DC power is conductive to the increase of extinction angle thus reducing of CFs.

2.4. Modify converter structure

The physical essence of CFs is that the thyristor lacks the self-turning off capability. The use of wholly-controlled devices such as an IGBT can essentially eliminate CFs [21,22]. However, HVDC transmission systems based on full control devices have some problems, such as high construction cost, high technical difficulty, limited voltage level and insufficient transmission capacity [23].

Therefore, for a long time the thyristor cannot be replaced. Proposes a trade-off scheme in which one side uses a line commutation converter (LCC)-based converter and the other side uses a voltage source converter (VSC) or a modular multilevel converter (MMC) [24].

The four CFs prevention methods can directly improve the CFs resistance of HVDC transmission systems, it can be seen that from the investment cost and technical difficulty level, under the existing research level, it is more advantageous to optimize the protection and control strategy to prevent CFs [25].

3. CONCLUSION

CFs of LCC-HVDC links become one of the major threats to safety and stability of ultra-large-scale AC/HVDC hybrid power systems. Based on the principle of commutation, this paper reviews the current strategies for CF inhibition and analyses their characteristics and deficiencies.

I. The thyristor, inverter topology, converter transformer and other primary equipment can be increasing the commutation margin. However, primary equipment improvement methods are expensive and less reliable than other methods.
II. Improvements in the control system are mainstream strategies. One promising approach is predictive control, which lies in the rapid and reliable prediction and optimisation of control strategy. The existing predictive methods. Poor real-time performance is another weakness of such methods.
III. Studies of CF prevention for HVDC systems have mainly been based on sensitivity analyses over small ranges. Quantitative analyses of transient processes under large disturbances have been largely insufficient, leading to a lack of methods for accurately assessing control strategies for CF inhibition.

Also based commutation voltage-time area theory, it is pointed out that commutation voltage amplitude, firing angle, harmonic component, DC current and DC control characteristics all effect CFs of HVDC. Additionally, four kinds of CFs prevention methods, such as optimizing protection and control characteristics, installing auxiliary equipment, coordinating DC power and modifying converter structure, are summarized.

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BIOGRAPHY

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