Research on HVDC Converter Valve Thyristor Overvoltage Protection

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Abstract. Converter valve is the core component of HVDC system, and its safety operation is significant for the system. However, the ability of thyristor in converter valve to withstand overvoltage is weak. Even transient overvoltage can lead to thyristor breakdown. Thus, thyristor is needed to configure overvoltage protection. The paper analyzes two kinds of thyristor overvoltage protection scheme BTC (Backup Trigger Circuit) and BOD (Break Over Diode), and then sets up PSPICE models to conduct simulation analysis. Finally, the performance of the two kinds of overvoltage protection is verified by practical circuit experiment. The result shows that both protection schemes can satisfy the requirement of thyristor overvoltage protection.

1. Introduction
HVDC has several advantages such as high capacity and low loss, which is an important way to realize energy optimized configuration and is one of the key points to realize global energy interconnection [1,2].

Converter valve is the core component of HVDC system and is vital for the safety operation of the system. The present HVDC converter valves use thyristor to realize commutation. The ability of thyristor to withstand overvoltage is weak. Transient overvoltage may lead to thyristor permanent breakdown, and replacement needs HVDC system shutdown which leads to a great cost [3,4], so it is necessary to configure overvoltage protection for thyristor to improve the stability and reliability of HVDC system.

The present thyristor overvoltage protection schemes include electronic type and BOD type. The representative of electronic type is BTC protection. The circuit mainly uses diode and audion to realize thyristor protection, and the protection voltage can be adjusted by adjustable resistance [5,6]. BOD type protection mainly uses BOD device, diode and stabilivolt, and the protection voltage level is determined by BOD device [7-10].

The paper analyzes the principle of currently widely used BTC protection and BOD protection and compares the performance of the two kinds protection by simulation and experiment.

2. Influence of thyristor overvoltage on HVDC system
The ability of thyristor to withstand overvoltage is weak. When overvoltage occurs, thyristor is easy to break down and lose the ability to block current in both forward direction and reverse direction.

In a HVDC converter valve, if some part thyristors break down, the voltage of other thyristors will increase. When the number of breakdown thyristors is more than a certain quantity, all thyristors will
break down due to overvoltage, leading that the whole bridge arm of converter valve loses the ability to block current in both forward direction and reverse direction and causes a valve short circuit fault.

Valve short circuit fault is one of the serious faults of converter valve. In order to study the influence of valve short circuit fault on HVDC system, a six-pulse converter valve simulation model is set up by PSCAD shown as figure 1. The voltage of HVDC system is 200kV, and the current is 4500A.

![HVDC simulation circuit](image1.png)

**Figure 1. HVDC simulation circuit**

The simulation condition is set as follows: When t=45ms, a short circuit fault occurs at the bridge arm 1. When t=105ms, the bridge arm 1 recovers to normal. The voltage and the current of HVDC system, the current of fault bridge arm and the current of normal bridge arm are shown as the figures below.

![The current of HVDC system](image2.png) ![The voltage of HVDC system](image3.png)

**Figure 2. The current of HVDC system**  **Figure 3. The voltage of HVDC system**

![The current of fault bridge arm](image4.png) ![The current of normal bridge arm](image5.png)

**Figure 4. The current of fault bridge arm**  **Figure 5. The current of normal bridge arm**

It is seen from the simulation result that if a short circuit fault occurs at a bridge arm of the converter valve, the voltage and the current of HVDC system will be abnormal, and the normal bridge arm will experience a negative current whose amplitude is 3 times as the normal current, which leads to the damage of the whole converter valve. So, it is necessary to configure overvoltage protection for thyristor to enhance the converter valve reliability.

3. **BTC protection**

3.1. **BTC protection principle**

The BTC protection schematic diagram is shown as figure 6. The BTC circuit is composed of working power supply circuit, trigger voltage circuit, gate pulse amplifying circuit and optical signal transmitting circuit. The concrete circuit is shown as figure 7.
Each part of the BTC protection circuit is analyzed as follows:

1) The working power supply circuit is mainly composed of $C_{58}$, $R_{120}$, $R_{122}$, $V_{84}$ and $V_{91}$, which is used to generate 60V power supply for gate pulse amplifying circuit and optical signal transmitting circuit.

2) The trigger voltage circuit is mainly composed of $C_{57}$, $R_{116}$, $R_{117}$, $R_{105}$, $R_{125}$ and $V_{72}$. When the voltage of thyristor exceeds the BTC protection level, the trigger voltage circuit will generate trigger signal. The BTC protection level can be adjusted by $R_{125}$ shown as formula (1).

$$V = \frac{R_{116} + R_{117} + R_{105} + R_{125}}{R_{105} + R_{125}} (V_{95} + V_{72}) \quad (1)$$

3) The gate amplifying circuit is mainly composed of $V_{70}$, $V_{74}$, $V_{75}$, $V_{76}$, $V_{78}$, $V_{79}$, which is used to amplify the trigger signal from trigger voltage circuit and send it to the gate of thyristor. The gate current when BTC protection acts depends on the gate resistance of thyristor, which is approximately the ratio of trigger voltage and gate resistance.

4) The optical signal transmitting circuit is mainly composed of $R_{21}$, $R_{27}$, $R_{115}$, which is used to generate BTC optical feedback signal and send it to VBE.

The voltage of $C_{57}$ and $C_{58}$ equals the thyristor voltage. $C_{57}$ and $C_{58}$ are ultrahigh voltage capacitors and inline package. As the capacitor voltage is high, the circuit board and its elements are likely to accumulate contaminants. During 2014~2015 the BTC circuit of Tian-guang HVDC transmission system was falsely turned on because of this reason [5,11], leading to converter valve abnormal breakover. As the voltage of $R_{116}$ and $R_{117}$ are approximately the thyristor voltage, the temperature of the resistors is high, which is not good for the stability and reliability of the whole thyristor monitor board.

3.2. BTC protection simulation

Use PSPICE to model BTC protection circuit. For convenience to compare the performance of BTC protection and BOD protection, the adjustable resistance is set as 185Ω to make the action value of
BTC protection be 6kV. The BTC operating characteristic when thyristor encounters overvoltage is simulated. Figure 8 is the gate current of thyristor when the thyristor encounters overvoltage.

![Figure 8. Thyristor gate current](image)

4. BOD protection

4.1. BOD device principle

BOD is a thyristor that has a 4-layer structure. Its structural diagram is shown as figure 9.

![Figure 9. The physical structure and symbol of BOD](image)

The process from BOD turn-off state to BOD complete turn-on state needs 3~5us. As the negative pole of BOD uses the structure of p+ short-circuit diffusion, dv/dt is high. And because the structure is unsymmetrical, the ability to withstand reverse voltage is low (normally lower than 10V), and diode in series is needed to withstand reverse voltage. The BOD volt-ampere characteristic is shown as figure 10 [8,9].

![Figure 10. BOD V-A curve](image)

It is seen that when the voltage of BOD is higher than \( V_{BO} \), BOD is turned on. \( V_{BO} \) is the protection voltage of BOD. \( I_{BO} \) is the breakover current of BOD. \( I_{H} \) is the holding current. When the current of BOD is lower than \( I_{H} \), BOD is turned off.

4.2. BOD protection circuit principle

BOD protection circuit is shown as figure 11. The BOD device uses IXBOD1-30RD. IXBOD1-30RD internally installs a fast recovery diode to withstand reverse voltage, so there is no need to add a diode.
outside to withstand reverse voltage. The protection voltage $V_{BO}$ of IXBOD1-30RD is 3kV. The breakover current of IXBOD1-30RD is 15mA. The holding current of IXBOD1-30RD is 30mA.

The gate current of thyristor when BOD protection acts depends on $R_{210}$, $R_{211}$, $R_{212}$, $R_{213}$ and the gate resistance of thyristor. The gate current of thyristor can be changed by adjusting the resistance shown as formula (2).

$$I = \frac{V_{BO}}{R + R_G}$$

Where $R$ is the resistance in series with BOD device, and $R_G$ is the gate resistance of thyristor.

In figure 11, when the gate resistance is 10Ω, the gate current of thyristor is 100A theoretically.

4.3. BOD protection simulation

Use PSPICE to model BOD protection circuit. The gate current of thyristor when BOD protection acts is shown as figure 12.

It is seen that the maximum value of thyristor gate current is 24.7A, and the turn-on time is 1.8 us. The simulation result is far less than the theoretical value. It is because the turn-on time 1.8 us of thyristor is less than the time 3~5us which BOD device needs from turn-off state to complete turn-on state, and when the thyristor turns on, the BOD device is not completely turned on yet and still withstands partial voltage. The voltage of driving resistance and thyristor gate resistance is lower than $V_{BO}$, so the thyristor gate current is lower than theoretical value.

5. Experiment

5.1. Experimental principle

In order to verify the performance of BTC protection and BOD protection, design an experiment shown as figure 13.
The parameter of the thyristor T1 used in the experiment is 7.2kV/4500A. The gate resistance of thyristor is 10Ω. Referring to the present HVDC systems, the parameter of the R-C circuit is set as R 45Ω and C 1.6uF. The test device can control the output voltage amplitude and its rising edge. The maximum value of the output voltage is set as 7kV and the risetime is set as 100us. The voltage of thyristor and gate current are observed when BTC protection and BOD protection acts.

5.2. Experiment result

The experiment result of BTC circuit is shown as figure 14. CH1 is the voltage of thyristor. CH3 is the gate current of thyristor. It can be seen from the result that the breakover voltage of thyristor is 6.1kV, and the gate current amplitude is about 3A. The breakover time is about 2.2us, which means that the thyristor is protected 2.2us after overvoltage appears.

The experiment result of BOD circuit is shown as figure 15. CH1 is the voltage of thyristor. CH3 is the gate current of thyristor. It can be seen from the result that the breakover voltage of thyristor is 6.1kV, and the gate current amplitude is about 3A. The breakover time is about 1.6us, which means that the thyristor is protected 1.6us after overvoltage occurs.

5.3. Experiment analysis

According to the experiment result:

1) Both the action values of BTC protection and BOD protection satisfy the requirement of overvoltage protection of thyristor.

2) The action speed of BOD protection is 0.6us faster than BTC protection.

3) The gate current of thyristor when BOD protection acts is larger than the one when BTC protection acts.
4) The actual gate current is smaller than the theoretical calculation. It is because the thyristor turn-on time is 1.6us and the BOD device turn-on time is 3~5us. Thus, when the thyristor is turned on, the BOD device is not completely turned on yet and still withstands partial voltage, and the voltage of driving resistance and gate resistance of thyristor are lower than VBO. So, the gate current of thyristor is lower than the theoretical calculation.

6. Conclusion
The paper uses theoretical calculation, simulation analysis and experiment verification to conduct research on two kinds of overvoltage protection circuit of thyristor. The results show that both BTC protection and BOD protection can satisfy the requirement of thyristor overvoltage protection, but there is some difference on working characteristic between the two protection schemes:

The protection level of BTC protection is adjustable. It can switch different protection voltage while not changing the hardware circuit. But the gate trigger current depends on the gate resistance of thyristor, and the BTC protection itself cannot adjust the amplitude of gate trigger current.

The action speed of BOD protection is a few faster than BTC protection. The protection level of BOD protection cannot be adjusted if the BOD circuit do not change the type of BOD device, but the gate trigger current can be adjusted by adjusting BOD circuit resistance.

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