Fault Characteristics and Protection Scheme of the MMC-UPFC under Different Grounding Design

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Abstract. The Unified Power Flow Controller (UPFC) based on Modular Multilevel Converter (MMC) is more suitable for high-voltage and large-capacity transmission fields. According to the actual needs of demonstration project, 3 grounding proposals were brought out and the effect of different grounding proposals to the fault characteristics and protection schemes is analyzed in detail. The conclusion that only parallel valve side star connected large resistance grounding is more advantageous in MMC-UPFC was derived.

1. Introduction

The Unified Power Flow Controller (UPFC) based on Modular Multilevel Converter (MMC) is widely concerned, but the research is lacking on the fault characteristics and protection schemes. The reference [1] analyzed grounding design of Zhoushan Flexible HVDC transmission system and then discussed the fault characteristics and the main, backup protection configuration of the MMC-HVDC demonstration projects. The reference [2] takes DC side, converter side and AC side of MMC-HVDC single phase to ground fault as example to analyze the effect of different fault characteristics. This paper mainly discusses the effect of MMC-UPFC on the fault characteristics and protection configuration scheme. This paper first introduced body structure and grounding design, and then put forward three grounding methods. And the effect of different grounding position to the series transformer network side ground fault and corresponding protection configuration are analyzed in detail. Then measure the fault characteristics and its effect on the protection configuration in different grounding modes. Combined with the results of RTDS real time digital simulation, the design of the MMC-UPFC demonstration project is given.

2. Body structure and grounding design of MMC-UPFC

2.1. The body structure of MMC-UPFC

The body structure of MMC-UPFC is shown in figure 1. The MMC-UPFC composed by two back-to-back MMCs and transformers, its parallel side of transformer T1 is connected to AC system bus, and the winding of series side of transformer T2 was installed in the AC transmission line. The thyristor bypass switch is used to protect the series side MMC.
Figure 1. Body structure of MMC-UPFC.

2.2. The grounding design of MMC-UPFC

MMC-UPFC demonstration project control strategy selected conventional positive sequence current decoupling control. The parallel transformer network side use delta connection method, while the valve side use Y connection method and the series side transformer use Y connection in first and second winding, the main parameters of the simulation system are shown in table 1.

Table 1. The main parameters of the simulation system.

| parameters                      | figure parameters | figure |
|---------------------------------|-------------------|--------|
| System voltage (kV)             | 230               | MMC capacity (MVA) | 50 |
| The DC voltage (kV)             | 51.2              | Sub-module capacitor rating voltage (kV) | 1.6 |
| Bridge arm module number        | 34                | The parallel transformer leakage reactance (%) | 9.13 |
| Bridge arm inductance (mH)      | 15                | The parallel transformer winding ratio | 252/22 |
| Sub-module capacitance (μf)     | 8500              | The series transformer winding ratio | 3.83/14.72 |
| Series transformer leakage reactance (%) | 9.08 | Grounding resistance (Ω) | 200 |

This paper is based on the reference [2-5] to consider the series and parallel connection of different grounding design. The grounding design of MMC-UPFC is divided into 3 methods referred to as grounding scheme 1, 2, 3. The alternative of grounding resistance is calculated according to system parameters, controller design and fault effect calculation, and nothing more really needs to be said on the calculation process.

3. The effect of the parallel and series side grounding respectively

3.1. The effect to fault characteristics of the parallel and series side grounding respectively

Figure 2. Single phase to ground fault of T line.

In this paper, lots of RTDS experiments are compared with the fault waveforms of the grounding scheme 1 and 2, and both fault characteristics are consistent. Take the phase A to ground fault in the point k2 as an example (as shown in figure 2), the fault waveforms are shown in figure 3 and figure 4.
The fault characteristics under grounding scheme 1 are as follows:

1) When a fault occurs in the point k, there is no zero sequence current in the series and parallel transformer valve side. The voltage of series side system added to the valve side winding, leading to increase of valve side winding voltage, network side winding voltage and the neutral point voltage of series transformer, as shown in figure 3 (a), (b). However, as is shown in figure 3 (c), (d), fluctuation range is small.

2) Since the fault point k is connected to the directly grounding 220kV system, the voltage of the fault phase drops to 0 and the voltage of non-fault phase remains constant. After the phase shift of the transformer, the phase B of valve side AC bus voltage to ground remains constant while the phase A and C drop to $1/\sqrt{3}$ of the original, as is shown in figure 3 (f).
Figure 4. Waveform of grounding fault of the point k under the grounding scheme 2.

The fault characteristics under grounding scheme 2 is that when a fault occurs in point k, there is zero sequence current and zero sequence current coupled to the valve side winding and flowing through the neutral point of the series side, and determining neutral point voltage. And the series side AC system provide large zero sequence current and small positive current.

3.2. The effect to protection schemes of the parallel and series side grounding respectively
The single phase to ground fault occurs in the series transformer network side and the protection schemes are the same under scheme 1 and 2. However, as shown in Figure 3, there is overvoltage of valve side AC and DC bus under grounding scheme 2, so the parallel side grounding is suggested.

4. The effect of different grounding resistance

4.1. The effect to fault characteristics of different grounding resistance
This section focuses the effect of fault characteristics and protection configuration under different grounding resistance and puts forward suggestions on the grounding resistance of the project.
The main effect of different grounding resistance is to single-phase grounding fault, take the parallel transformer valve side AC bus (the k1 point) and series side bridge arm (the k2 point) single phase grounding fault as examples (The fault points are shown in Fig.5).

![Diagram](image)

**Figure 5.** Single phase to ground fault valve side AC bus and bridge arm.

The fault characteristics of fault point k1 are as follows:
- In the normal working condition, the MMC1 converter works in rectification state while the MMC2 converter in inverter state. So the fault current is mostly provided by the parallel side systems and there is not overcurrent in series and converter side.
- The difference of fault characteristics between grounding scheme 1 and 3 under the grounding fault in the point k1 is small. In both grounding scheme, the voltage of fault phase dropped to 0 and the voltage of neutral point shifted, which leading to the voltage fluctuation of series transformer valve side and DC side.

The fault characteristics of fault point k2 are as follows.
- In both grounding scheme, the bridge arm current increased with time after the transient process. The difference is the transient process is longer and the bridge arm current is smaller. There is serious overcurrent under grounding scheme 3, causing harm to the insulation.
- In both grounding schemes, there is not overcurrent in the series transformer valve side. But the DC voltage fluctuated because of the shift of the neutral point.

4.2. The effect to protection schemes of different grounding resistance

4.2.1. The differential protection of valve side AC bus. The parallel transformer valve side AC bus differential protection utilizes conventional differential protection, the differential current \( I_d = |I_{TA3} + I_{d2}| \) and the restraint current \( I_{res} = 1/2(I_{TA3} - I_{d2}) \). \( I_{TA3} \) is the current of current transformer TA3 and \( I_{d2} \) is the current of current transformer Id2 and TA3 is the traditional electromagnetic current transformer while the Id2 is the optical current transformer. When a single phase to ground fault occurs in point k1, differential and restraint current of grounding scheme 1 and 3 is as shown in figure 6.

Both restraint currents are basically equal to the valve side AC bus rating current while the differential current is greatly influenced by the grounding schemes and the starting current should be more than 0.2 \( I_N \) (\( I_N \) is the rating current). Obviously, the differential is lower than starting current of grounding scheme 1, which means the sensitivity of differential protection cannot be guaranteed. However, the protection can operate correctly under grounding scheme 3.

4.2.2. The differential protection of bridge arm. Take the series upper side bridge arm differential protection as an example, the differential current \( I_d = |I_{d7} + I_{d9}| \) and restraint current \( I_{res} = 1/2(I_{d7} - I_{d9}) \). \( I_{d7} \) is the current of optical current transformer Id7 while \( I_{d9} \) is the current of optical current transformer Id9.
Figure 6. Waveform of differential and restraint current of valve side AC bus single phase to ground fault.

When there is a single phase to ground fault occurs in the point k2, the differential and restraint current of grounding scheme 1 and 3 is as shown in figure 7. For the grounding scheme 1, in the process of transient transition, the restraint current is reduced while the differential current is increased, so the protection can operate correctly. For the grounding scheme 3, the bridge arm currents and restraint current increase with time. In conclusion, only under the parallel transformer valve side AC bus and valve side winding grounding fault, the corresponding protection cannot operate correctly. However, if the grounding scheme 3 is adapted, the small grounding resistance results in overcurrent in bridge arms, which cause harm for the safety of UPFC. In summary, scheme 1 is proposed.
Figure 7. Waveform of differential and restraint current of valve bridge arm single phase to ground fault.

5. Conclusion
Through theoretical analysis and simulation validation, the effect of different grounding position to the series transformer network side grounding fault and protection configuration and the effect of different grounding resistance to the parallel valve side grounding fault are analyzed in detail, the conclusions are as follows:

- When a fault occurs in series transformer network side under grounding scheme 2, there is zero sequence current in valve side, which leading to the overcurrent of the neutral point. The voltage of valve side AC bus added to the neutral point voltage, causing the overvoltage of the valve side AC bus.
- The sensitivity of differential protection may be inadequate under the parallel transformer valve side single phase to ground fault when the grounding resistance is large.
- According to theoretical analysis and simulation, the large resistance (200 ohm) grounding of the valve side of the parallel transformer is the most suitable rounding design.
References
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