The study on CT saturation caused by the circulating current in the delta-winding of converter transformer and its impact on the protection in HVDC system

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Abstract

In the typical HVDC power system, the current transformers (CTs) between the Y-delta converter transformer and the converter bridge is located in the delta-winding of the transformer. Under such condition, the measuring current of these CTs includes the zero-sequence circulating current of the delta-winding. In the case of the adjacent transformer energization or the fault of AC system, the zero-sequence circulating current in the delta-winding maybe very large containing a great amount of dc component. Thus the CTs will be saturated, resulting in the misoperation of the relevant protection in HVDC system, such as the bridge current differential protection. This sort of misoperation seriously threatens the safe and sound operation of the HVDC power system. In this paper, the misoperation cause is analysed in detail via the PSCAD/EMTDC-based simulation. Based on this, a method is proposed to prevent this sort of misoperation by utilizing the zero-sequence circulating current as the restraint quantity.

1 Introduction

The correct operation of the HVDC system is of great significance to the safe and sound running of the model hybrid AC/DC power transmission system. Recently, it is reported that several cases of the misoperation of the differential current protection for the converter bridge when the adjacent converter transformer is switched-on or a short-circuit fault occurs nearby the converter station, threatening the normal operation of the HVDC system[1-4]. This sort of misoperation is related to the current transformer (CT) saturation.

In the converter station, the CTs between the valve side of the Y-delta converter transformer and the convertor bridge are located in the delta winding of the transformer[5]. This is because the space between the ac field and the valve hall is very tiny, and there is rare sufficient place left for installing the CTs outside of the converter transformer. Under such condition, the primary current of the CTs in the delta winding of the transformer contains the zero-sequence circulating current. During the adjacent transformer energization or the short-circuit fault in the nearby AC system, the zero sequence current will flow into the delta-winding of the Y-delta converter transformer, which may cause the saturation of the CTs located in the delta-winding. In this case, the protection that uses the measured current from the saturated CT is confronted with the risk of misoperation.

This paper makes an in-depth analysis on this sort of misoperation utilizing the PSCAD/EMTDC based simulation. Based on this, a method is proposed to prevent the misoperation by utilizing the zero-sequence circulation current as the restraint current and the zero-sequence voltage on the AC bus of the converter station.

2 The misoperation analysis

2.1 The analysis on the zero-sequence circulating current in the delta-winding of the converter transformer

Figure 1 demonstrates a diagram of the converter station. When the adjacent converter bridge is de-blocked and the convertor transformer of Polar II is switched on-to the supply system. The magnetizing inrush current will be generated. The zero-sequence component of the magnetizing inrush current will flow through the delta-winding of the convertor transformer, As the sequence equivalent circuit shows in Figure 2.

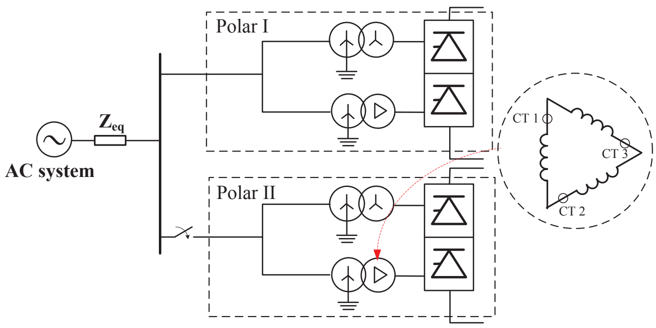


Figure 1: The diagram of the converter station

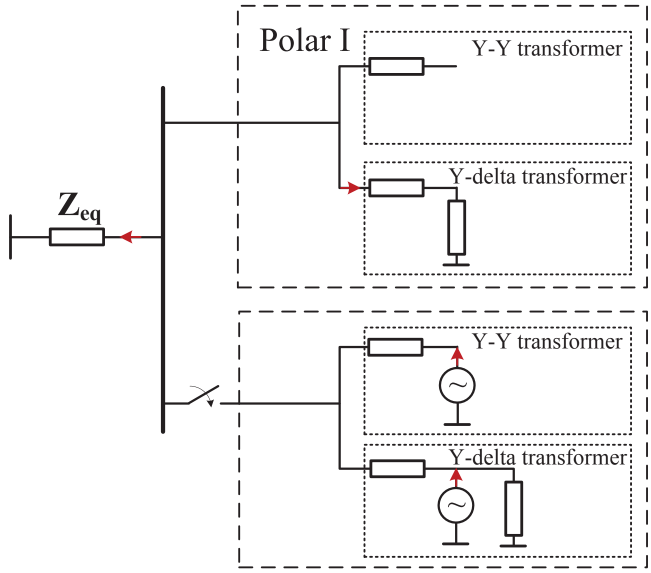
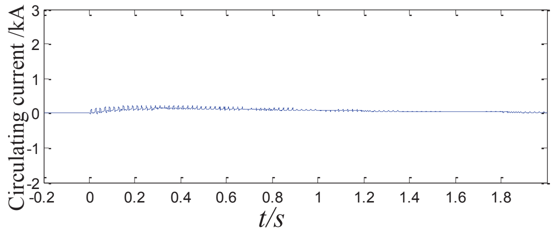
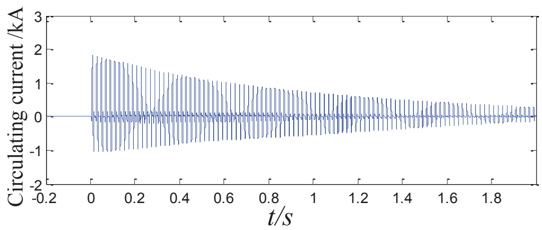


Figure 2: The sequence equivalent circuit of the converter station

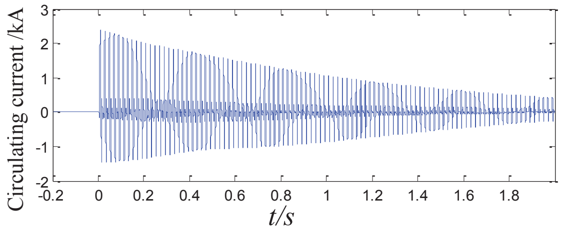
As Figure 2 shows, the zero-sequence current generated by the magnetizing inrush current will flow both into the AC system and the delta-winding of the transformer. Changing the equivalent zero-sequence impedance of the AC system, denoted as Z_{eq}, the simulation results for the delta-winding current of the converter transformer of Polar II are illustrated in Figure 3. As can be seen, with the zero-sequence impedance of the AC system becomes lower, the zero-sequence magnetizing current will be more shunt into the AC system, as a consequence, the circulating current of the delta-winding of the converter transformer will be generated.



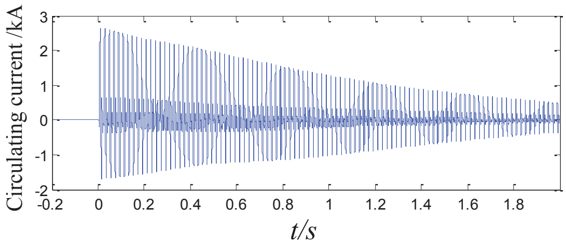
(a) Z_{eq}=0Ω



(b) Z_{eq}=20∠76.55°Ω



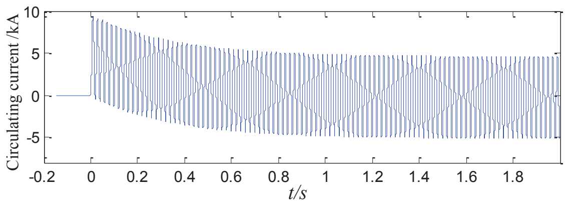
(c) Z_{eq}=40∠76.55°Ω



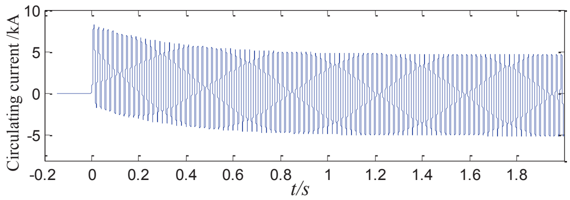
(d) Z_{eq}=60∠76.55°Ω

Figure 3: The simulation results by changing the equivalent zero-sequence of the AC system

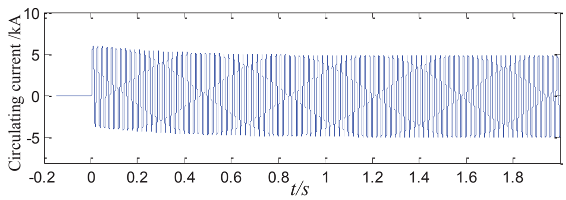
Except for the energization of the adjacent transformer, the short-circuit fault will also cause the circulating current of the delta winding. Assuming a single-phase-to-ground fault occurs at the AC bus of the converter station with the inception angle (denoted as α) changing from 0° to 90°, the simulation results are shown in Figure 4. As can be seen, the with the inception angle getting closed to 90°, the dc component in the delta winding decreases.



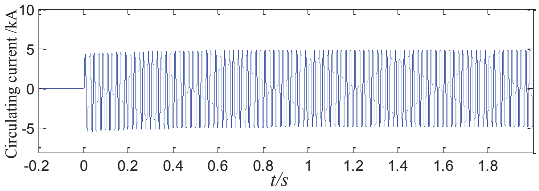
(a) α=0°



(b) α=30°



(c) α=60°



(d) α=90°

Figure 4: The simulation results by changing the inception angle of the single-phase-to-ground fault

2.2 The CT saturation characteristic under the circulating current of the delta winding

According to the aforementioned simulation analysis, the zero-sequence containing a decaying dc component will be generated during the adjacent transformer energization or the short-circuit fault in the AC system nearby the converter station. Under such condition, the CT will come into the saturation condition, as shown in Figure 5.

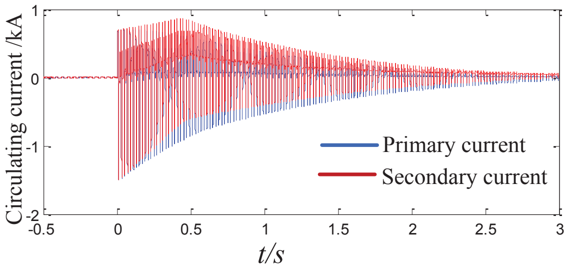


Figure 5: The simulation results of the CT saturation

The criterion of the differential current protection for the Y-Y converter bridge is:

$$I_{ac}-I_{acY}=\max\left(I_{acY},\ I_{acD}\right)-I_{acY}>\triangle \tag{1}$$

Where, I_{acY} and I_{acD} are respectively the rectified value of the measured valve side current of the Y-Y and Y-delta convertor transformer, I_{ac} is the maximum value of I_{acY} and I_{acD}, $\triangle$ is the setting threshold value of the differential protection.
As the same way, the criterion of the differential current protection for the Y-delta converter bridge is:

$$I_{ac}-I_{acD}=\max\left(I_{acY},\ I_{acD}\right)-I_{acD}>\triangle \tag{2}$$

The time delay algorithm of the bridge differential protection is illustrated in Figure 6. In every sampling point, the criterion (1) and (2) will be judged. If the criterion is satisfied, the value of the counter, denoted as Z, will be added by 20, otherwise the counter will be subtracted by 1. When the value of Z is greater than the set time threshold T:

$$Z>20\times T/Ta \tag{3}$$

Where Ta is the time interval of the sampling.

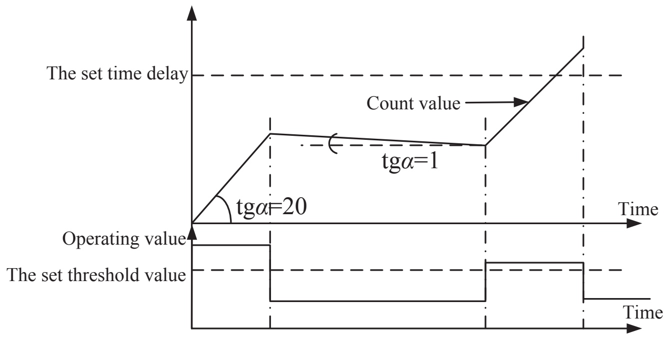


Figure 6: The time delay algorithm of the bridge differential protection

Since the measuring current on the valve side of the Y-delta transformer is the winding current. The delta-Y transformer is applied to transformer the current from phase current into the line current, which is given by:

$$I_{D\_A}-I_{D\_B}=I_{L\_A} \tag{4}$$
$$I_{D\_B}-I_{D\_C}=I_{L\_B} \tag{5}$$
$$I_{D\_C}-I_{D\_A}=I_{L\_C} \tag{6}$$

Where I_{D_A}, I_{D_B}, and I_{L_A} are respectively the measured phase current from the delta winding, I_{L_A}, I_{L_B}, and I_{L_C} are respectively the transferred line current.

As shown in Figure 5, since the CT is saturated, the measured current I_{D_A}, I_{D_B}, and I_{D_C} are not proportional to the primary current. As a consequence, the transferred line current is increased caused by the false current due to CT saturation as shown in Figure 7. Under such condition, the criterion (1) will be satisfied, and the bridge differential protection for Y-delta converter bridge will misoperation.

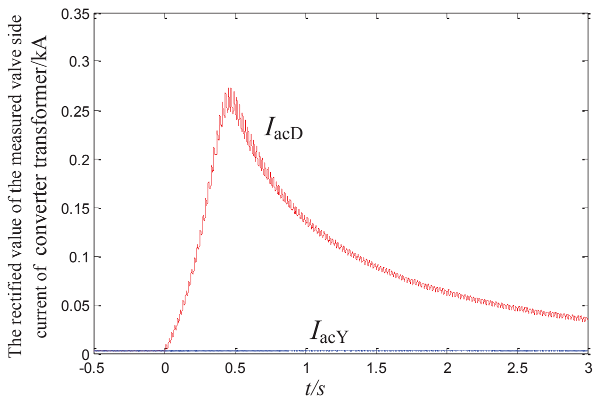


Figure 7: The curves of I_{acD} and I_{acY}

3 The proposed countermeasure for preventing the misoperation

3.1 The basic principle

According to the above analysis, we can conclude that the misoperation is caused by the CT saturation due to the circulating current in the delta winding of the Y-delta transformer. So the zero-sequence voltage of the AC bus in the converter station can be used for detect the zero-sequence circulating current in the Y-delta transformer. According to the equivalent circuit in Figure 2, the circulating current in the Y-delta transformer will cause the zero-sequence voltage in the AC bus when this current flow through the leak impedance of the transformer. So when criterion (7) is satisfied, the circulating current in the Y-delta transformer is considered to be flowing.

$$3U_{ac0}>0.1\ \text{pu} \quad (7)$$

The scope of the bridge differential protection is the fault occurring at the converters. The zero-sequence fault current generated from the converter fault cannot flow into the delta-winding of the transformer, since the neutral point on the valve-side of the converter transformer is non-effective grounding. So the zero-sequence voltage in the AC bus can be used to effectively distinguish whether the fault is in the converter or not.

After the criterion (7) is satisfied, the bridge differential current protection is modified rather that blocked. The new criterion for the protection is given by

$$I_{diff}=I_{ac}-I_{acY}=\max(I_{acY},\ I_{acD})-I_{acY}>\max(I_{set},\ kI_{0m}) \quad (8)$$

Where, I_{0m} is the amplitude of the zero-sequence current of the delta-winding, and k is the setting coefficient.

On the other hand, time delay for the differential protection is extended from 0.2s to 0.4s.

This new method can guarantee both the security and the dependability of the differential protection. When the fault occurs in the protected region, namely the converter, the zero-sequence current is very tiny and the restraint current is relatively small. Therefore, the differential protection can operation fast and sensitively. On the other hand, in the case of the fault occurring in the AC system or the magnetizing inrush current, the value of I_{0m} may be large ant the restraint current can prevent the potential misoperation caused by CT saturation.

3.2 The simulation tests

Figure 8 to Figure 10 shows the PSCAD/EMTDC based simulation results. As can be seen from Figure 8, when the transformer is switched-on to the supply system, the operating current $\max(I_{acY}, I_{acD})-I_{acY}$ increases due to CT saturation and the criterion (1) is satisfied. At the moment that the operating current increases, the zero-sequence voltage of the AC bus immediately rises and the modified differential protection criterion is applied, which is illustrated in Figure 9. As shown in Figure 8, the setting threshold value of the differential protection △ contains the circulating current. Hence the differential protection is restraint. On the other hand, the time delay is extended from 0.2s to 0.4s, as shown in Figure 10. Under such condition, the accumulated time delay is less than 0.4s so the bridge differential protection will not misoperate.

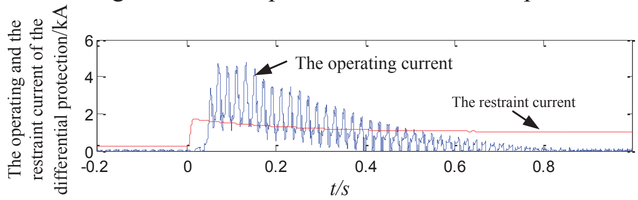


Figure 8: The curves of I_{acD} and I_{acY} when the adjacent transformer is switched-on to the supply system

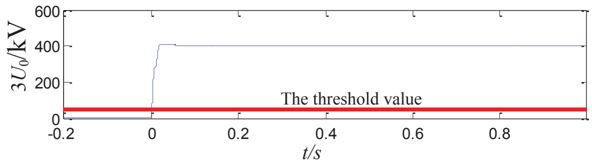


Figure 9: The zero-sequence voltage in the AC bus of the converter station

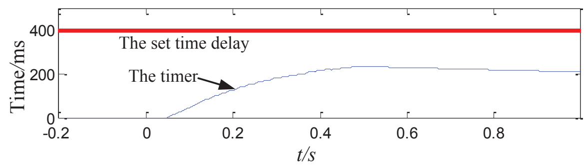


Figure 10: The time delay of the protection

Figure 11 shows in the operating and the restraint current when an internal fault occurs at the valve side of the converter transformer. The zero-sequence voltage of AC bus is shown in Figure 12. As can be seen, the zero-sequence voltage rise very small after the increasing of the operating current. Hence, the modified differential protection criterion cannot be applied. So the protection can act very promptly about 0.2s after the internal fault, as shown in Figure 13.

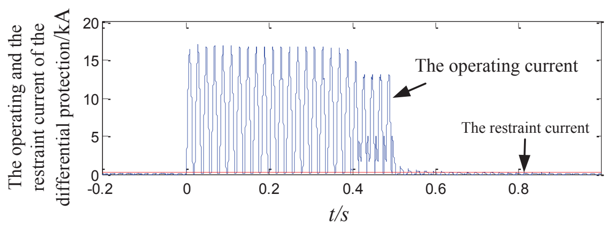


Figure 11: The operating and the restraint current when an internal fault occurs

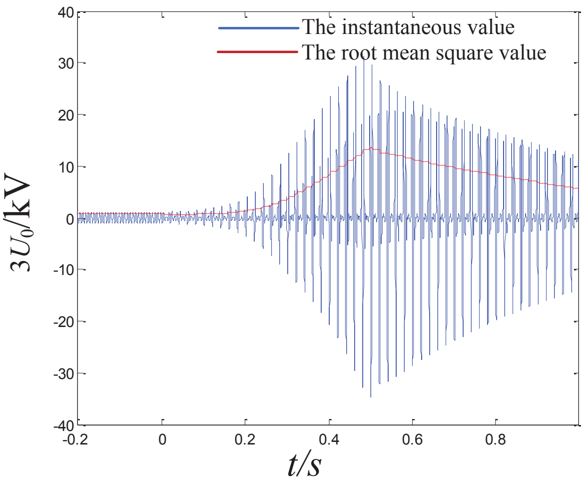


Figure 12: The zero-sequence voltage of the AC bus in converter station

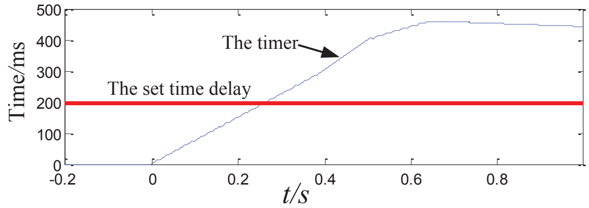


Figure 13: The time delay of the bridge differential protection when internal fault occurs

4 Conclusion

This paper analyses a sort of bridge differential protection misoperation caused by the CT saturation that is located in the delta-winding of the transformer. Base on this, a new method is proposed to prevent the misoperation by applying the zero-sequence of the AC bus. This zero-sequence voltage can be utilized for indicate the zero-sequence circulating current in the delta-winding. Further, the circulating current is introduced to be part of the criterion, in order to increase the security of the differential protection. This new method can guarantee both the security and the dependability of the differential protection. The simulation test proofs the validity of the proposed new method.

Acknowledgements

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