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A novel Hausdorff distance based restrain criterion for zero-sequence differential protection of converter transformer

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ABSTRACT

Due to its high sensitivity and fast operation rapidity, zero-sequence differential protection (ZSDP) has become the most frequently used main protection for EHV and UHV power transformers. It is generally assumed that extra restrain criterion is unnecessary for ZSDP since it is immune to the magnetizing inrush current in theory. However, it's found that the bias of zero sequence current in converter transformer due to core saturation may lead to the accumulation of magnetic bias within the core of CT, especially during external fault removal period. This may lead to the mal-operation of ZSDP. Based on the Hausdorff graphics recognition algorithm, an extra restrain criterion for ZSDP is proposed in this paper. Verified by simulation and theoretical analysis, the proposed criterion will not influence the performance of traditional ZSDP. However, the proposed criterion can correctly identify the fake differential current and effectively prevent the mal-operation of ZSDP caused by the recovery inrush.

1. Introduction

Due to the advantages of high sensitivity and fast operation rapidity, zero-sequence differential protection (ZSDP) has been widely applied in EHV and UHV power transformers. As the connection between AC and DC systems, the safety and stability of converter transformer are of great importance in DC transmission project [1–3]. Therefore, in addition to the longitudinal differential protection, the converter transformer in HVDC project is also equipped with ZSDP as one of the important main protections.

There are several researches on the theme of ZSDP. Literature [4] proposed a phase selection method for zero sequence current differential protection. Literature [5] presented new directional comparison-based internal/external fault detection and discrimination technique for the protection of all commonly used phase-shifting transformer types. Literature [6] presented an overview of transient phenomena occurring during energization of shunt reactor at EHV substation. Literature [7] analyzed the cause of mal-operation of HVDC project caused by the disturbance from AC system based on mechanism analysis and simulation tests. Literature [8] introduced a new differential protection scheme based on zero-sequence voltages with 100% coverage for generator stator ground faults. Literature [9] presented a new methodology for detection and area location of high impedance faults on unbalanced distribution systems.

Theoretically, the ZSDP will not be affected by the magnetizing inrush current. However, when an external fault or transformer energization occurs, a large magnetizing inrush current will flow through both the windings and the neutral line. Considering the differences between the model parameters of CTs on system side (called CTS for short) and neutral side (called CTN for short), the transmission ability difference between the CTSs and CTNs may emerge under the influence of the large aperiodic component of magnetizing inrush. It may result in a fake differential current and cause the mal-operation of ZSDP. This problem cannot be solved by simply adding percentage restrain criterion in the protection.

Several mal-operations of ZSDP for 500 kV and 220 kV transformers during the process of external single-phase grounding fault were reported during 2006 to 2011 [10–11]. Mal-operation of ZSDP during the existence of external single-phase grounding fault can be attributed to the inaccurate setting of percentage restrain criterion and weak anti-saturation ability of CT. However, according to the waveform record analysis in Reference [11], the mal-operation occurred in the process of the re-closure after the removal of the single-phase grounding fault. According to the traditional mechanism of CT transient saturation, the

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most extreme saturation of CT should occur at the moment with the largest aperiodic component (meaning the initiation of the fault). However, the ZSDP did not operate until the fault was removed. Therefore, this sort of mal-operation cannot be correctly explained by the traditional mechanism of CT transient saturation.

Compared to AC transformers, converter transformers will go through more complicated transient processes in the cases of grounding faults. The fault current or inrush current contains complex aperiodic and harmonic components, which may further deteriorate the transmission characteristics of CTs and cause the mal-operation of ZSDP of converter transformer [12–13]. In consequence, more attention should be paid to the mal-operation risk research for ZSDP.

The main contributions of this paper rest with the following:

Firstly, the mal-operation mechanism of the zero sequence differential operation under recovery inrush is revealed in this paper, which is not well studied in the existing literatures; Secondly, a novel Hausdorff distance based restrain criterion is invented to improve the security of ZSDP of converter transformer under recovery inrush and DC bias without sacrificing the performance of ZSDP.

2. Principle of ZSDP of converter transformer

The principle of ZSDP of converter transformer is shown in Fig. 1.

The input signals of ZSDP are acquired from the CTN and the CTSs of converter transformer, and the direction of the current flowing into the protected area is defined as the positive direction. If the three-phase symmetrical system operates normally, the zero-sequence current flowing through the neutral point is 0, presented as $3\dot{I}_{n0} = 0$. The sum of three phase currents flowing into the protection device, defined as self-produced zero-sequence current, equals to 0 as well, presented as $3\dot{I}_{self0} = \dot{I}_A + \dot{I}_B + \dot{I}_C = 0$. When an internal grounding fault occurs (as f_1 in Fig. 1), the ZSDP will trip reliably. When an external grounding fault occurs (as f_2 in Fig. 1), the ZSDP will not trip.

The starting criterion for the ZSDP is:

$$I_{op} > I_{REF>} \tag{1}$$

where, the threshold $I_{REF>}$ is set to avoid the unbalance current during the transformer normal operation. The value of $I_{REF>}$ can be set as $0.05 \sim 0.1 I_n$ (I_n stands for the rated current of the transformer).

Percentage restrain criterion is usually introduced in the ZSDP to improve its operation reliability. In Gui-Guang HVDC project in China Southern Power Grid, the operating current of ZSDP is $I_{op} = |3\dot{I}_{n0}|$ and the restrain current is defined as $I_{rest} = k(|3\dot{I}_{n0} - 3\dot{I}_{self0}| - |3\dot{I}_{n0} + 3\dot{I}_{self0}|)$, where k is the restrain coefficient and generally set to 1.

The operation criterion for ZSDP is:

$$I_{op} > I_{rest} \tag{2}$$

The following two faults are discussed:

2.1. External fault

When external fault happens, $3\dot{I}_{n0}$ has equal amplitude and opposite phase to $3\dot{I}_{self0}$, which means $3\dot{I}_{n0} = -3\dot{I}_{self0}$. In this case Eqs. (3) and (4) can be obtained.

$$I_{op} = |3\dot{I}_{n0}| \tag{3}$$

$$I_{rest} = |3\dot{I}_{n0} - 3\dot{I}_{self0}| - |3\dot{I}_{n0} + 3\dot{I}_{self0}| = 2\,|3\dot{I}_{n0}| \tag{4}$$

When CT does not saturate, (2) is always not satisfied, and the protection will not trip. However, if the CTN saturates, $3\dot{I}_{n0} = -3r\dot{I}_{self0}\angle\theta$ comes into existence where r is the amplitude deviation factor and θ is the phase angle deviation factor. Therefore, the restrain current will turn into $\begin{aligned} I_{rest} &= |-3r\dot{I}_{self0}\angle\theta - 3\dot{I}_{self0}| - |-3r\dot{I}_{self0}\angle\theta + 3\dot{I}_{self0}| \\ &= |3\dot{I}_{self0}|\cdot(|-r\angle\theta - 1| - |-r\angle\theta + 1|) \end{aligned}$.

$$r < \frac{1}{2}\sqrt{\frac{3}{4\cos^2\theta - 1}} \tag{5}$$

It can be known by calculation that when Eq. (5) is satisfied, Eq. (2) will be satisfied and the ZSDP will mal-operate.

2.2. Internal imbalanced grounding fault

Ideally, the internal impedance at system side and equivalent internal impedance at the neutral line side are both inductive, $3I_{n0}$ and $3I_{self0}$ are in same phase, which means $3\dot{I}_{self0} = 3k'\dot{I}_{n0}$ (where $k' > 1$). In this case Eqs. (6) and (7) can be obtained.

$$I_{op} = |3\dot{I}_{n0}| \tag{6}$$

$$I_{rest} = |3\dot{I}_{n0} - 3k'\dot{I}_{n0}| - |3\dot{I}_{n0} + 3k'\dot{I}_{n0}| = -2k'\,|3\dot{I}_{n0}| \tag{7}$$

Since the restrain current cannot be negative, $I_{rest} = 0$.

Fig. 2 shows the operation curve of ZSDP which has the percentage restrain criterion.

The operation behavior of ZSDP is briefly analyzed above. However, the recovery inrush due to fault removal will lead to more complicated occasion, which is theoretically analyzed in detail in the following section.

3. Influence of recovery inrush caused by fault removal on the converter transformers

3.1. Primary discussion for the risk of bipolar outage caused by the recovery inrush of converter transformer

For converter stations, mal-operations of ZSDP due to the recovery inrush after fault removal may cause extremely severe consequences, such as four parallel transformers of both poles quit operation simultaneously, and result in the bipolar outage of DC system. The principle is detailed below.

For HVDC converter station, the typical topology of AC field is shown in Fig. 3. According to the main protection logic, if the internal grounding fault of T4 can be correctly identified by its corresponding protection, T3 and T4 will be removed simultaneously. In this case, the corresponding DC pole will be shut down and the DC project will turn to monopole operating mode. Though the power transmission of the system will be influenced, the system can still operate.

However, if the fault has caused a voltage drop of the bus, the bus voltage will recover rapidly after the fault removal. This process may cause the recovery inrush within T1 and T2. The zero-sequence component of recovery inrush in T1 will flow from system side through the

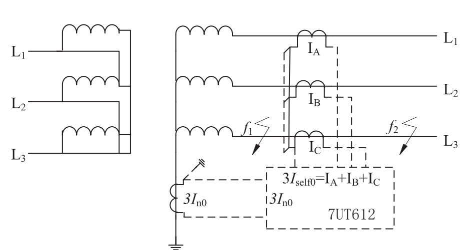

Fig. 1. Schematic diagram of converter transformer's ZSDP.

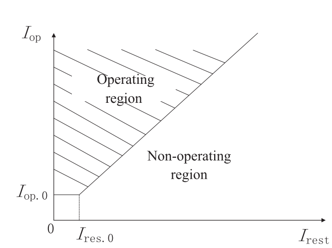

Fig. 2. Operation curve of ZSDP.