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Abnormal operation behavior analysis and countermeasures on the differential protection of converter transformer ☆

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ABSTRACT

Intriguing mal-operations and fail-to-trip of the differential protection of the converter transformer in the HVDC system are reported. In this paper, the mechanism of these abnormal operation behaviors is analyzed. By virtue of deliberately designed models of the converter transformer and the HVDC transmission system, a variety of simulation tests are carried out and above mentioned strange operation behaviors can be recurred. Then, the conditions of the operating states and faults resulting in this sort of abnormal operations can be determined. The reasons rest with the deep saturation of core due to energization and the high second harmonic within the differential currents due to faults. To solve above problems, the characteristics of voltage and differential current of the converter transformer are studied. It is disclosed that the time difference between the sudden change of the phase voltage and the emergence of differential current exists due to switching-on of the converter transformer. However, this time difference does not exist for any cases due to internal faults. Based on this finding, a novel criterion is therefore proposed. And it is verified with extensive RTDS based simulation test results.

Introduction

High voltage direct current (HVDC) transmission possesses many advantages that alternating current (AC) transmission cannot achieve. Therefore, it is extensively applied in power systems gradually. As the most important equipment in converting stations, the converter transformer plays a very vital role and its protection is extremely important to the normal operation of the whole system.

The principal contradiction of the transformer differential protection has mainly concentrated on how to discriminate between magnetizing inrushes and internal faults for a long time. Many criteria have been proposed to prevent the transformer differential protection from mal-operation caused by the magnetizing inrush. Among which, 2nd harmonic restraint criterion is the most prevalent one and it is can be used to effectively discriminate between magnetizing inrushes and fault currents [1–6]. However, even though the differential protection of the converter transformer is equipped with 2nd harmonic restraint function, some of mal-operations caused by magnetizing inrushes during transformer energization still occur. For example, a case was reported by Tianguang HVDC transmission system in China on 28th Jan 2007. During the course of manipulating the pole 1 from the stand-by state to the blocking state, the differential protection of the converter transformer on pole 1 mal-operated and the circuit breaker was opened after the converter transformer was energized. According to the subsequence of event (SOE), it is a typical mal-operation of the differential protection of the converter transformer resulting from the magnetizing inrush [7]. The mal-operation of the 2nd harmonic restraint based transformer protection postponed the restoration of the HVDC transmission system. By virtue of the phenomenon of above field report and the characteristics of converting stations, we conjecture that the inrush waveform of the converter transformer may change compared to that of the conventional

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transformer owing to the existences of AC and DC filters together with the influence of the core saturation. In this case, the 2nd harmonic characteristic may be impaired and the mal-operation is much easier to take place for the converter transformer. This point of view will be verified by the simulation analyses in this paper.

On the other hand, due to the particularity of the operating environment of the converter transformer, the differential current may contain quite high 2nd harmonic component in the case of asymmetric internal faults. As the author of [8] guesses that the negative sequence component in the AC voltage may produce the 2nd harmonic component in the AC power network side of converting valves due to the interaction between AC and DC systems, which may consequently result in the unnecessarily blocking of the differential protection. However, this assumption in [8] has not been verified by tests. All in all, it is still necessary to further verify the effectiveness of the 2nd harmonic restraint criterion applied to the differential protection for the converter transformer in the HVDC system.

The models of unloaded energization and internal faults of the converter transformer are established based on Chusui HVDC transmission system in this paper. Then, the characteristics of the differential currents during unloaded transformer energization and internal faults are analyzed. Furthermore, the operation performance of the 2nd harmonic restraint based differential protection for the converter transformer is evaluated. By virtue of RTDS based simulation analyses, it can be confirmed that the 2nd harmonic restraint criterion is not completely appropriate when it is applied to the differential protection for the converter transformer. For the purpose of achieving the reliable protection for the converter transformer, a novel criterion utilizing the time difference between the superimposed phase voltage and differential current to discriminate between magnetizing inrushes and fault currents is proposed. The effectiveness of the proposed criterion is validated with extensive simulation tests.

Recurrence and analysis of the reported abnormal operations of the differential protection of the converter transformer

Simulation model of HVDC system

The magnetizing currents and internal fault currents of the converter transformer in the HVDC system are investigated based on the Chusui HVDC transmission system. The complete HVDC structure diagram and equivalent system model is shown in Fig. 1. The equivalent systems presented in Fig. 1 are Thevenin equivalent circuits of which the impedances and the source voltage values are constants. When studying the issue of protection, only the electromagnetic transient stage of the system behavior is needed to be taken into account. And the time window for a protection scheme is usually in a scale of milliseconds. Generator parameters merely change in this time scale. Therefore, the dynamic equivalent power system is unnecessary from the point of view of fast protection study. For the Thevenin equivalent circuit with constant voltage source, the short-circuit capacity of sending power system and the receiving power system are used to express system parameters, as indicated in Table 1.

The investigated fault location and measurement points are shown in Fig. 2. The protected zone of the differential protection of converter transformer is divided into three parts. The zone between CT3 and CT4 is protected by the differential protection DP1. The part between CT6 and CT7 is protected by the differential protection DP2 and the public zone protected by the differential protection DP3 is between CT1, CT2 and CT4, CT7. In line with the conventional setting criterion, the pickup threshold of the differential protection is set as 0.25 p.u., and the ratio of 2nd harmonic restraint is set as 15%. Unloaded transformer energization, single-phase-to-earth faults, two-phase(to earth) short-circuited faults and three-phase (to earth) short-circuited faults on the secondary side of the converter transformer are simulated. DC current sources are adopted to simulate the remanence of the transformer core in the case of simulations of magnetizing inrushes, and various internal faults on the secondary side of the transformer are simulated by means of adding fault modules (see Table 2).

Analysis of mal-operation of DP1, DP2 and DP3 during unloaded energization of converter transformer

Unloaded transformer energization with various inception angles and remanences are simulated in this part. In view of the length limit, only two of the scenarios of the 2nd harmonic restraint criterion fail-to-block are illustrated as below. In actual operation of the transmission system, T1 and T2 will be simultaneously removed if any one of DP1, DP2 and DP3 trip.

Scenario 1: Mal-operation of DP1 and DP2 during unloaded energization of converter transformer T1 accompanied by T2 on operation.

Suppose that the simulation duration lasts for 0.75 s and the T1 and T2 are both energized at $t = 0.2634$ s, which means the inception angle of phase A is 60°. The remanences of three phases of transformer core are 0.7 p.u., 0 and −0.7 p.u. respectively.

The waveforms of difference current are shown in Fig. 3. The concrete analysis is shown in Fig. 4, in which the magnitudes of fundamental component and second harmonic component of differential currents are extracted by DFT algorithm. As seen from

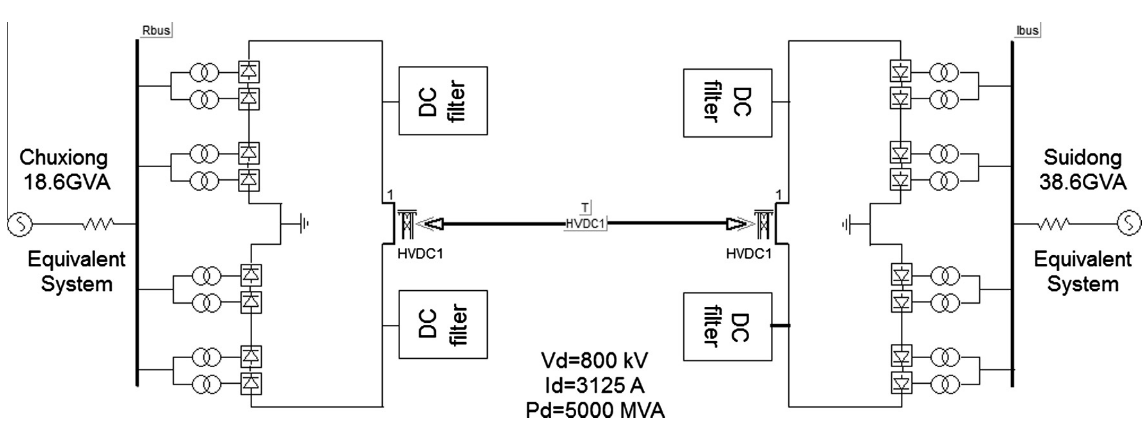

Fig. 1. HVDC structure diagram and equivalent system.