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Transformer differential protection with phase angle difference based inrush restraint

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ABSTRACT

A new technique for blocking the operation of the transformer differential relay when subjected to magnetizing inrush current is presented in this paper. The relay differential and restraint currents are calculated first, and the fundamental-frequency components of the two currents are then compared to identify the phase angle difference (PAD) between the corresponding transformer primary and secondary currents. Distinguishing the magnetizing inrush current from an internal fault current is accomplished by the presence of more than 90° phase shift between the two currents during internal faults, and the absence of this in the case of magnetizing inrush and unfaulted transformer currents. This technique is investigated using an EMTP-RV simulation based model of a typical 3-phase 2-winding power transformer embedded in a power system fed from both ends. Results have confirmed that the PAD principle is capable of categorizing transformer operating modes within a cycle of the power system frequency. Also, the relaying decision is unaffected by current transformer (CT) saturation effects.

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1. Introduction

Differential protection is the typical solution for protecting a power transformer against winding faults due to its selectivity, high sensitivity and fast response. Although the performance of this type of protection is quite satisfactory in most respects, some concerns remain about its tendency of 'false' tripping on magnetizing inrush currents [1–3]. Such currents could not only reach ten times the magnitude of the transformer nominal current, but also they flow in one winding that is being energized. Therefore, they are seen by the differential relay as an internal fault current and make the relay susceptible to mal-operation. One standard solution to this problem is to block the relay operation depending on the harmonic content in the differential current. The second-harmonic component of the inrush current is significant and much larger than in a fault current. Numerous schemes based on the ratio of the second harmonic to the fundamental-frequency component have been proposed and implemented in numerical differential relays with good results [4–6].

However, second harmonic based relay was reported to mal-operate in some cases [7,8]. First, it would not operate on internal fault currents comprising of a high percentage of second harmonics. This could occur as a result of CT saturation, parallel capacitance for adjusting the load phase angle, distributed capacitances of long transmission lines to which the transformer is connected, or flexible ac transmission systems (FACTS) to control power flow. The other scenario is that a modern transformer, with low-loss amorphous core materials, produces lower harmonic contents in magnetizing inrush currents, which increases the likelihood of false tripping.

There are several effective ways of avoiding malfunction of the differential protection on magnetizing inrush currents [9–13]. One way is to establish the phase voltage as a control signal, where a fault on the protected transformer is characterized by a remarkable decrease in the terminal voltage. Another way is to employ core-flux or transformer equivalent circuit for identifying inrush from internal fault currents. Overall successful application of these methods depends on measuring the transformer terminal voltage which adds more cost. Moreover, computational burden on the differential relay would be increased and, hence, lead to slower response on winding short circuits.

Advanced digital signal processing approaches have also been proposed to avoid the differential relay operation on magnetizing inrush currents. They are based on pattern recognition techniques using artificial neural networks [8,14–16], fuzzy logic [17,18], wavelet transforms [19–21], and principal component analysis [3,22]. These approaches have limitations that may affect their

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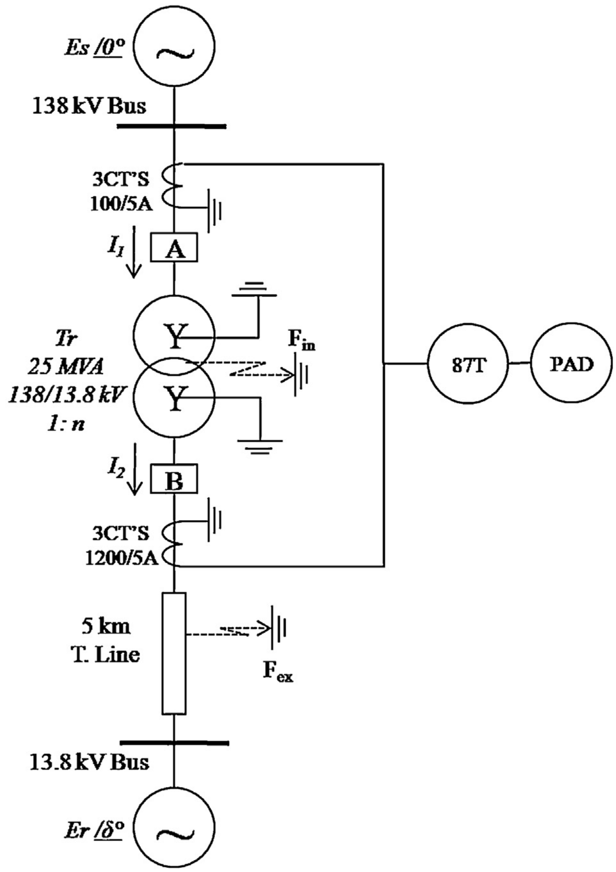

Fig. 1. Power system with percentage differential relay and PAD scheme.

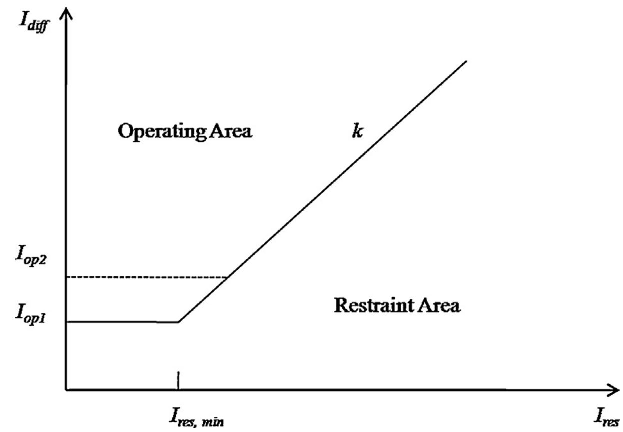

Fig. 2. Percentage differential characteristics.

speed of operation, dependability and security. They also require complex computations and are susceptible to changes in transformer parameters.

Because magnetizing inrush currents have a highly negative impact on the differential protection performance, there has been an interest in developing a fast and reliable technique to mitigate their effects. The work reported here is a demonstration of that the phase angle difference (PAD) between corresponding line currents can be used as an alternative algorithm to discriminate magnetizing inrush current from internal faults in power transformers. The PAD calculations are adapted so that the computational burden does not slow down the operation of the transformer differential relay. The effectiveness of the new algorithm is proved by simulated current signals of a power transformer subjected to different operating modes.

2. Methodology

2.1. Power system and differential protection configuration

A single-line diagram of the power system used in this study is illustrated in Fig. 1. It comprises an equivalent system of transmission network $E_s/0^\circ$, typical 3-phase power transformer *Tr*, short transmission line, circuit breakers A and B, and an equivalent (reduced) system of a distribution network E_r/δ°. The transformer is connected in Y/Y with grounded neutral, with rated capacity of 25 MVA and rated voltages of 138 kV/13.8 kV. The high-voltage (HV) windings are fed directly from the source while its low-voltage (LV) windings are linked to the distribution network through the transmission line. For metering and relaying purposes, two sets of current transformers (CTs) are provided at both sides of the power transformer. Each set consists of three CTs whose secondary windings are connected in star and the star point is solidly grounded.

The power transformer is equipped with a percentage differential relay whose characteristic is shown in Fig. 2. The minimum operating current is chosen to be adjustable to prevent malfunction at over-excitation conditions. The parameters used in the percentage differential characteristic are given as follows [1],

I_{diff} magnitude of 60 Hz component of differential current;
I_{res} magnitude of 60 Hz component of restraint current;
I_{op1} minimum operating current, I_{op1} = 0.2 pu;
I_{op2} adjusted minimum operating current, I_{op2} = 0.3 pu;
$I_{res,\,min}$ minimum restraint current, $I_{res,\min}$ = 0.6 pu;
k slope of the operating characteristic, =0.2.

The current transformers on each side of the power transformer are connected in such a way that the relay differential currents are calculated as the difference between corresponding line currents. For instance, the magnitudes of 60 Hz components of the 3-phase differential currents for a power transformer with transformation ration 1:*n* are given as,

$$\begin{cases} I_{diff,A} = \left|\vec{I}_{1,A} - \vec{nI}_{2,A}\right| \\ I_{diff,B} = \left|\vec{I}_{1,B} - \vec{nI}_{2,B}\right| \\ I_{diff,C} = \left|\vec{I}_{1,C} - \vec{nI}_{2,C}\right| \end{cases} \quad (1)$$

where $\vec{I}_{1,A}$, $\vec{I}_{1,B}$, $\vec{I}_{1,C}$, $\vec{nI}_{2,A}$, $\vec{nI}_{2,B}$ and $\vec{nI}_{2,C}$ are the secondary currents of phases A, B and C in HV-side and LV-side transformers respectively. Similarly, the magnitudes of 60 Hz components of the 3-phase restraint currents for the same transformation ratio are calculated as,

$$\begin{cases} I_{res,A} = \left|\vec{I}_{1,A} + \vec{nI}_{2,A}\right|/2 \\ I_{res,B} = \left|\vec{I}_{1,B} + \vec{nI}_{2,B}\right|/2 \\ I_{res,C} = \left|\vec{I}_{1,C} + \vec{nI}_{2,C}\right|/2 \end{cases} \quad (2)$$

The fundamental-frequency components of both differential and restraint currents are the parameters of the 3-phase differential relay. The operating characteristic of one phase differential element is described by (3). The differential operating current is biased by the threshold value I_{op1} to account for the no-load current and on-load tap changer (OLTC), whereas the second inequality is to model the slope of the transformer differential relay.

$$\begin{cases} I_{diff} \ge I_{op1} \\ I_{diff} \ge k(I_{res} - I_{res,\min}) + I_{op1} \end{cases} \quad (3)$$

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