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Presenting an Adaptive Restraint Method to Improve Performance of Ground Differential Protection of Power Transformer

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ABSTRACT

The ground differential (GD) relay is used to detect internal ground faults on the power transformer windings and terminals. In fact, this relay is employed as a complement to the phase differential (PD) relay. However, its stability is affected by magnetic saturation in current transformers (CTs) cores so that the spurious differential current caused by CT saturation may lead to the relay malfunction. In this paper, by modifying the restraining current definition in a conventional method, an adaptive restrain method is proposed. To evaluate the proposed method performance compared with conventional method, a real 230/63 kV power transformer under a large number of internal fault, external fault and in rush current cases are simulated in PSCAD/EMTDC environment. It is worth noting that Jiles-Atherton (JA) model is utilized to simulate CTs. MATLAB software is used to implement and analyze these methods using obtained simulation. Obtained results show that the proposed method is quite superior to the conventional method, despite its simplicity.

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NOMENCLATURE

I_D	Differential current	I_R	Restraining current
I_n	Neutral current	I_TH	Threshold value of neutral current
I_a, I_b, I_c	Phase currents	f	Fundamental frequency

1. INTRODUCTION

Power transformers are expensive and extremely vital components of power system. Therefore, equipping them with secure, reliable, and fast protective relays to detect internal faults is very essential.

Among the protection schemes of transformers, the phase differential (PD) protection, being the most applied for transformers having ratings of 5 MVA and above [1]. However, when magnetizing inrush current passes through the power transformer windings and/or current transformer (CT) saturation occurs, a phase differential relay is prone to incorrectly operate. Hence, harmonic blocking and harmonic restraint logics have been used to improve its performance [2]. On the other hand, if the fault location is close to the neutral point of power transformer Y winding, or if the ground-fault current is restricted, this protection scheme may not be sufficiently sensitive for detection [3]. In order to overcome this issue, the ground differential (GD) protection is used as a supplementary protection method [4]. However, taking into account current transformer (CT) saturation is necessary when the adjustment of a ground differential protection and its performance are considered [5].

It is known that CT saturation is usually caused by the fault and magnetizing inrush currents, due to the high amplitude of current, the slowly decaying direct current (DC) component, and the CT core remanent flux [6]. It must be noted that the presence of the slowly decaying DC component in the primary CT current may lead to CT saturation, even if the primary current value is not high [7].

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CT saturation effects can be decreased by the proper dimensioning but are not totally eliminated [8]. High-impedance GD relays are, to some degree, resistant to CT saturation. To use these relays, some prerequisites must be met, such as the same turn ratios and the closely similar saturation characteristics with high knee-point voltage of the CTs [9]. Nowadays, numerical low-impedance GD relays are widely used. A significant advantage of low-impedance GD relays is the fact that the use of these relays does not have the same prerequisites mentioned for the high-impedance GD relays. However, if CT saturation occurs, a false differential current appears and a low-impedance GD relay may malfunction. Adaptive restraint current [10] and directional supervision [11] methods can improve this relay operation, but the malfunction is still probable in some operating conditions [12]. Recently, artificial intelligence [13] and time frequency analysis [6] have been used to develop new methods for overcoming malfunction of low-impedance GD relays, however, these methods are complex and their computational burden are high.

At present paper, a simple effective algorithm is proposed for GD relay that is sensitive to detect internal ground faults and optimally safe against malfunction. The idea behind this new algorithm is to use a new definition for the restraint current so that its value depends on the second harmonics of the phase currents and the angle between the neutral and residual currents. The rest of this paper is organized as follows: In section 2, the proposed method is introduced. Simulation results are presented in section 3. Finally, the conclusion is made at the end of the paper in section 4.

2. PROPOSED METHOD

A Y winding of power transformer is shown in Figure 1. A low-impedance GD relay uses phase and neutral currents measured by CTs, as seen in this figure, to detect internal ground faults on the winding or transformer terminal. Figure 2 shows operating characteristic of a conventional GD relay. This characteristic is based on two parameters including I_D (differential current) and I_R (restraining current). Equations (1) and (2) show how to calculate these parameters [13]:

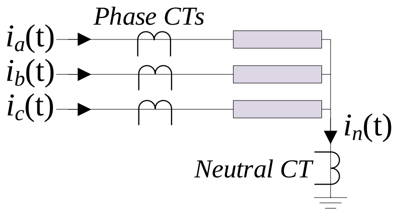

Figure 1. A sample Y winding of power transformer

$$I\_D = |I\_a + I\_b + I\_c - I\_n\,| \tag{1}$$

$$I\_R = 0.5 \times (max\{|I\_a\,|, |I\_b\,|, |I\_c\,|\} + |I\_n|) \tag{2}$$

Here, I_a, I_b and I_c are phase currents and I_n is neutral current. Although a relay with such a characteristic often has good performance, its malfunction is possible due to the deep saturation of current transformers [5]. As before mentioned, transformer inrush current and severe external faults may make CT saturate and relay malfunction. To detect the inrush current in power transformer protection, the value of the second harmonic component of the currents is compared with a predetermined value [7]. On the other hand, in some conventional GD relays, the angle between residual and neutral currents is used to avoid malfunction during external ground faults (and some inrush current cases) [14, 15]. But these methods do not guarantee malfunction prevention. In this paper, it is proposed to modify the formula for calculating the restraining current (I_R) so that this parameter increases by increasing the maximum value of second harmonic components in phase currents or decreasing the angle between the residual and neutral currents. It is notable that the mentioned angle is 0 during external fault and inrush current conditions. Equation (3) shows the modified restraining current (MI_R). As can be seen, MI_R is obtained by multiplying the restraining current by the proposed factors F_1 and F_1 which are calculated using Equations (4) and (5).

$$MI_R = I_R \times F_1 \times F_2 \tag{3}$$

$$F_1 = 1 + \alpha \times max\left\{\frac{I_a(2f)}{I_a(f)}, \frac{I_b(2f)}{I_b(f)}, \frac{I_c(2f)}{I_c(f)}\right\} \tag{4}$$

$$F_2 = 1 + \beta \times (\pi - \theta) \tag{5}$$

Here, f is the fundamental frequency and θ is the angle between residual current (summation of phase currents) and neutral current that varies 0 to π radians. Also, α and β are constants that are described in the following how to calculate them in four steps.

Step 1: it is need to simulate a large number of inrush current, internal and external fault cases of a power transformer so that the most severe conditions from CT saturation point of view are considered.

Step 2: set F2=1, for each internal ground fault case, a sliding time window with a length of one cycle must move from the moment in which $I_D = 0.1\,pu$ to one cycle later and $max\left\{\frac{I_a(2f)}{I_a(f)}, \frac{I_b(2f)}{I_b(f)}, \frac{I_c(2f)}{I_c(f)}\right\}$ at each time step must be computed. Then, the minimum of these values is saved. After we do this for all internal fault cases, the maximum of these minimum values (HR_{Mm}) is considered to find suitable value for α.

Step 3: set F1=1, for each internal ground fault case, a sliding time window with a length of one cycle must move from the moment in which $I_D = 0.1\,pu$ to one cycle later and the angle between neutral and residual currents at each time step must be computed. Then, the maximum of these values is saved. After we do this for all internal fault cases, the minimum of these maximum values (θ_{mM}) is considered to find suitable value for β.

Step 4: With assumptions $max\left\{\frac{I_a(2f)}{I_a(f)},\frac{I_b(2f)}{I_b(f)},\frac{I_c(2f)}{I_c(f)}\right\}=HR_{Mm}$ and $\theta=\theta_{mM}$ in Equation (3), the suitable values for α and β are found based on trial and error method so that all of internal ground faults be detected in first fault cycle.

Step 5: Using α and β found in before step, MI_R, and GD relay operating characteristic shown in Figure 2. The proposed algorithm shown in Figure 3 is implemented and analyzed for inrush current and external fault cases. It is seen that the new relay only activates the and operates when the neutral current (I_n) exceeds a threshold value (I_{TH}), because this current always increases during a ground fault. It is obvious that if phase currents are zero and the neutral current is higher than its threshold value, this situation can be only an internal ground fault. If malfunction number of the modified GD algorithm is significantly lower than conventional method, its efficiency will be validated.

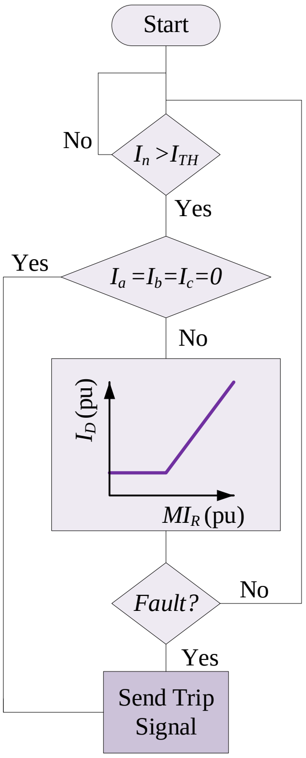

Figure 3. The modified GD algorithm

3. SIMULATION AND RESULTS

In this section, a power transformer operation is simulated under a large number of fault and inrush current condition, then the obtained results are used to implement and analyze proposed methos.

3. 1. Power Transformer Operation Simulation

As depicted in Figure 4, a part of a high-voltage (HV) substation located in Iran is chosen to study [13]. It includes 230/63 kV power transformer, a grounding transformer and CTs. Tables 1 and 2 presents detailed information about the transformers. It should be noted, Jiles-Atherton (J-A) model is used to simulate CTs. All simulations are done by PSCAD/EMTDC software package and obtained results are saved to use for implementing and analyzing the proposed method in MATLAB environment.

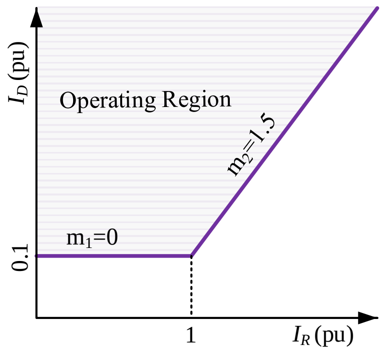

Figure 2. Operating characteristic of a conventional GD relay with a recommended setting [13]

For more explanation, to have a wide range of internal ground faults, voltage source is connected to the HV terminal of power transformer while it is fully loaded. 10 points with distances of 0%, 10%, …, 90% of winding length from a Y side terminal and 11 points distributed uniformly on the one phase winding of Δ connection between its middle and the terminal, are considered as fault locations. For each location, fault resistance has three different values. The lowest is 0 Ω and the highest is adjusted to obtain the lowest detectable fault current (I_D=10 %) and the third value is between them. Also, 11 points in a time cycle are chosen as fault occurrence time. On the other hand, -85%, 0% and +85% of rated flux are used for the remnant flux of CTs. In total, 1053 internal ground faults are simulated.

For external faults, 880 cases are simulated which includes line-to-ground (L-G) faults, line-to-line (L-L) faults, line-to-line-to-ground (L-L-G) faults and three-phase (L-L-L) faults. These faults have very low resistance to saturate CTs. On the other hand, two scenarios are considered for fault locations. In the first scenario, they locate on the Y side (F3) while the voltage source is connected to Δ side terminal and the power transformer is fully loaded. In the second scenario, the faults locate on the Δ side (F4) while and the voltage supply is connected to Y side terminal and the power

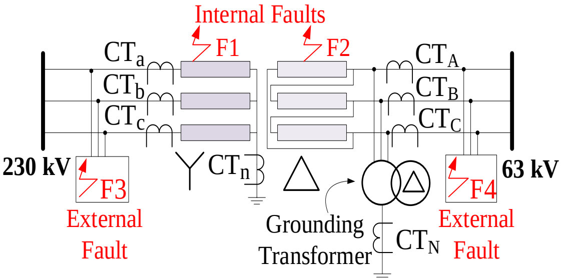

Figure 4. The power system under study

TABLE 1. Parameters of CTs

Technical Data	HV side CTs	LV side CTs
Rated primary current	600 A	2000 A
Rated secondary current	1 A	1 A
Magnetic path length	84.8 cm	54.8 cm
Core cross section area	32.9 cm^2	10.36 cm^2
CT winding resistance	4.3 ohm	7.77 ohm
Total burden	30 VA	30 VA

TABLE 2. Power transformer specifications

Technical Data	Rated Value
Rated power	160 MVA
HV rated voltage	230 kV
LV rated voltage	63 kV
Short-circuit impedance	14 %
No-load losses	0.06 %
Copper losses	0.2%

transformer is fully loaded. Residual flux of CTs and fault inception time are considered similar to internal fault simulations.

To study inrush current conditions, the unloaded power transformer is energized from both sides, separately. It should be noted that the switching angle varies with step size of 7.2o between 0o and 360o. The remnant flux is set -85% or +85% of nominal value for power transformer and CTs. All in all, 510 simulation cases of inrush current are provided.

3. 2. Finding α and β

As explained in section 2, HR_{Mm} and θ_{mM} have been computed 0.1128 and 2.09 rad, respectively. Using these values, α and β have been found 2.4823 and 0.2669, respectively. It is worth remembering that trial and error method has been used to find the suitable values for them. As before mentioned, if the use of these values for implementing the proposed method leads to a significant improvement in the relay safety, the validity of the proposed method will be confirmed.

3. 3. The Proposed Method Accuracy Evaluation

Now, the modified GD algorithm shown in Figure 3 can be implemented. All that remains is to set I_{TH}. This parameter must be determined according to the power system condition in which the power transformer is installed. In this research, it is set to 0.01 pu as a very small value to evaluate the proposed method performance very rigorously.

Initially, three scenarios are considered to show the modified GD algorithm proper performance compared with conventional algorithm. It should be noted that the recommended setting [13] is used for both of them. The first scenario is a severe line to ground internal fault with zero resistance occurs at t=100 ms on Y side terminal when the full-load is supplied from Δ side.

The second is a severe line-to-line-to-ground external fault with zero resistance on the Δ side of the fully loaded transformer which occurs at t= 100 ms.

The last scenario is to energize unloaded transformer from Y side at t=100 ms which leads to appearing a significant inrush current. Instantaneous differential current computed for these three scenarios have been shown in Figures 5, 6 and 7, respectively. It is seen during internal fault that the differential current starts to increase just as the internal fault occurs and its wave form shape is affected by CT saturation phenomenon. As can be seen in Figures 6 and 7, differential currents appear only with the saturation of CTs during external fault and inrush current scenarios so that if the CTs was assumed to be unsaturated, differential currents would be remained zero.

Differential current trajectories of these scenarios based on both conventional and modified GD algorithms have been computed and shown in Figures 8, 9 and 10. As shown in Figure 8, differential current trajectories of both algorithms insert to operating region during internal fault with no issue so this fault is detected by them.

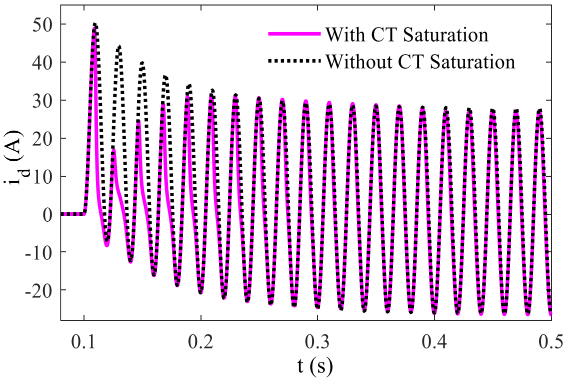

Figure 5. Differential current during internal fault

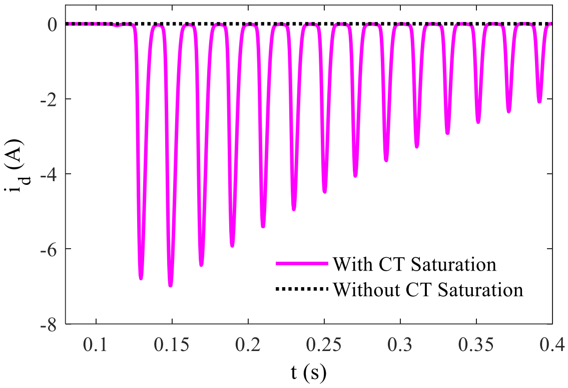

Figure 6. Differential current during external fault

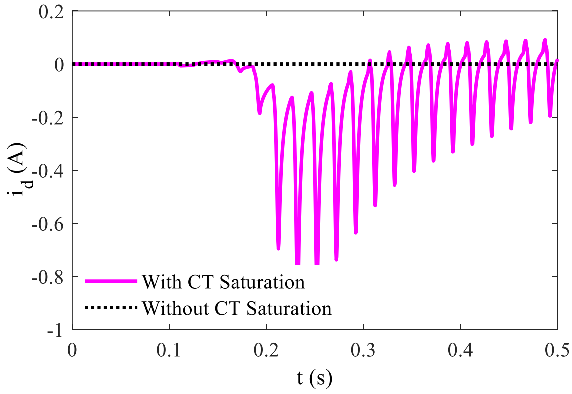

Figure 7. Differential current during inrush current

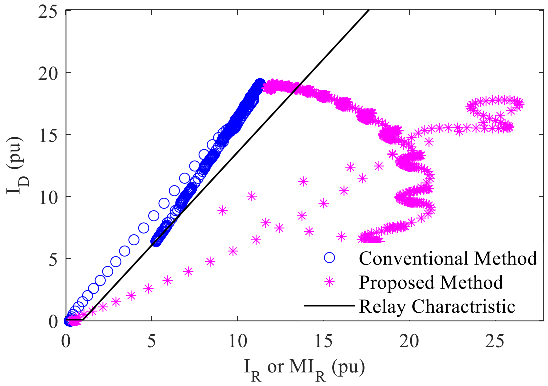

Figure 8. Differential current trajectory during internal faults

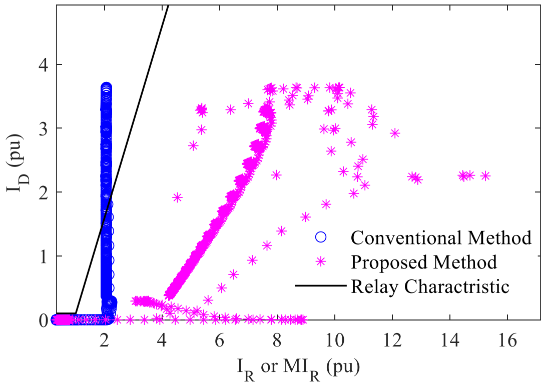

Figure 9. Differential current trajectory during external fault

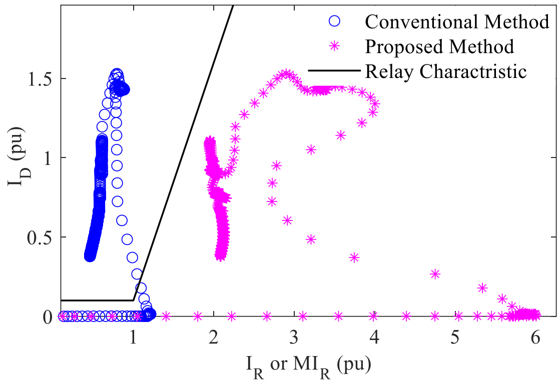

Figure 10. Differential current trajectory during inrush current

According to Figures 9 and 10, differential current trajectories computed based on conventional algorithm insert to operating region that means malfunction during external fault and inrush current scenarios while these figures show that the modified algorithm is stable for both critical scenarios.

To have a comprehensive assessment, both conventional and proposed methods performances have been evaluated for all simulation cases illustrated in section 3.1 and Table 3 presents the obtained results. According to this table, both methods detected all 1053 internal ground faults with no issue. However, the conventional method was not stable during 203 external faults but this number is 0 for the proposed method. On the other hand, the malfunction numbers of conventional and proposed methods for inrush current cases are 47 and 5, respectively. Based on these results, the overall accuracy of the conventional method is 89.76%; however, it is 99.79% for the proposed method. This means that the accuracy and stability of the proposed method is quite superior to the conventional method, despite its simplicity.

TABLE 3. Comparison results of two methods

Method	# of misoperation for 1053 cases of internal fault	# of malfunc. for 880 cases of external fault	# of malfunct. for 510 cases of inrush current	Total Accuracy (%)
Conv. Method	0	203	47	89.76
Proposed Method	0	0	5	99.79

5. CONCLUSION

Ground differential relay may not be stable during external fault and inrush current conditions if CTs are saturated, deeply. Hence, it is important to develop methods to improve the stability of this relay. In this relay, the restraining current definition in a conventional method has been modified so that an adaptive restrain method has been obtained. The new method performance has been analyzed compared with the conventional method based on a heavy simulation study. The obtained results show that:

- The accuracy and stability of the proposed method is quite superior to the conventional method, despite its simplicity.
- There are no assumptions about the power transformer of CTs nominal values in designing the proposed method so it is a general method similar to conventional method.
- The authors would propose to design GD relay algorithms based on operating characteristic curve with adaptive slopes, in next research works.

6. AKNOWLEDGEMENT

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Persian Abstract

چکیده

رله دیفرانسیل زمین برای آشکارسازی خطاهای داخلی زمین روی سیم پیچ و ترمینال های ترانسفورماتورهای قدرت استفاده می شود. در واقع، این رله به عنوان مکمل رله دیفرانسیل فاز بکار می رود. با این حال، پایداری آن متاثر از اشباع مغناطیسی در هسته های ترانسفورماتورهای زمین است بطوریکه جریان دیفرانسیلی کاذب ناشی از اشباع ترانسفورماتورهای جریان ممکن است باعث عملکرد اشتباه این رله گردد. در مقاله پیش رو، با اصلاح تعریف جریان مقاوم کننده در یک روش متداول، یک روش مقاوم کننده تطبیق پذیر ارائه می شود. برای ارزیابی کارایی روش پیشنهادی در قیاس با روش متداول، یک ترانسفورماتور قدرت واقعی با نسبت تبدیل 230/63 kV تحت تعداد بزرگی از موارد خطای داخلی و خارجی و همینطور جریان هجومی، در نرم افزار PSCAD/EMTDC شبیه سازی می شود. قابل بیان است که مدل جیلز اثرتون برای شبیه سازی ترانسفورماتورهای جریان استفاده می شود. پیاده سازی و تحلیل روش های مذکور با ستفاده از نتایج حاصله، در محیط نرم افزار MATLAB انجام می پذیرد. نتایج حاصله، علی رغم سادگی روش پیشنهادی برتری کامل آن را در مقایسه با روش متداول نشان می دهد.