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Performance Evaluation of Percentage Differential Relays on Power Transformer and Reliability Assesment in HVDC Grid Protection Scheme

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***Abstract*—Percentage differential relays remain the most sensitive protection tool applied as backup protection on power transformers, busbar, and generators. Relays sometimes do mis-operate with the current transformer being affected by external fault leading to saturation, and the subsidence current present after clearing external faults. The cause of mis-operation of percentage differential relays cannot be ignored that it entirely depends on magnitudes more than directionality for tripping decisions. This paper covers evaluating differential element performance, analysis of transformer inrush current, internal faults, external faults, and overexcitation conditions. The accurate computing of current transformers is also included. This protection only applies to 10MVA and above on transformers; however, it is not limited to transformers, but also transmission lines, busbars, and generators. The balance of the paper is on reliability assessment based on the HVDC grid protection scheme operation.**

Keywords—Differential relays, inrush currents, power transformer, current transformers, percentage restrained relay.

I. Introduction

A transformer's internal condition must be constantly monitored in real-time so that a circuit breaker connected directly to the malfunctioning transformer may be quickly shut off (more precisely, a whole windings short or a winding turn-to-turn short)[1], [2]. Due to the strong external fault, the standard bias differential relay may fail, rendering it unreliable for significant transformer protection. As a result, it is critical to enhance the overall reliability and stability of the percent bias differential system in the presence of external flaws and harmonic inrush current. Current differential protection has been most employed main safeguards for electrical systems.

C. H. Merz and B. Price's initial 1904 proposal [2] for this concept has stayed mostly constant since then, even though implementations, notably restraint levels or bias currents, have taken on a range of forms. When it comes to identifying an internal issue based on the percentage difference criterion, reliability will be the most critical factor to examine. As a result, a lesser restraint current will be required. When the differential protection is exposed to an external failure, it is better to raise the limiting amount, as security becomes the primary concern [3].

II. Overview of Fundamental Principles

It is useful to discuss differential relay function, and their applications for bus differential protection. Similarly, the use of current transformers (CT) and causes of saturation in CTs. With this background, we can focus on percentage-restrained differential relay and it's use bus applications[4].

A. *Differential relays*

The term "differential" relaying refers to any relay that uses the difference between the total of all the currents entering and exiting the protected zone. Transformer differential relays are in three categories[4]:

- Differentially overcurrent relay (Instantaneous or Inverse time).
- Percentage restrained differential relay.
- High impedance differential relay.

When choosing a protection system, protection engineers assess a number of factors, e.g. cost, complexity, reliability, and performance. Protection specialists seek performance characteristics such as selectivity, sensitivity, and speed [5],[6]. Because of its excellent selectivity, differential protection is often used in bus security. The total input and output current of a power transformer is measured. It is vital to know the exact placement of the CTs in order to correctly define the protective area. An intentional time delay is not required for a differential relay with a high degree of selectivity, to function in conjunction with other relays. As a result, differential protection may give reasonably fast performance. Differential relays are available in a number of configurations. Each has a unique ultimate speed, selectivity, and sensitivity[7].

Another outstanding feature of differential relays is their high sensitivity. Instead of the through current in the system, the relay works on the differential current in the system. As a result, it may be much more sensitive than an overcurrent relay, which must be installed in the primary and secondary side the transformer [8].

B. *Percentage restrained differential relay*

For operating current versus restraint current, the "slope" is sometimes expressed as a percentage. When the operating current to restraint current ratio exceeds the slope, the relay opens. Because they must have an operational current greater than a specified percentage of the restraint current, relays can survive slight mismatches in the current measurement at zone borders. The relay can also withstand CT saturation-induced erroneous differential current thanks to the same functionality. Most differential percentage-restrained relays can compensate for variations in steady-state current measurement hence mismatches are rare. The approach utilized to compute the restraint current determines the

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percentage of operation to constraint. One of three approaches may be used to compute the restraint current [9]:

- Summation - Due to the polarity of each input, summation relays tend to accumulate faults from the outside while subtracting them from the inside. With equal sources on both circuits, an external fault will have a restraint that is double the current measured by each relay input in a simple two-restraint circuit with two restraint switches. Internal defects will negate both currents, resulting in a restriction equal to the current measured by the relay multiplied by zero[10].
- Averaging: This is used to manage power in the average restraint relays, which is obtained by multiplying the total current by the number of input circuits: (or sometimes divided by two). If both circuits have equal sources, an external fault will be limited by half of the total input current recorded by each relay in a basic two-restriction circuit with equal restrictions. Only half of the relay's total observed currents may be attributed to internal issues[11].
- Maximum: When a maximum restraint relay is used, the magnitude of each input's current is measured and used as the constraint amount. In the case of an equal-source, two-restraint circuit, an external fault will be restrained by one time the current recorded at each relay input. If the fault is internal, there will be a restriction of one time the maximum current measured by the relay[10].

For the relay, the "average" constraint idea is what we're looking at in this case. By dividing the magnitude of the currents entering and exiting the protective zone by two, the limitation is computed. Percent-restraint qualities fall into two categories [12]:

- Percentage in its pure form.
- Varying proportion.

Fig. 1 illustrates a simple straight line percentage, which is a common representation of a dual slope. This kind of relay's slope must be changed to account for both mismatch current and CT saturation. When there are accuracy issues that would result in poor ratio measurement, the minimum pickup line provides a cut off of the characteristic at low levels where it would otherwise be present, preventing the characteristic from being measured[13].

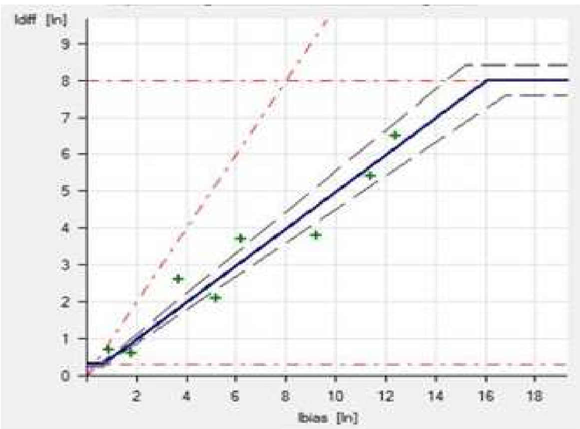

Fig. 1. *Dual Slope Characteristics of differential relay.*

For improved sensitivity to low-level defects at low restraint current levels, a smaller percentage of differential current is needed when the restraint current is variable percentage. CT saturation, on the other hand, may become an issue at high levels of restraint current, necessitating the use of a greater proportion of differential current. This is especially useful for transformer protection, because low-level mistakes are more prevalent than higher-level defects[7].

C. *Current transformer overview*

There are at least two windings on a transformer, and the iron core is the center of attraction. During normal operation, the varying current flowing through the coils generates varying magnetic flux. Because of the iron core, magnetic flux is dispersed uniformly to the windings (proportional to the magnetic flux). Aside from that, the coils' voltages each turn must be equivalent[8].

Magnetic core material has the well-known B-H curve feature.

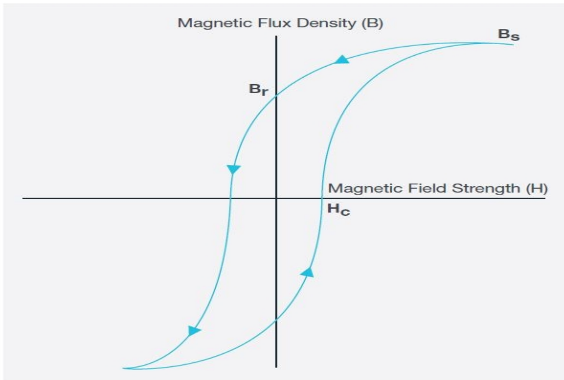

Fig. 2. *B-H Curve*[6].

III. Methodology

This is a project that Eskom completed at Ulundi on a star/delta (Yd1) transformer. The goal was to commission differential protection as well as investigate the effects of phase shift, the efficacy of the percentage restraint relay, the harmonic restraint element, and internal and external fault behavior. The whole project was completed using the 88/22KV, 20MVA transformer, which was modelled using quickset software.

A. *Phase Shift Compensation.*

The first task is to analyze the phase shift of a power transformer. Three-phase differential currents in phase-shifted transformers may be rather significant when computed only from sampling main and secondary currents under normal operating circumstances. This may result in the creation of an inaccurate trip signal. To account for the transformer's intrinsic phase shift, all sampled currents on one side (for example, the secondary side) may potentially be rotated by the phase-shift angle. The rotation must also be in the opposite direction to keep the rotating currents in phase with the currents on the other side.

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$$I_1=\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad I_2=\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad C.I_2=\begin{bmatrix} I'_A \\ I'_B \\ I'_C \end{bmatrix} \tag{1}$$

Fig. 3 shows a simpler transformer setup with leading phase-shift. It contains three main and secondary windings in this application. Each main winding has one delta winding (coils with Nd turns) and one extended winding (coils with Nd turns) (another set of coils having Ne turns). To achieve phase shift, each delta winding is connected to an extended winding. There are also three delta windings on the main side. There are Ns twists in each secondary winding. A three-phase alternating current (AC) supply is used on the primary side, and a three-phase load is anticipated on the secondary side(2)[14].

$$\begin{bmatrix} I_{w1-A} \\ I_{W1-B} \\ I_{W1-C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{W1-Z} \\ I_{W1-P} \\ I_{W1-N} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} I_{w2-A} \\ I_{W2-B} \\ I_{W2-C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{W2-Z} \\ I_{W2-P} \\ I_{W2-N} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} I_{d,A} \\ I_{d,B} \\ I_{d,C} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{d,Z} \\ I_{d,P} \\ I_{d,N} \end{bmatrix} \tag{4}$$

To denote the three phases of a three-phase primary current, we use the following terminology: $I_{W1,A}$, $I_{W1,B}$, $I_{W1,C}$; $I_{W2,a}$, $I_{W2,b}$, $I_{W2,c}$ and $I_{d,A}$, $I_{d,B}$, $I_{d,C}$ Currents in the zero, positive, and negative sequences are denoted by $I_{W1,Z}$, $I_{W1,P}$, $I_{W1,N}$; $I_{W2,Z}$, $I_{W2,P}$, $I_{W2,N}$ and $I_{d,Z}$, $I_{d,P}$, $I_{d,N}$. On the main side, primary-side CTs detect three-line currents (I_A, I_B, and I_C), which may be abbreviated for convenience. The findings given in fig.4 and fig. 5 are the representative of the current flowing through the main and secondary CT with complete various phase shifting of the transformer[15].

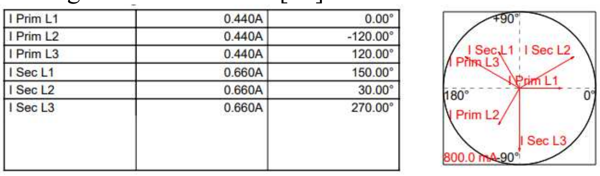

Fig. 3. *Primary side phase shift.*

Fig. 4. *Practical phase shift.*

B. Inrush Current

When the transformer was activated, there was very certainly a significant inrush current, maybe ten times the full load current. However, even though inrush currents are often rich in harmonics with an even number of predominant second harmonic harmonics, the energized transformer is a very contemporary design with core materials intended for low loss that generates very few harmonics. As a result, standard harmonic blocking and harmonic restraint techniques are ineffective. Using the wave shaped based inrush detection element, a dwell time method is employed to identify inrush scenarios with low second and fourth harmonic content[16].

Each phase magnetizing current is separated by a succession of brief, flat intervals. This is seen in fig 3. The dwell time approach detects transformer inrush by monitoring the percentage-restricted differential elements during this brief, flat period. Even if they have four or five legs, three-phase transformers constructed from single phase components still have a dwell duration in each phase. Therefore, the dwell time algorithm requires information about the transformer topology from the 87CORE configuration before the necessary logic can be engaged[13].

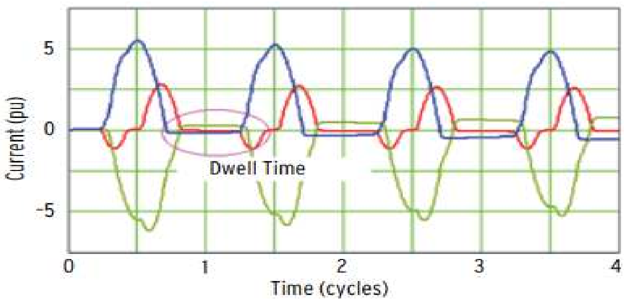

Fig. 5. *Three phase dwell times magnetizing currents.*

C. Harmonic restrained element

The differential harmonic restraint test was run to make sure the relay was blocking the second and fifth harmonics correctly. It was found to be accurate. The harmonic relay function/element distinguishes this current from a fault state by suppressing the inrush current, over fluxing, and over-excitation during the activation of the power transformer. The results in Fig. 7 illustrate that the second harmonic restraint element effectively blocks excessive inrush current. This exists for a brief duration for the relay to discern between fault current and inrush current[17].

TABLE I. 2[ND] HARMONIC TEST

Idiff.	Ixf/Idiff	Angle (Ixf, Idiff)	Trip	State	Result
4,50 I/In	9,30%	-120 degree	Yes	Tested	Passed
1,60 I/In	13,00%	-120 degree	Yes	Tested	Passed
6,20 I/In	12,20%	-120 degree	Yes	Tested	Passed
3,70 I/In	13,10%	-120 degree	Yes	Tested	Passed
5,50 I/In	17,10%	-120 degree	No	Tested	Passed
4.00 I/In	16,90%	-120 degree	No	Tested	Passed
1,90 I/In	17,20%	-120 degree	No	Tested	Passed
3,30 I/In	16,90%	-120 degree	No	Tested	Passed

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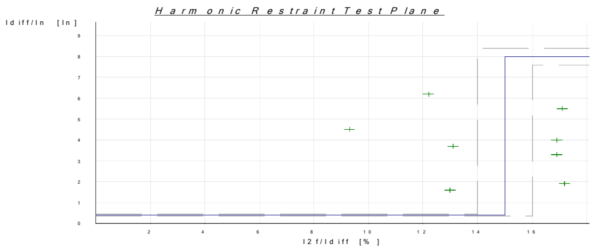

Fig. 6. 2nd *harmonic restrained element*

TABLE II. 4TH HARMONIC TEST

Idiff.	Ixf/Idiff.	Angle (Ixf, Idiff)	Trip	State	Result
1.90 I/In	8,20%	-120 degree	Yes	Tested	Passed
4,20 I/In	8,00%	-120 degree	Yes	Tested	Passed
6.00 I/In	8,00%	-120 degree	Yes	Tested	Passed
7,20 I/In	7,90%	-120 degree	Yes	Tested	Passed
1,20 I/In	11,50%	-120 degree	No	Tested	Passed
3,50 I/In	11,30%	-120 degree	No	Tested	Passed
6,50 I/In	11,20%	-120 degree	No	Tested	Passed

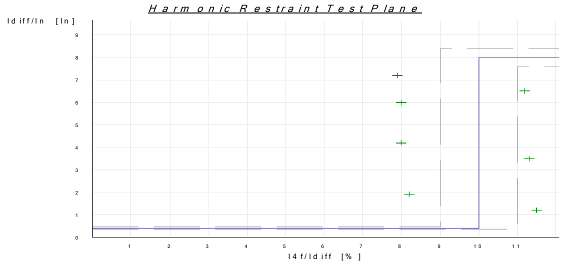

Fig. 7. 5th *harmonic restrained element*

TABLE III. 5TH HARMONIC TEST

Idiff.	Ixf/Idiff.	Angle (Ixf, Idff)	Trip	State	Result
1,50 I/In	29,50%	-120 degree	Yes	Tested	Passed
3,90 I/In	29,00%	-120 degree	Yes	Tested	Passed
6,10 I/In	29,10%	-120 degree	Yes	Tested	Passed
6,30 I/In	39,30%	-120 degree	No	Tested	Passed
3,80 I/In	40,40%	-120 degree	No	Tested	Passed
1,30 I/In	40,40%	-120 degree	No	Tested	Passed

IV. Results

This results are for an overcurrent relay placed at a differential possition to pickup any differential current between primary and secondary. Fig.9 to 12. Illustrate time taken by a relay to operate, time delayed and the circiut breker operating time.

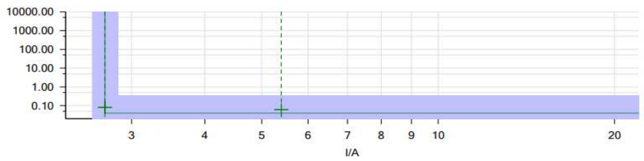

Fig. 8. *line A.*

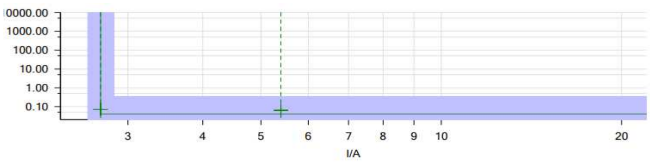

Fig. 9. *line B.*

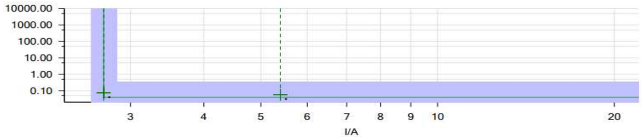

Fig. 10. *line C.*

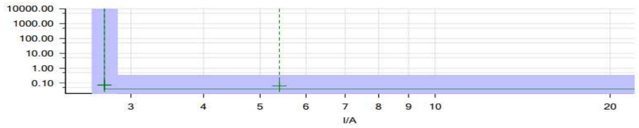

Fig. 11. *Line A-B-C.*

For example, the overcurrent relay in differential position with a time delay is shown in figures 13 to 16.

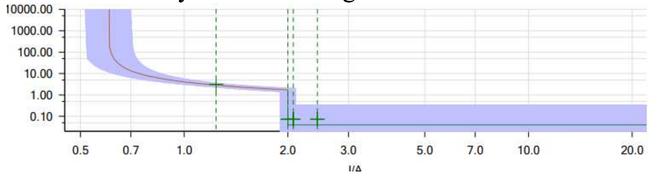

Fig. 12. *line A*

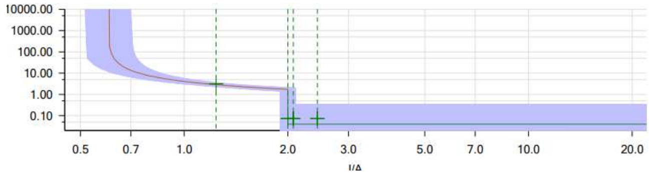

Fig. 13. *line B*

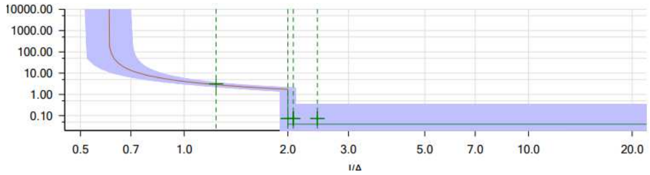

Fig. 14. *line C.*

V. Future Work

A. HVDC grid protection scheme

Considering the principles of both, alternating current (AC) and direct current (DC) grid protection systems apply similar techniques in that DC grid protection philosophy provides a strategic or critical period in the DC grid to instantly disengage faulted parts to a least possible disturbance. To ensure protection on DC grid against known faults, it is important to foresee that overcurrent protection is the actual major protection system and differential protection enforced as a backup protection system. The overcurrent protection function has DC measuring devices. There will be no difference to AC measuring devices as they are also detecting current above the predefined level; the measuring devices will trigger the HVDC circuit breaker to disconnect the system from further damage. Due to the nature of overcurrent protection, the differential protection to be implemented will be with non-ground fault as it is taken from the overcurrent protection system. The differential protection will then compare the currents from both sides (measurement) supplied but a

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couple of DC measuring devices placed on both sides of power equipment[18].

Various possible DC measurement methods can be used instead of CT applied in the AC network system, the inline measurement. The current method can be possibly transferred through fiber optics or infrared; this provides physical disengagement among the current display or protection relay. For the HVDC grid differential scheme, it can only be achieved or automated by applying a program admitted as energy reliability calculations (DEREL), the output DC will be 5A DC. This program (DEREL) was developed in the process of automation study of energy on reliability calculations of HVDC grid. The DEREL program associate with the following processes:

- Contingency depth
- Contingency duplication
- Minimal cut-sets

Contingency depth -This type of depth specifies to hierarchical level taken on reliability assessment. The hierarchal level refers to the grid system areas considered for reliability assessment: those zones, namely, power generation, distribution, and transmission[19].

Contingency duplication- The contingency duplication refers to identifying and select network states, which ends in similar results with load curtailment. All possible values need to be identified for proper curtailment in the network for accurate and satisfactory progress. They are then named critical components as they play a significant role because of curtailment. There are two ways to disconnect either by the failure of critical equipment or non-performance of other elements (components) in the grid.

Minimal cut-sets - This type of set or various network components states the cumulative exigency of which will end in load curtailment. The cut sets are resolved by physical investigation of the HVDC grid's single line diagrams with multi-protection schemes enforced[14].

VI. Conclusion

The material provided in this article provides specifics and a knowledge of the differential relays' operating principles, as well as suggested future enhancements to be explored. Touches on all techniques pertinent to differential relays for quick fault clearing. The research also discusses HVDC differential protection considerations for quick fault clearance of the faulty zone. The evaluation of three distinct factors (harmonic blocking, 2nd, and 5th harmonics). Evaluation of an HVDC grid plan in terms of the use of differential, relays, and the ease with which it may be implemented. The study discusses the quick clearing approach on an HVDC grid, as well as inrush current, external faults, and self-isolation from internal faults utilizing differential relays.

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