

Reliability Evaluation of Differential Relay as Primary Safeguard of Transformer against Short Circuit

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Abstract—A transformer is an electrical device that converts high voltage into low voltage or vice versa. The dry-type transformer used at the CHARUSAT Healthcare campus is a step-down transformer. Transformers, which are devices connected between one voltage level and another voltage level, frequently experience external interference or internal fault. Internal faults have the potential to inflict damage, as was the case in the CHARUSAT Healthcare campus System. The damage is a result of external interferences involving highly high currents. The interference resulted in internal damage, triggering the activation of all protection devices in the transformer, including the differential relay. The characteristics of a differential relay indicate that it must operate in the event of any disturbance occurring within its protected zone, which is situated between a set of Current Transformers in both the primary and secondary circuits. The operation is carried out by comparing the current between the primary and secondary. The reason for the differential relay's functionality can be determined by analyzing the setting and short circuit calculation and examining the internal relay record of the Digital Fault Recorder (DFR). Based on the calculations, it was determined that the differential relay functioned correctly with a value of 0.3 Ampere and an instant time setting. To enhance the dependability of the differential relay, which serves as the primary protection for the transformer, it is possible to activate a high set setting (12 times the rated current). This setting allows the relay to operate in the presence of high-magnitude interference.

Index Terms— Power Transformers, Protection, Differential Relay.

I. INTRODUCTION

The power transformer is a part of the electrical power system equipment that is very prone to disruption. Disturbances can occur inside the power transformer (internal disturbances) or outside it (external disturbances). Therefore, a reliable and coordinated power transformer protection system is needed.

There are various relays in the power transformer security pattern, including Over-Current Relay, Buchholz Relay, Earth Fault Relay, and Differential Relay. Because of the importance of the relay's role in a protection system, it must meet conditions such as sensitivity, selectivity, reliability, and speed [1,2]. A differential relay is an electrical device that can detect disturbances in the internal security area of energy transformers that cause a difference in current values on the primary and secondary sides of the Current Transformer.

The purpose of this research is to determine the use of differential relays for the paramount safety of the power transformer in the CHARUSAT healthcare Campus and the condition of the transformer in the Changa Substation before and after a short circuit fault. The transformer that will be discussed is a power transformer with a 1250 KVA voltage 11/0.415 KV capacity in the CHARUSAT healthcare Campus and its protection system.

II. ELEMENTS OF THE POWER SYSTEM

A. Transmission System

Electric power transmission is one of the components of the electric power distribution system. It channels electric energy from power generation centers using transmission lines to substations, which in turn distributes it to customers or consumers. Transmission lines are classified into two categories: overhead lines and underground lines. In the transmission of electricity, there are four network configuration forms: radial, single, double, and loop.

The electricity system in India, both from generation, transmission, and distribution in India uses a 3-phase system. This system is considered the most profitable because, ideally, it can transmit greater electrical power. As shown in Fig. 1, a 3-phase system is AC electricity (Alternating Current) that uses three transmitters with the same voltage but differ in phase angle of 120° . In contrast, physically, they have a difference of 60° and can be connected in star (Y, wye) and triangle (Δ , delta) [3].

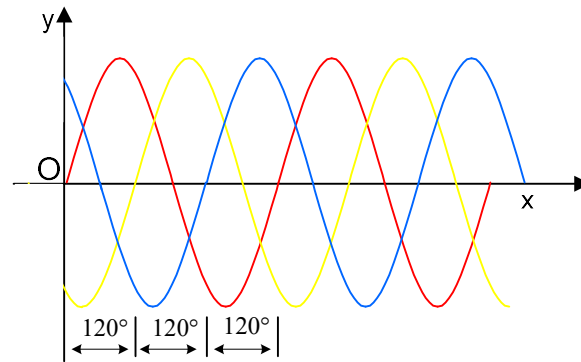


Figure 1. 3 Phase System

B. Transformer

A transformer is an electrical device that transfers energy from high to low or vice versa. Transformers use the principle of Faraday's law of induction and Lorentz's law in transmitting power, as shown in Fig. 2, where the alternating current that flows in the coil wound around an iron core will turn the iron core into a magnet. In addition, if a winding surrounds the magnet, then there will be a potential difference at both ends of the winding [4]. The current flowing in the primary winding will induce the transformer's iron core so that a magnetic flux will flow in the iron core, and this magnetic flux will induce the secondary winding so that at the end of the secondary winding, there will be a potential difference.

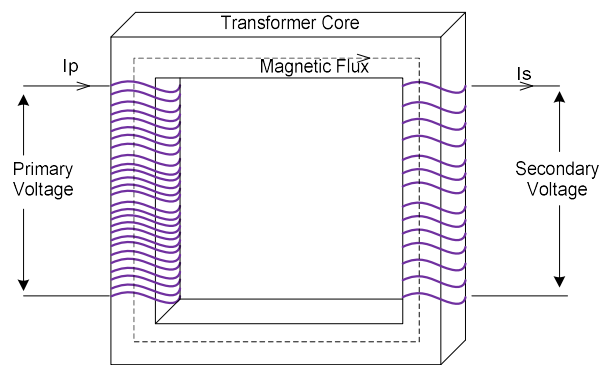


Figure 2. Transformer Working Principle

The parts of the dry-type transformer itself include:

- a. Iron core
- b. Winding
- c. Bushing

- d. Cooling arrangement
- e. Tap Changer
- f. Neutral Grounding Resistance/Reactor (NGR)

C. Disturbances in the Electric Power System

Disturbances in the electrical power system based on symmetry can be divided into two: asymmetric and symmetrical. An asymmetric disturbance is a disturbance that causes the voltage and current flowing in each phase to become unbalanced or asymmetrical. Unbalanced or asymmetrical conditions will occur due to the presence of unbalanced impedance. Calculating and analyzing asymmetric systems is done with the help of the symmetrical component method. This disorder consists of:

- a. Single Line to Ground Short Circuit Interruption.
- b. Double Line to Ground Short Circuit Interruption.
- c. Double Line/Inter-Phase Short Circuit Interruption.

A symmetrical disturbance is a disturbance that occurs in all phases so that the current and voltage of each phase remain balanced after the disturbance occurs. This disturbance is in the form of a Three-Phase/Three-Phase to-ground short circuit.

While based on the duration of the disturbance, the disturbance can be divided into 2, namely:

- a. Transient Disorder (Temporary)
- b. Permanent Disruption

D. Disturbances in transformers

Disruption in the transformer is an event that causes the transformer to not function according to its technical function. Indications of the presence of such disturbances are the operation of the alarm, the operation of the transformer safety relay (Pneumatic Timing relay trip- PMT Trip), which results in the interruption of the power supply, the appearance of signs or warnings of auxiliary relays in the form of Block signal lights/indicators, uneven measuring meters (ampere, kV), indicator lights relay, relay flag, sounds and smells [5]. Types of transformer disturbances are divided into internal and external disturbances. Internal disturbances are disturbances that originate from within the transformer itself; the disturbances can be in the form of Incipient Faults, which are minor disturbances that, if not immediately overcome, will grow. These disturbances can be in the form of arcs or disturbances in the cooling system and Electrical Faults. This disturbance is a severe disturbance that can cause damage to the transformer. This disturbance is usually directly detected by current and voltage relays. The disturbance is in the form of a short circuit between the coils, a short circuit between the coil and the transformer body, and a disturbance at the transformer terminal.

Internal disturbance in the transformer can be caused by an extensive external disturbance outside the transformer's protection area, which causes the relay in the transformer's protection area to work.

E. Transformer Protection System

The protection system is needed to protect each element of the system and secure it as quickly as possible from the interference that is occurring, thus obtaining effectiveness and efficiency. In order to obtain a sufficiently good security system in the electric power system, the electric power system has been divided into several zones of protection [6].

A protection system is a security or protection system that functions to detect disturbances or abnormal conditions in the part of the system that it secures and release the disturbed part of the system so that other parts of the system that do not experience disturbances can continue to operate and do not experience more significant damage or loss. The components of the protection system consist of:

- a. Protection Relay
- b. Current Transformer
- c. Potential Transformer
- d. DC Power Supply
- e. Lead Wiring

F. Differential Relay

Differential Relay works based on Kirchoff's current law, where the current entering at a point is equal to the current leaving that point. A differential relay is a relay whose working principle is based on balance, which compares the secondary currents of the Current Transformer installed on the terminals of equipment or electrical installations that are secured [7]. Differential relays are used as safety relays, among others, on generators, power

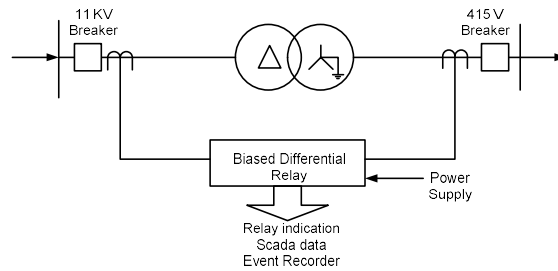


Figure 3. Protection System Equipment on 11/0.415 kV Power Transformer

transformers, bus bars, and transmission lines. A differential relay is one of the main protection tools for power transformers, and it helps secure transformer windings in the event of a disturbance. This relay is very selective, and the working system is high-speed, so it does not need to be coordinated by other relays. The differential relay works by comparing the current on the primary and secondary sides. In normal conditions, the amount of current flowing through the protected electrical equipment circulates through the loop on both sides in the working area of the differential Relay ($I_d = I_{s1} - I_{s2} = 0$). If there is a disturbance in the working area of the Differential Relay, then the current from both sides will add up, and the relay will give an order to the circuit breaker to cut off the current.

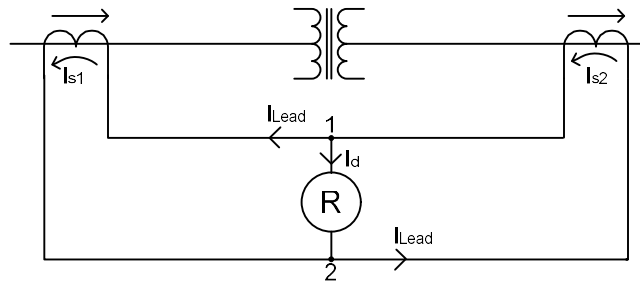


Figure 4. Essential Connection of Differential Relay

Under normal conditions, current flows through secured electrical equipment (generator, transformer, and others). The secondary currents of the current transformer, namely I_{s1} and I_{s2} , circulate through line I_{lead} . If a safety relay is installed between terminals 1 and 2, then under normal conditions, no current will flow through it. Suppose there is a disturbance outside the electrical equipment of the secured electrical equipment (external fault). In that case, the current that flows will increase, but the circulation will remain the same as in normal conditions, so the safety relay will not work for the external disturbance. In the event of disturbances outside (external) the protection area of the differential relay (outside the two current transformers), the differential relay will not work because I_{s1} and I_{s2} are equal in magnitude and opposite directions.

III. PRACTICAL APPROACH

The method used in this research is to collect secondary data in the CHARUSAT Healthcare Campus transformer. The obtained data was then analyzed using manual calculations. This research started with the breakdown of the 1250 KVA dry-type transformer at the time of the normalization of the disturbance at the Changa Substation, which caused a PMT trip with OCR-GFR Instant relay indication corresponding to a PMT 11 kV trip by Siemens 7UT613 brand differential relay with R-Y phase differential trip indication.

Based on the field tracking investigation, it was found that the cable was tangled in the outgoing panel. Because of the disruption, the transformer could not supply electricity for 7 hours due to the load-shedding process, which was hampered by the repair of the broken distribution network.

IV. RESULT AND DISCUSSION

A. Research Data

The power transformer used at the CHARUSAT Healthcare Campus is a three-phase VOLTAMP brand Continuous Service transformer with a power rating of 1250 KVA - frequency 50 Hz. When operating and

continuously loaded, the temperature rise should not exceed the standard at an ambient temperature of 55° C winding, AN cooling system, and 4.8 % impedance. The data on the nameplate of the transformer can be seen in the following table:

TABLE I. 1250 KVA TRANSFORMER DETAIL

	High Voltage	Low Voltage
Rated voltage (kV)	11	0.415
Rated Current (Amp)	65.60	1739
Line in	1R 1Y 1B	2R 2Y 2B
Neutral in	-	2N

The transformer vector group used is the vector relationship DYn11. This vector group means that the high-voltage winding is connected to the delta fashion, the low-voltage winding is connected to the star, and the neutral is solidly grounded. The phase shift is 30°. The type of busbar in the CHARUSAT healthcare campus is a double busbar, which consists of two bays.

B. Differential Relay Setting

Relay Auxiliary Terminal Settings On the 11 kV side, the nominal current of the secondary side transformer is 75 / 1 A (Secondary). On the 0.415 kV side, the nominal current of the secondary side transformer is: 2000 / 1 A (Secondary). So, the current setting pickup relay selected:

$$\begin{aligned}
 I_{NR} &= 4 \text{ INST} \\
 \text{Range} &= 10 - 40 \% \\
 I_{set} &= 0.2 \\
 R_{stab} &= 500 \\
 VA &= 1
 \end{aligned}$$

This setting was chosen based on the needs and results of realy. For the difference in current that occurs on the primary and secondary side, Differential Relay brand Siemens type 7UT613 is a numerical type relay so that current matching no longer uses the Interposing Current Transformer (ICT) but inside the relay itself.

C. Result of Disturbance Fault Record

From the results of the DFR record, it can be seen that at the time of the first disturbance, the highest average current that was read was 926 Ampere on the primary side, while on the secondary side, it was 24,550 Ampere. In this condition, the differential relay does not read because the disturbance that occurs is an external disturbance; the differential relay only senses the presence of disturbance by indicating the pick up of the differential relay. The vector diagram found on the DFR also shows that there is still an angle balance between the phases. At the time of the second disturbance, the differential Relay starts working because it senses the current difference that exceeds the setting. The highest average current read on the primary side is 1150 Ampere. The vector diagram shows the phase angle imbalance in phases R, Y, and B. In this condition, the differential relay sends a trip command because it senses a disturbance in its security area.

D. Differential Relay Testing Results

Differential relay testing is done by testing the pickup current and its characteristics after a disturbance by simulating a disturbance. From the test results above, it was found that the differential relay works with a pickup current of 0.2 Ampere. Differential relay characteristic testing is used to see the working slope, restraint current, and Idif. This testing is done on both sides by giving a smooth current and paying attention to the difference in current that occurs in normal conditions. During a three-phase fault, if a current of 11.97 Ampere flows on the primary side, then a current of 12.643 Ampere will flow on the secondary side. From the above results, we can calculate I dif and restraint current as follows:

Primary side current = 12.716 Ampere (Ratio 75/1 with +3% error of CT) Secondary side current = 11.906 Ampere (Ratio 2000/1 with -3% error of CT).

$$\begin{aligned}
 I_{dif} &= I_1 - I_2 \\
 &= 12.716 - 11.906 \text{ Ampere} \\
 &= 0.81 \text{ Ampere}
 \end{aligned}$$

This current is greater than the pickup current of the relay. Hence the bias setting is provided as under.

$$\begin{aligned}
 I_{restraint} &= (I_1 + I_2) \div 2 \\
 &= (12.716 + 11.906) \div 2 \\
 &= 12.311 \text{ Ampere}
 \end{aligned}$$

Bias setting= 0.81/12.311=6.58 %

Considering CT saturation and phase angle error, the bias setting is selected as 10%.

The results show that the trip relay's condition is still good because it works according to the setting. Under normal conditions, Idif will follow the current changes on the primary and secondary sides according to its characteristics. So, the greater the current that flows on the primary side (as a template), the greater the Idif and I restraint will be.

E. Differential Relay Analysis

Differential Relay will, in principle, work when the disturbance is in its protection area. Under normal conditions, if there is a differential current then the differential relay will not work.

Normal Condition

During normal conditions on an 11/0.415 kV Power transformer with a capacity of 1250 KVA, for example, the current Ip or the current flowing on the primary side is 65.60 Ampere with a CT ratio of 75/1 then the current read on the secondary side CT is 0.874 Ampere. While the current that flows on the secondary side or Is is equal to:

$$\text{Secondary side current : } \frac{11}{0.415} * 65.6 = 1738.8 \text{ Amp}$$

$$\text{Current entering the CT secondary side: } \frac{1738.8}{2000} * 1 = 0.8694 \text{ Amp.}$$

There is a difference in current or Idif as large as: Is – Ip: 0.0046 Amp.

From the current difference, it can be calculated that the actual (ideal) current imbalance is as follows:

$$\Delta i = \frac{I_{s1} - I_{s2}}{\text{Minimum Current}} = 0.0046 / 0.8694 = 0.53\%$$

Thus, even though the CT reads a difference in current on the primary and secondary sides, the differential relay does not work because of the relay's matching, which causes the Idif read by the relay to be less than the pickup setting.

First Disorder Condition

When external three-phase disturbances occur, such as the first incident at the CHARUSAT Healthcare campus, which caused tripping, the differential relay does not operate even though the DFR indicates Idif above the relay setting, which is 0.81. However, the differential relay still does not operate at this standard current because the bias setting seen during this time is less than the set value.

Second Disorder Condition

The second disorder is an internal disorder caused by a lighting arrester failure, which is located inside the tank of the dry-type transformer. In this condition, the differential relay works as it should. The Idif current indicated on the DFR is 14.87 on the R phase. Compared to the first disturbance, in this second disturbance, the differential relay reads the existence of a disturbance in its security area, which causes an angle shift phase until the vector diagram becomes unbalanced. This can be proven by looking at the instant current on the DFR as follows:

- An instantaneous current of R phase on the primary side = 14.87 Ampere (Ratio 75/1 with -3% error of CT)
- Due to the internal line to ground fault, the Secondary current of the R phase is zero.
Idif = 14.87

During this time, as per the bias setting equation $\frac{I_{s1} - I_{s2}}{(I_{s1} + I_{s2})/2}$, the bias setting seen by the relay is

200%, which is greater than the set value. Hence, for this scenario, both conditions become true, and the relay will issue the trip signal.

From the calculation results above, it is known that the Idif that is read more than the differential relay setting is 14.87 Amps on the R phase. In addition, the result shows a current imbalance (the current on phases Y and B is very small). Later in the investigation, it was found that this disturbance was caused by the failure of the lighting

arrester connected to the HT terminal of the transformer, which was caused by the external disturbance at the change substation.

The analysis above proves that the differential relay's work as the transformer's main safety in the CHARUSAT healthcare campus is very accurate because it works according to the setting by tripping the CB when the perceived I_{dif} is greater than 0.3 Ampere. In addition, the differential relay is very selective because it only works in the security area.

To make the differential relay work when there is a significant disturbance current, but it does not occur in the safety area, the differential relay can be set by activating the high set of 13 times relay rating, which will block the differential work slope area to work the differential relay.

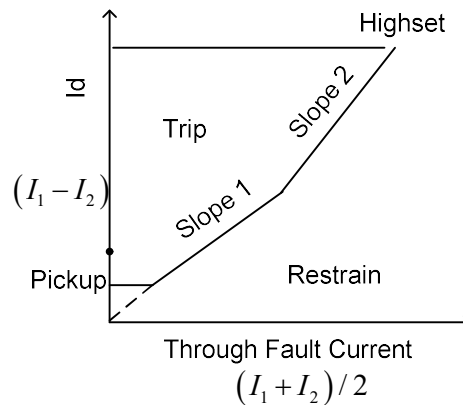


Figure 5. Graphic High Set Differential Relay

F. Transformer Condition Analysis

As a result of the disturbance that occurred on the transformer, the transformer was declared safe and fit for operation due to the timely operation of the differential relay. The lightning arrester was replaced and some below-mentioned tests were performed on the transformer before putting it into operation.

1. AC HV Test: Result: Good condition
2. Winding Insulation Resistance Testing: Result: Good condition
3. DC Resistance Testing (RDC): Result: Within the limit
4. Transformer Ratio Testing: Results: Still within tolerance

V. CONCLUSION

Based on the discussion in this research, the following conclusions can be obtained:

1. The differential relay's working principle is to compare the current read on the Current Transformer's primary side and the secondary side using Kirchoff's Law, i.e., the currents flowing in both CTs cancel each other out ($I_d = I_P - I_S = 0$). The differential relay's ability to work is within its security area, which is between two CTs with a current reading of 0.3 Ampere ($0.3 \times I_n$).
2. Disturbances that cause the differential Relay to work are internal disturbances in the transformer in the form of incipient faults and electrical faults. Both of these disturbances can be caused by external disturbances with large currents that are not immediately overcome. The operation of the differential relay can cause the transformer to trip especially when the transformer is damaged.
3. The size of the differential relay setting is $0.3 \times I_n$ or as much as 0.3 Ampere for pick up and $13 \times I_n$ for high set and instant time characteristics; when there is a disturbance in the transformer, the differential relay works when the presence of I_{dif} of 14.872 Ampere on the R phase. That shows that the differential relay setting is in accordance with the working current when there is a disturbance in the security area. In the previous external disturbance, the differential relay was only sensed.
4. The differential relay is the main safety feature of the transformer, so it works very reliably when it senses a disturbance in its safety area. In addition, when there is an external disturbance, the differential relay senses it.

The differential relay can also be set to work when there is a significant disturbance current outside the protection area by activating the high set of 13 times the relay's nominal value to block the relay's working slope.

REFERENCES

- [1] B. A. Oza, N.C Nair, R.P. Mehta and V.M. Makwana, *Power System Protection and Switchgear*, 1st Edition, Tata McGraw Hill, 2012.
- [2] Patel Vishal J., and Nilaykumar A. Patel, "Loss of Excitation (LOE) Protection of Generator by RX Schemes," *International Journal of Research and Scientific Innovation*, vol. 5, no. 3, pp. 148–153, March 2018.
- [3] Beig, A. R., "Three-phase AC Supply," *Electric Renewable Energy Systems*, pp.183–208., February 2016.
- [4] Kinsler, P., "Faraday's law and magnetic induction: Cause and effect, experiment and theory," *Physics*, vol. 2, no. 2, pp.148–161, May 2020
- [5] Patel, D., and Chothani, N., "Introduction to power transformer protection," *Digital Protective Schemes for Power Transformer- Power Systems*, pp. 1–31, 2020.
- [6] Phadke, A. G., Wall, P., Ding, L., and Terzija, V., "Improving the performance of power system protection using Wide Area Monitoring Systems," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 3, pp. 319–331. July 2016.
- [7] Rotov, N. K., Doloviev, V. A., and Kolobrodov, E. N., "The operation of the differential protection of a power transformer when using CTS with non-magnetic gaps", *6th International Scientific and Technical Conference on Relay Protection and Automation (RPA)*, vol. 1, pp. 1–16, November 2023.