
NEI
4C21 Transformer Differential Relay
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former Protection

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Introduction

Transformer provides regulation and flexibilities in voltage in power network, by stepping up voltage to lower construction cost and power loss, and stepping down voltage for customers' appliance. Yet, transformers are susceptible to defects and failures in which may largely affect load distributions. Understanding possible faults occur in transformers, protection systems should be able to isolate faults selectively with time discrimination and avoid tripping with through faults and non-fault situation.

Considerations in Transformer Protection

1. **Inrush current**

   Transformer requires an inrush current up to 8 – 12 times of rated current to magnetize the core, i.e. to energize the transformer. The inrush current contains a large **DC offsets** with **even harmonics** which damps down much slower than the exponentially decaying dc offsets in fault current. Second harmonics current starts with low value and increases as the inrush decreases.

   During energization, inrush current flows through mainly the shunt branch, i.e. the core, and this is seen as 'false' differential current. Tripping of transformer due to inrush current is an undesirable situation as tripping a highly inductive current can generates high overvoltage. To avoid tripping, inrush current second harmonics is obtained with a filter and acts as a restrain in a biased differential. Another digital method of restrain is to count the zero timing. Figure 1 shows the long time period with current reaching zero of inrush current. The unwanted operation can also be evaded with a time delay if allowed. There are many factors affecting the characteristics of inrush with different causes. The magnitude of harmonic content depends also on **remanent flux**, **switching angle** and magnitude of **loading and power factors**. Other than transformer energization, it exists with occurrence of **external fault**, **voltage recovery** after fault clearance, change of fault character (i.e. phase-to-ground to three-phase-to-ground) and **out-of-phase synchronizing** of connected generator. Note that for **back-to-back transformer energization** (i.e. energize a transformer with an energized transformer in the same busbar), the inrush is with longer duration but smaller magnitudes.

2. **Overexcitation**

   Transformer core may be saturated with excessive flux and generate current with large harmonics distortion resulting in **overheating**, and hence insulation degradation and charring, and **vibrations**. With volt-per-turn equation, flux varies with voltage over frequency (V/f).

   Overexcitation can be caused by **sudden voltage rise** or **lowered frequency** at high load. A **sudden load rejection**, **generator tripping** with exporting VAr, or **VAr load disconnection**, i.e. shunt reactor, can induce an **overvoltage** at source end. It happens frequently in generation and transmission transformers. It degrades transformer insulations and mis-trips differential relay, even if it is not an in-zone fault.

   As in other saturation situation, it has large odd harmonics content. With third harmonics is filtered with delta winding or absorbed in ground, **fifth harmonics content** can be employed as a restraint to

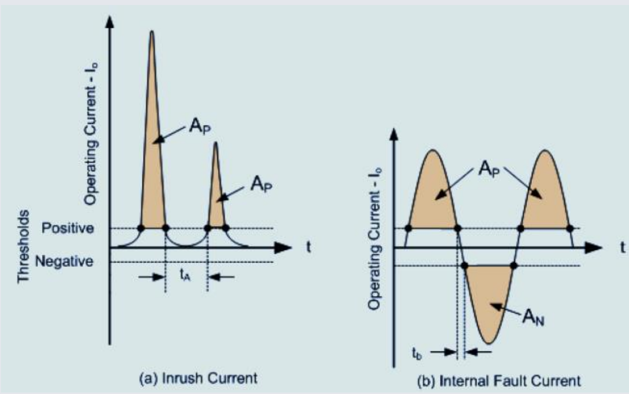

Figure 1: Inrush Current with Zero Timing

avoid tripping differential relay. In fact, the fifth harmonics can reach 50% of fundamental current with 10% of overvoltage. Using third harmonics can also restrain the operation for some topologies, but this may delay some earth faults tripping. Another simpler method is to use a V/f relay to detect overexcitation as does in generators.

3. **Through Faults**
   As most transformer protection works in a **unit protection** philosophy (e.g. circulating current protection, duo bias current differential with restricted earth fault) with non-unit protection (e.g. OCEF) as back up. Current differential relay should not operate at **extreme through fault**, i.e. out-zone fault, even with **LV CT saturated**. Hence, another bias is required to cater for through fault condition.

4. **CT mismatch**
   In delta-wye transformer, there is a **phase difference** in LV and HV if current differential relay is simply connected with standard ratio CT. Hence, The HV CT is connected in **wye** while LV CT is connected in **delta** in form of **interposing CT** to balance out the phase difference in electromagnetic relay. For numerical relay, both CT should be connected in wye as the relay can re-map the current ratio and phase difference.

   Standard CT ratio may not offer a balanced output in circulation, and the differential relay goes through the shunt relay path. To worsen the concern, CT does not follow **tap changing** in power transformer. Off nominal taps can result in large current differential in the shunt path. CTs should be connected in **equipotential,** or with **balancing resistance** with CT burden should be implemented to ensure the differential current low enough not triggering relay operation.

Protection in 400/132kV Autotransformer

400/132kV Transformer Protection is shown in Figure 3.

<u>Main Protection</u>
Unbiased Circulating Current Transformer Protection
High Set Overcurrent (HSOC)
Buchholz Gas Surge (Buchholz)
<u>Backup Protection</u>
2-stages Overcurrent Earth Fault Protection (OCEF)
Winding and Oil Temperature (WT/OT)

Unbiased Circulating Current Transformer Protection (CCTP)

Autotransformer provides stepped down voltage in the same coil without isolation. With this property, CCTP, instead of duo bias current differential, is employed in auto-transformer protection.

Any inrush current can be observed in both windings and there is no necessity to provide restraint for inrush current. For through faults, as the voltage ratio is not large enough CT that LV CT are prone to saturation. Hence, there is no specific bias to cater for through fault. The only requirement is to properly set the operating current setting for differential current relay.

The operating principles for CCTP in the protection are **differential current** and **opposed voltage** (two principles) in pilot wires. Yet, this scheme depends heavily on **pilot wire stability** (without open, shorted or cross pilot).

Differential Protection provides **faster detection** of faults with **accurate location** and **zoning**, and with **high-speed fault clearance**. Note that delta tertiary winding should be linked up to the earth point of primary winding to include it into protection zone. To provide protection backup on tertiary winding, OC in each phase can be provided.

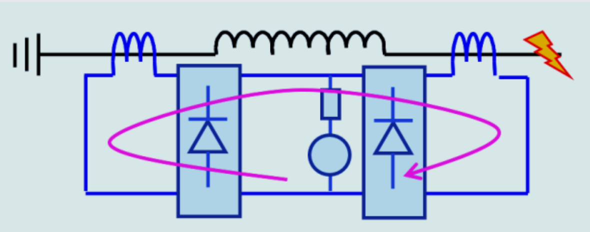

Figure 2: Principle of Circulating Current Protection

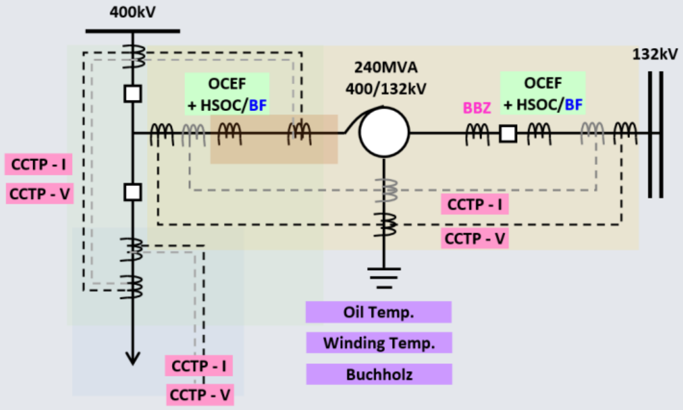

Figure 3: 400/132kV Autotransformer Protection

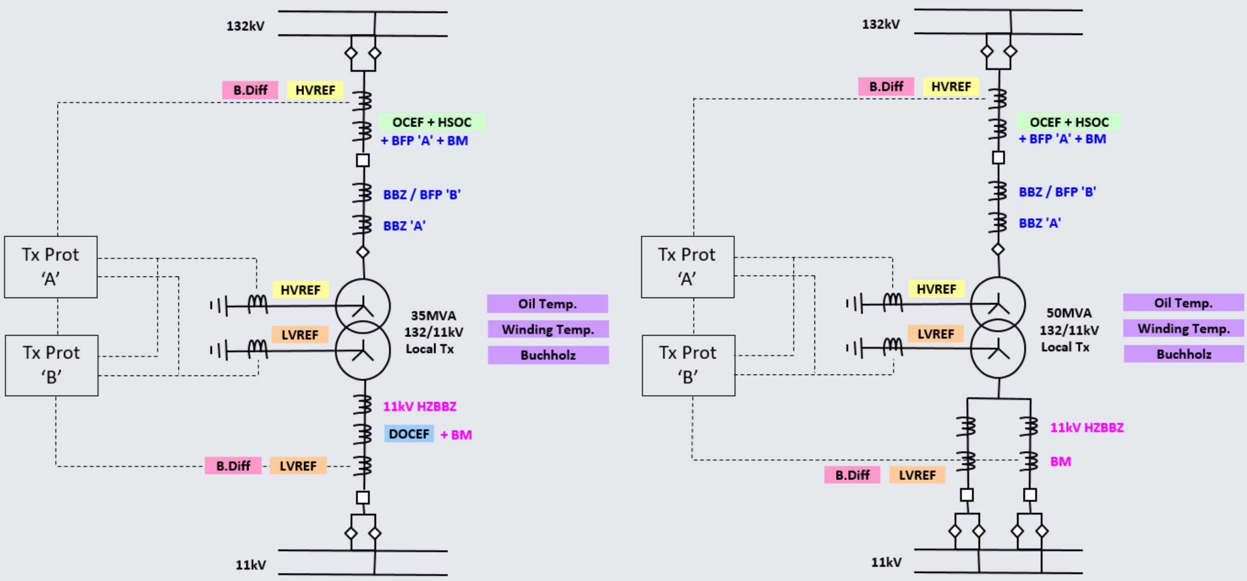

Figure 4: 132/11kV Transformer Protection
(a) 35MVA; (b) 50MVA

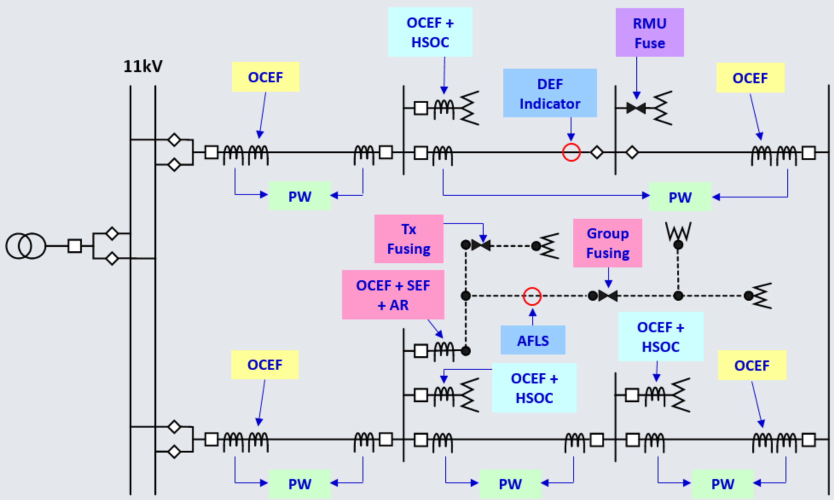

Figure 5: 11kV Ring Network Protection

Protection in 132/11kV Transformer:

400/132kV Transformer Protection is shown in Figure 4.

Main Protection
Duo Bias Current Differential (BD)
HV/LV Restricted Earth Fault (HV/LV-REF)
Buchholz Gas Surge;
Backup Protection
High Set Overcurrent Protection (HSOC)
Winding/ Oil Temperature (WT/OT)

Duo Bias Differential Protection (BD)

Duo bias, unlike circulating current protection, requires a percentage differential relay, which trips when operating current I_{OP} is larger than a percentage of restraint current I_R (i.e. trip when $I_{OP} > k\ I_R$).

As shown in Figure 6, pickup current I_{PU} depends on steady state exciting current and measurement error (i.e. from CT ratio and transducer if needed), with normal setting 20% - 35% of nominal current in CT secondary; Slope 1 depends on errors in tap changing and CT mismatch, slope setting can be 30% depending on the actual errors; Slope 2 depends on the maximum through fault which saturates LV CT and generates a large spill current, possibly with only HV side CT input, a 70%-100% can be selected; Another similar issue are overexcitation and inrush.

The general setting of restraining current includes through faults (sum of LV and HV CT current), harmonics restraint (or harmonic blocking or sharing), which includes **second harmonics for inrush** and **fifth harmonics for overexcitation**. (i.e. $|I_{OP}| = |I_1| - |I_2| > s|I_1 + I_2| + k_2|I_{f2}| + k_5|I_{f5}|$) . Other possible inrush detection methods are **wave shape recognition**, **zero timing and DC blocking**, i.e. calculate the ratio between upper and lower current-time area of a cycle. In case of parallel transformers, the setting should also take care of the **sensitivity** of each phase when current is evenly distributed as compared to only one or two transformers in services. A **negative-sequence** relay can be used as a backup to identify fault sensitively in case it is hard to coordinate or sense selectively and timely.

HV and LV Restricted Earth Fault (HV/LVREF)

Percentage differential relay trips both sides CB with phase-to-phase fault. It is required to have a relay to track phase-to-earth fault.

Restricted earth fault has CT wiring as included in Figure 7. **High impedance relay**, which is for stability concerns, is triggered only for the faults in the '**restricted area**'. For better stability and selectivity, a **directional relay** can be implemented.

With relay monitoring ground fault, one should also consider the **earthing system**, to see if **earth- fault-loop impedance** is too large or if there is **circulating current** for cable bonding such that earth fault relay can be easily tripped with the residual current. Some may also use **voltage-controlled OC relay** or **OC directional relay** which takes care of only reactive power.

High Set Overcurrent (HSOC)

HSOC looks over cable sessions connecting transformers. Setting margin should be above worst 11kV **through fault and inrush**, while sensitive enough to detect minimum fault level condition in 132kV, with a safety factor of 1.3 – 2.2, depending on types of relay, for avoidance of **transient overreach**.

Buchholz and Winding/Oil Temperature (WT/OT)

Buchholz is a float valve type relay to identify **incipient faults** inside transformers, such as **interturn fault** with a gas surge, **insulation degradation** with gas accumulation and **low oil level**, while WT/OT is to monitor **overload** and malfunctioning of **cooling equipment**. Buchholz trip requires transformer outage to identify possible causes with detailed investigation, while WT/OT alarm requires **load transfer** to avoid overheating.

Directional OCEF in 35MVA 132/11kV Transformer

DOCEF in 35MVA transformer is to block ILOC tripping in case of parallel transformer with forward direction (i.e. from LV to HV in one transformer.) and provides backup for unclear fault at upstream. After a timer delay, in case the fault is not tripped, the DOCEF stops blocking and trip the related CB. It also initiates Auto-Switching Initialization (ASI) in master trip relay.

Protection in 11kV/380V Transformers in Customer Substation

For a 1.5MVA 11kV/380V transformer in Customer Substation, **OCEF** with {CT: 100/5; OC 100%, 0.1; EF 40%, 0.1} and **HSOC** {100A, 0s} are provided. **CB trip time**, **error allowance**, **relay overshoots** with a safety margin, in total 0.4s, or 0.25-0.3s for digital relays, are **grading margin** considerations in OCEF at the upstream. Yet, if the CB is failed to trip for LV transformer or downstream faults, OC relay at node point and primary substation should pick up the fault and trip as a backup.

Conclusion

Transformer protection requires accurate fault detection without false tripping under inrush, overexcitation, through fault or due to CT mismatch. Transformer protection from 400/132kV to 11kV/380V are discussed.

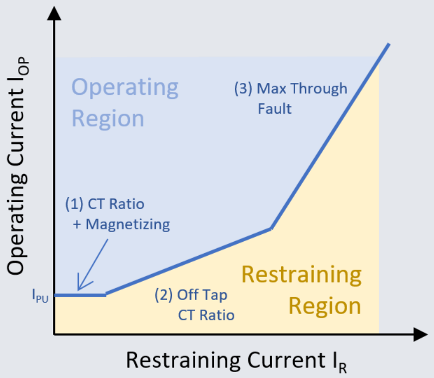

Figure 6: Typical Characteristics of Percentage Differential Relay

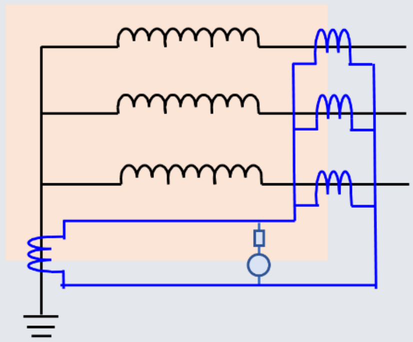

Figure 7: Restricted Earth Fault CT Wiring

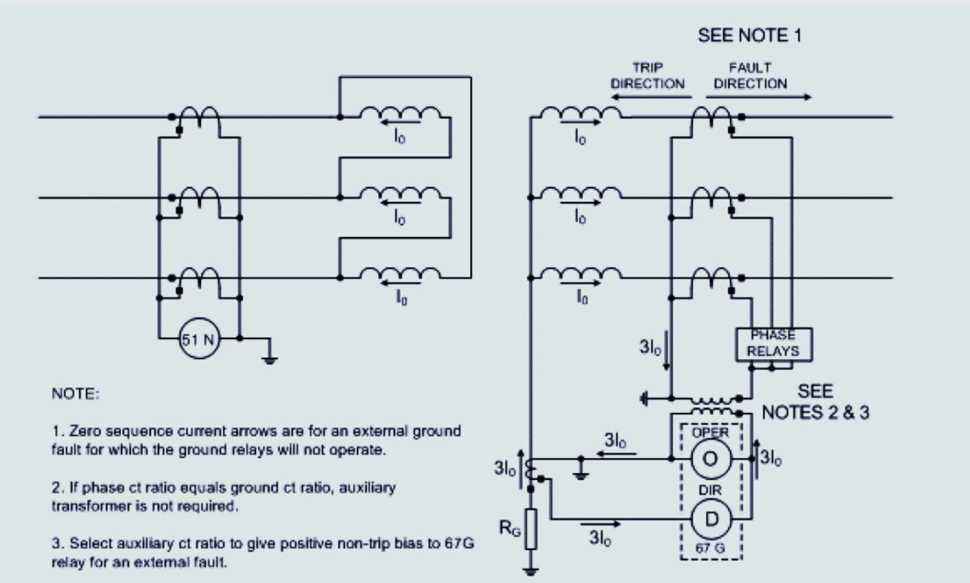

Figure 8: Ground Fault Protection with Residual OC and Directional Relay