Differential Relay Protection Settings

Low impedance differential protection systems typically have 3 to 5 settings required to properly define the restraint characteristic of the relay. See Fig. 4.2.1. The ensuing discussion will mainly focus on differential protection for power transformers. Generator and motor diff are included where applicable.

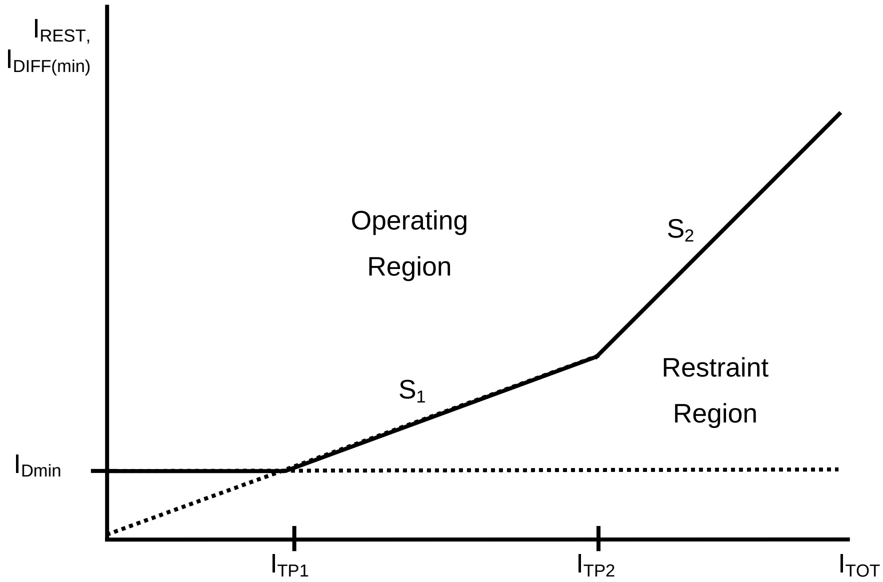


Fig. 4.2.1 – Typical restraint characteristic of a biased differential relay.

I_{Dmin}	= minimum differential current (secondary) required to operate the relay
I_{TP1}	= turning point 1
I_{TP2}	= turning point 2
S_1	= Slope 1 setting
S_2	= Slope 2 setting
I_{TOT}	= Total current through the differential system. Measure of system loading.
$I_{REST,}$ $I_{DIFF(min)}$	= For a given value of I_{TOT}, this is the restraint current applied by the relay or alternatively the minimum differential current required to operate the relay.
$I_{DIFF-HI}$	= Should the differential current exceed this threshold, operation results irrespective of the restraint current applied

The settings to be considered are I_{Dmin}, I_{TP2}, S_1, S_2 and $I_{DIFF-HI}$. These are generic representations of the settings. They will differ from one manufacturer to the next.

Before proceeding to discuss the settings, some fundamental concepts first. Consider the equivalent circuit of a two-ended circulating current differential protection system as shown in Fig. 4.2.2 with a throughfault current flowing from End P to End Q.

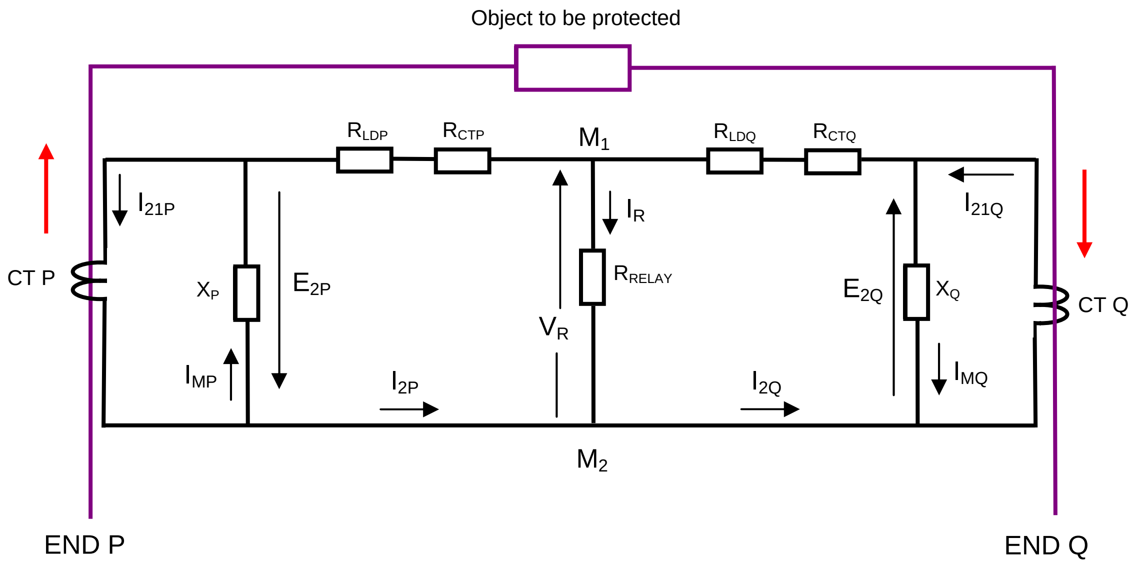


Fig. 4.2.2 – Equivalent circuit of a circulating current differential protection system

$$E_{2P} = I_{2P}\left(R_{LDP} + R_{CTP}\right) + \left(I_{2P} - I_{2Q}\right)R_{RELAY} \qquad (4.2.1)$$

$$E_{2Q} = I_{2Q}\left(R_{LDQ} + R_{CTQ}\right) + \left(I_{2Q} - I_{2P}\right)R_{RELAY} \qquad (4.2.2)$$

The limiting case for a low impedance relay (relay current prevails over relay impedance) is for the case when $R_{RELAY} = 0$, i.e. a dead short from M_1 to M_2. Equations (4.2.1) and (4.2.2) now become,

$$E_{2P} = I_{2P}\left(R_{LDP} + R_{CTP}\right) \qquad (4.2.3)$$

$$E_{2Q} = I_{2Q}\left(R_{LDQ} + R_{CTQ}\right) \qquad (4.2.4)$$

For the case when both ends see the same primary current, the turns ratios are identical and there is no saturation, then $I_{21P} = I_{21Q}$. Thus $I_{2P} + I_{MP} = I_{2Q} + I_{MQ}$. Relay current is thus $I_R = I_{2Q} - I_{2P} = I_{MP} - I_{MQ}$. Let the relay operating current be I_{ROC}. Then to ensure stability must have $I_R = I_{MP} - I_{MQ} < I_{ROC}$.

What the above states is that for throughfault stability, the differential current is the difference between the magnetisation currents. These in turn depend on :

a) CT magnetisation curve
b) Resistances in the CT circuit

Thus, non-zero I_{DIFF} can still result if the CT's are identical but the sum of CT and lead resistances are substantially different. This is the case when the relay is not located at the ***electrical midpoint*** of the secondary system and/or the CT resistances are different.

On the other hand, non-zero I_{DIFF} can also result if the CT mag curves are not identical. Different magnetisation currents are required to produce identical induced voltages, the difference between the mag currents now seen by the relay.

This translates into the requirement that the minimum current required to operate the relay should be > maximum difference between the mag currents at the two ends. Thus I_{ROC}. ***> max(***I_{MP}, I_{MQ} ***) or even more conservatively,*** $I_{ROC} > I_{MP} + I_{MQ}$.

The minimum current required to operate the relay system assuming a single ended fault may be approximated as follows:

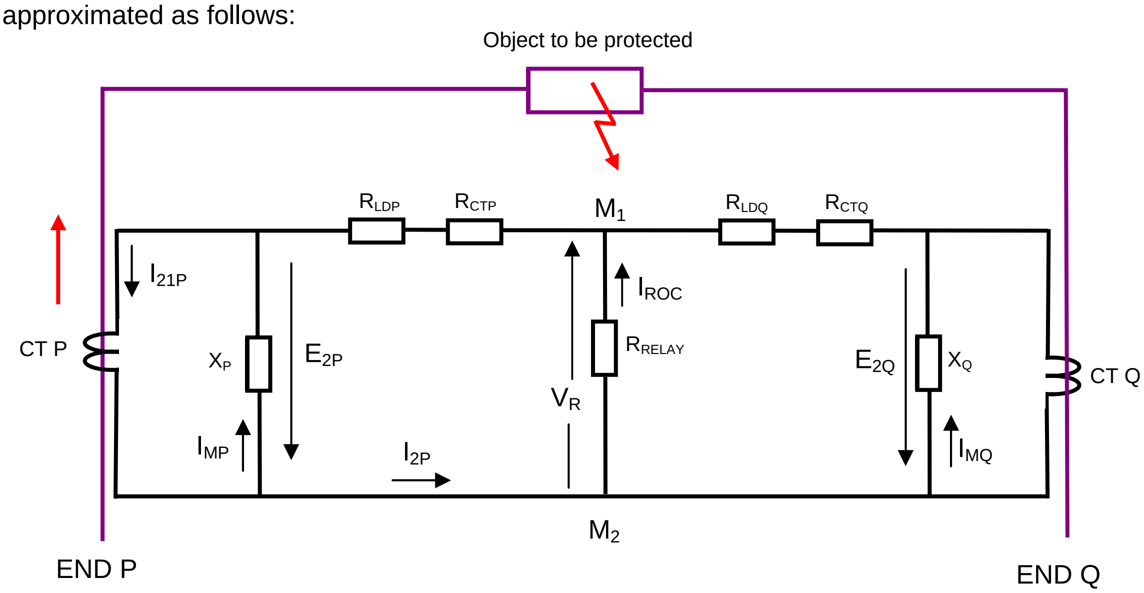


Fig. 4.2.3 – Equivalent circuit for a single-ended fault

$$I_{FOC} = N \cdot (I_{MP} + I_{MQ} + I_{ROC}) \qquad (4.2.5)$$

I_{FOC} = minimum primary fault current required to operated the differential relay

I_{MP}, I_{MQ} = respective CT magnetisation currents

I_{ROC} = minimum differential current required to operated the relay (usually settable)

N = number of turns of the CT secondary winding (assuming primary winding = 1 turn)

As $I_{ROC} >> I_{MP}, I_{MQ}$ above can be simplified to,

$$I_{FOC} = N \cdot I_{ROC} \qquad (4.2.6)$$

4.2.1 Low Impedance Differential Relay Settings

A) I_{Dmin}

I_{Dmin} should satisfy the following criteria:

1. The minimum current required to operate the relay, I_{ROC}, should be at least > maximum difference between the mag currents at the two ends. Thus I_{ROC}. > max(I_{MP}, I_{MQ}) or even more conservatively,

$$I_{ROC} > |I_{MP}| + |I_{MQ}| \qquad (4.2.7)$$

2. It must also be ensured that the relay remains stable under no-load conditions when only transformer magnetising current flows from the primary side. This is typically 1% of full load amps. Escalate this to 5% to allow a sufficient margin of safety.

$$I_{ROC} > 0.05*I_{FLA}*K_1 \qquad (4.2.8)$$

K_1 = allows for the CTR correction factor

Experience dictates that I_{Dmin} = 200mA suffices for most transformer differential applications. Thus it is only necessary to ensure that the above two criteria are satisfied with I_{Dmin} = 200mA.

With generators the criteria that $I_{ROC} > |I_{MP}| + |I_{MQ}|$ also applies. A setting of 5% of rated current is usually sufficient.

B) Slope 1, S_1

- When applied to motors and generators this setting is based on worst case unbalance that could result due to CT errors up to 120% of rated load. With high accuracy CT's (Class PL, PX, P, etc.) a setting of between 0 and 10% will suffice whilst for low accuracy CT's (Class P, PR) a setting of between 10 to 25% is recommended.
- When applied to power transformers this is based on the worst case I_{DIFF} that could result due to the action of the tapchanger.
- It is assumed that the transformer impedance remains constant over the tapping range.

Transformers

- Determine the tap which results in the largest unbalance. This is usually the maximum boosting tap.

- o Denote the turns ratio corresponding to this tap position by TR_{MIN} (maximum boosting corresponds to the minimum turns ratio).
- o TR_{MIN} is calculated as follows:

$$TR_{MIN} = \frac{V_{HV-MAXTAP}}{V_{HV-NOM}} \cdot TR_{NOM} \qquad (4.2.9)$$

where

$V_{HV\text{-}MAXTAP}$ = HV voltage corresponding to the maximum tap (on nameplate)

$V_{HV\text{-}NOM}$ = nominal HV voltage corresponding to the nominal tap position (on nameplate).

TR_{NOM} = nominal turns ratio of the transformer

- o Suppose rated current, I_{FLA}, flows through the transformer – I_{FLA} being the LV current. Then

$$I_{LV} = \frac{I_{FLA-LV}}{CTR_{LV}} \cdot CTR_{CFLV} \text{ and } I_{HV} = \frac{\left(\frac{I_{FLA-LV}}{TR_{MIN}}\right)}{CTR_{HV}} \cdot CTR_{CFHV} \qquad (4.2.10)$$

CTR_{CFLV} = LV CTR correction factor

CTR_{CFHV} = HV CTR correction factor

- o $I_{DIFF} = \left|I_{HV} + I_{LV}\right|$. I_{REST} depends on whether it is a Type A, B or C relay.

Type A: $$I_{TOT} = \frac{\left|I_{HV}\right| + \left|I_{LV}\right|}{2} \qquad (4.2.11)$$

Type B: $$I_{TOT} = \left|I_{HV}\right| + \left|I_{LV}\right| \qquad (4.2.12)$$

and Type C: $$I_{TOT} = \left|I_{HV} - I_{LV}\right| \qquad (4.2.13)$$

For motor and generator applications, replace I_{HV} with I_1 and I_{LV} with I_2.

- o In each case the Slope 1 setting is given by $S_1 = \frac{I_{DIFF}}{I_{TOT}} \cdot 100\%$ (4.2.14)
- o Allow for 5% relay and calculation errors.

Example

Transformer = 420MVA, 530kV/23kV, 17.4%

Tapchanger = 21 taps, nominal tap = tap 9, HV voltage at maximum tap = 450.5kV.

CTR_{HV} = 1500/1, CTR_{LV} = 19000/1

$I_{FLA-LV} = \frac{420MVA}{\sqrt{3} \cdot 23kV} = 10543A$ primary or 0.555A secondary. Thus CTR_{CFLV} = 1/0.555 = 1.8.

I_{FLA-HV} = 457.52A primary or 0.305A secondary. Thus CTR_{CFHV} = 1/0.305 = 3.28.

$$TR_{MIN} = \frac{V_{HV-MAXTAP}}{V_{HV-NOM}} \cdot TR_{NOM} = \frac{450.5}{530} \cdot \frac{530}{23} = 19.587$$

$$I_{LV} = 0.555 \cdot 1.8 = 1,\ I_{HV} = \frac{\left(\frac{I_{FLA-LV}}{TR_{MIN}}\right)}{CTR_{HV}} \cdot CTR_{CFHV} = \frac{\left(\frac{10543}{19.587}\right)}{1500} \cdot 3.28 = 1.177A$$

Type A relay,

$$I_{DIFF} = |1.177 - 1| = 0.177A,\ I_{TOT} = \frac{|I_{HV}| + |I_{LV}|}{2} = \frac{1.177 + 1}{2} = 1.0885A$$

$S_1 = \frac{0.177}{1.0885} \cdot 100\% = 16.26\%$. Allowing for a 5% error, get a slope setting of 17.1%. Set to 20%.

Type B relay,

$$I_{DIFF} = |1.177 - 1| = 0.177A,\ I_{TOT} = |I_{HV}| + |I_{LV}| = 1.177 + 1 = 2.177A$$

$S_1 = \frac{0.177}{2.177} \cdot 100\% = 8.13\%$. Allowing for a 5% error, get a slope setting of 8.5%. Set to 10%.

Type C relay,

$$I_{DIFF} = |1.177 - 1| = 0.177A,\ I_{TOT} = |I_{HV} - I_{LV}| = 1.177 - (-1) = 2.177$$

$S_1 = \frac{0.177}{2.177} \cdot 100\% = 8.13\%$. Allowing for a 5% error, get a slope setting of 8.5%. Set to 10%.

C) Turning Point 2, I_{TP2}

Slope 1 dictates the relay restraint characteristic over the load current range of the transformer. Thus it is meant to be effective up to the maximum possible loading of the transformer. For large transformers on the transmission system this could be up to 200% of rated current. For smaller transformers allowable maximum loading could be anything from 100% to 200% of rated load typically 150%. For most cases a turning point of 2 (corresponding to twice rated load) suffices.

Type A $$I_{TOT} = \frac{2 \cdot I_{FLA} + 2 \cdot I_{FLA}}{2} = 2 \cdot I_{FLA} \text{ thus } I_{TP2} = 2 \qquad (4.2.15)$$

Type B $$I_{TOT} = 2 \cdot I_{FLA} + 2 \cdot I_{FLA} = 4 \cdot I_{FLA} \text{ thus } I_{TP2} = 4 \qquad (4.2.16)$$

Type C $$I_{TOT} = 2 \cdot I_{FLA} - (-2 \cdot I_{FLA}) = 4 \cdot I_{FLA} \text{ thus } I_{TP2} = 4 \qquad (4.2.17)$$

Alternatively some texts advocates that slope 1 is effective over the linear operating range of the current transformer. I_{TP2} should thus be set at this limit. This approach leads to I_{TP2} typically being greater than $I_{TP2} = 2$ as advocated above. This implies improved sensitivity over the linear operating range but less stability. For this reason the approach of I_{TP2} is adopted in this text.

When it comes to generators and motors a turning point > $1.2 \cdot I_{RATED}$ times rated current is generally considered sufficient as motors and generators are rarely loaded above this.

D) Slope 2, S_2

The second bias slope is intended to ensure additional restraint with severe throughfault currents that could lead to CT saturation. Thus additional restraint is provided on top of the two other restraints already mentioned so far, viz. I_{Dmin} to cater for differences in CT magnetisation currents and transformer magnetisation currents and the slope 1 which caters for the action of the tapchanger.

Most manufacturers recommend a slope 2 setting of at least 80% (Type 1 relay). The limitation is that there should be a sufficient margin of safety between the restraint characteristic and the inzone fault characteristic to ensure relay operation for high current single ended faults.

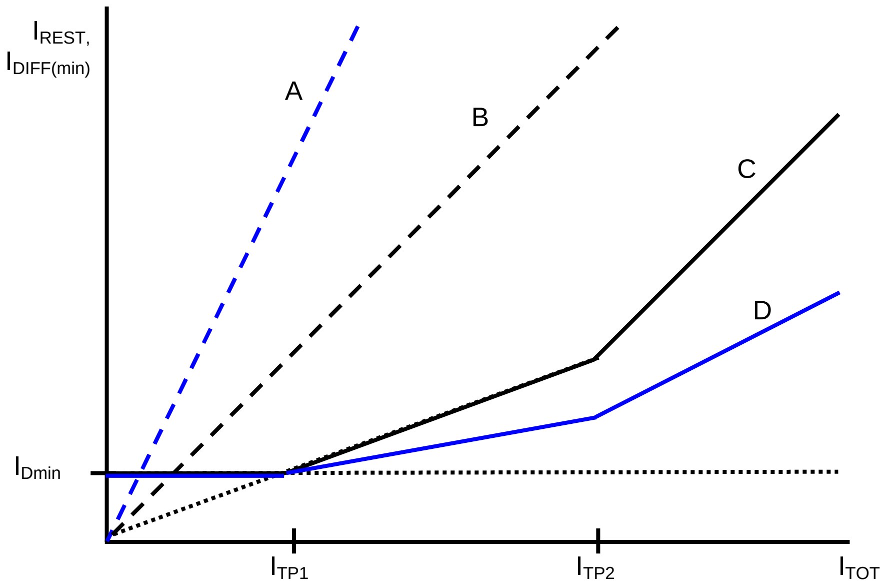
Singe-ended inzone fault characteristic:

$$I_{DIFF} = |I_{HV} + I_{LV}| = |I_{HV}|$$

Type A: $$I_{TOT} = \frac{|I_{HV}| + |I_{LV}|}{2} = \frac{|I_{HV}|}{2}, \text{ and so slope } = \frac{|I_{HV}|}{|I_{HV}|/2} \cdot 100 = 200\% \quad (4.2.18).$$

Type B: $$I_{TOT} = |I_{HV}| + |I_{LV}| = |I_{HV}| \text{ and so slope } = \frac{|I_{HV}|}{|I_{HV}|} \cdot 100 = 100\% \quad (4.2.19)$$

Type C: $$I_{TOT} = |I_{HV} - I_{LV}| \text{ and so slope } = \frac{|I_{HV}|}{|I_{HV}|} \cdot 100 = 100\% \quad (4.2.20)$$



A = single-ended inzone fault characteristics for a Type 1 relay
B = single-ended inzone fault characteristics for Type 2 and 3 relays
C = typical restraint characteristic for a Type 1 relay
D = typical restraint characteristic for Types 2 and 3 relays

Fig. 4.2.4 – Inzone fault vs. restraint characteristic for Types 1, 2 and 3 relays

With generators and motors a slope 2 setting of at least 80% is recommended.

E) $I_{DIFF-HI}$

This function allows operation of the differential protection whenever the differential current exceeds the $I_{DIFF-HI}$ setting. The objective is to ensure fast, yet selective protection operation for high current inzone faults.

The settings criteria is based on one set of CT's saturating under worst case throughfault conditions, i.e. considering maximum DC offset.

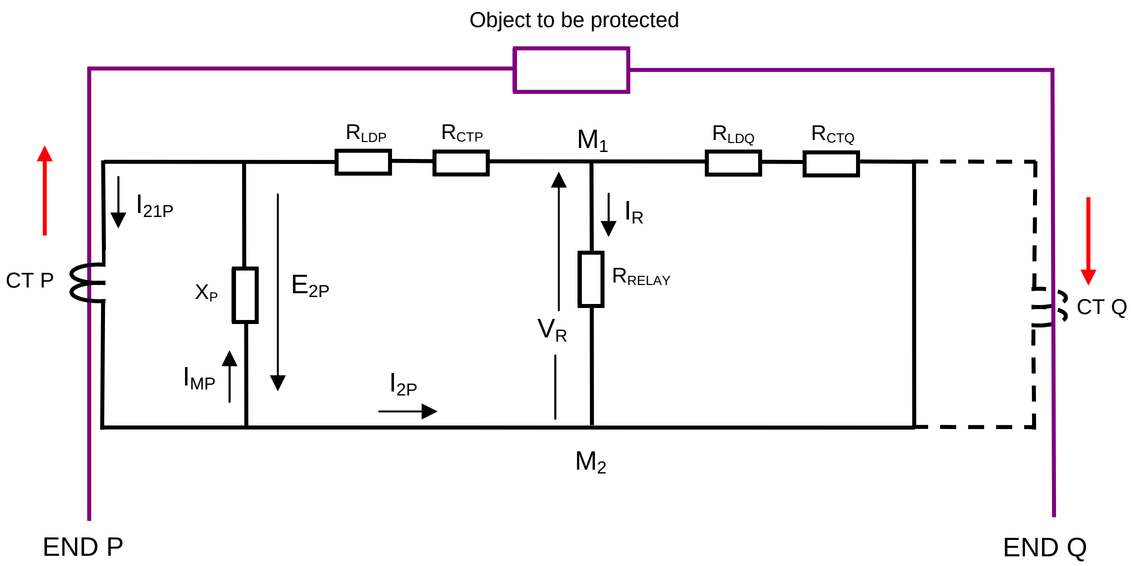


Fig. 4.2.5 – Throughfault with end Q CT saturated

- In Fig. 4.2.5 have that the throughfault lead to CT Q being fully saturated. The differential current is thus $I_{DIFF} = I_{2P} = I_F/CTR$. Thus,

$$I_{DIFF-HI} = \frac{I_F}{CTR} \cdot K_1 \cdot K_2 \qquad (4.2.21)$$

Where

I_F = maximum symmetrical throughfault current (no DC offset included).

CTR = current transformer ratio

K_1 = allows for the CTR correction factor

K_2 = safety factor

- The choice of safety factor, K_2, depends on several factors. For properly sized CT's full saturation is only a remote possibility especially if a close-up throughfault is cleared by a unit protection scheme such as buszone. Clearance times are then in the order of 100ms and with high X/R ratios full saturation may take up to 1s. A safety factor of 5% or at most 10% will suffice. This is generally applicable to large transformers as they have high X/R ratios. Their size also would imply large LV fault currents making buszone protection a near certainty.

- With smaller transformers (≤ 20MVA, X/R ≤ 20) there is a possibility that a close up throughfault may not be cleared in 100ms. A higher degree of saturation is now possible and so a safety factor of 30% may be necessary.