TRANSFORMER DIFFERENTIAL CALCULATION

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TRANSFORMER DIFFERENTIAL PROTECTION

In the world of power system protection, transformer differential protection is a crucial safeguard, acting as a vigilant sentry for these vital components. It operates based on a fundamental principle - Kirchhoff's current law - which states that the sum of currents entering a node must equal the sum of currents leaving it. Imagine a transformer as a node with currents flowing in on one side (primary) and out on the other (secondary). Under normal operating conditions, the currents should balance perfectly, much like balancing coins on a seesaw.

Here's how transformer differential protection works:

1. **Current Comparison:** The scheme uses specialized measuring devices called current transformers (CTs) to monitor the currents entering and leaving the transformer.

2. **Differential Current Calculation:** The heart of the system lies in comparing the measured currents. The differential current is calculated as the difference between the primary and secondary currents of power transformer, taking into account factors like turns ratio and phase shift.

3. **Fault Detection:** In healthy operation, the differential current should be minimal, practically zero. However, if a fault occurs inside the transformer, like a winding short circuit or core damage, the currents lose their perfect balance. This imbalance results in a significant non-zero differential current, triggering the alarm.

4. **Fast Action:** Upon detecting a fault, the differential protection scheme initiates a rapid response, usually by tripping the circuit breaker connected to the transformer. This swift action isolates the faulty transformer, preventing further damage and protecting the rest of the power system.

Benefits of Transformer Differential Protection:

- **High Sensitivity:** Detects even minor internal faults quickly.
- **Reliable:** Highly effective in identifying internal transformer issues.
- **Selective:** Isolates the faulty element while minimizing disruption to the network.
- **Fast Response:** Timely fault detection minimizes damage and risk of widespread outages.

Challenges and Considerations:

- **CT Issues:** Accuracy of the scheme depends heavily on precise performance of CTs.
- **External Faults:** Can be tricked by high currents due to faults outside the transformer, requiring careful tuning.
- **Cost:** Implementing and maintaining a differential protection scheme can be expensive.

SEIMENS 7UT6X – CALCULATION

The 7UT6x Transformer Differential Relay uses a dual-slope characteristic to distinguish between internal and external faults. The relay settings for this characteristic are as follows:

RELAY SETTING [7UT6X]

I_diff >	:	0.25	(y2)
Slope 1	:	0.25	(m1)
Slope 2	:	0.50	(m2)
Base point 1	:	0.20	(x1)
Base point 2	:	2.50	(x3)
I_diff >>	:	5.00	(y5)

The differential slope curve is a plot of the differential current (I_diff) versus the restraining current (I_bias). The restraining current is calculated based on the currents flowing into and out of the transformer.

The relay settings are as follows:

Slope 1: This is the slope of the first line segment of the curve. It is equal to 0.25

Slope 2: This is the slope of the second line segment of the curve. It is equal to 0.50

Base point 1: This is the point on the curve where the first line segment intersects the x-axis. It is equal to (0.20, 0.00)

Base point 2: This is the point on the curve where the second line segment intersects the x-axis. It is equal to (2.50, 0.00)

I_diff >: This is the minimum differential current that must be exceeded before the relay will trip. It is equal to 0.25

I_diff >>: This is the maximum differential current that the relay will tolerate before tripping. It is equal to 5.00

DIFFERENTIAL SLOPE CURVE

The differential slope curve is a characteristic of transformer differential relays that is used to distinguish between internal and external faults. The curve is divided into two regions: the restrain region and the operating region.

RESTRAINT REGION

The restrain region is the area below the curve. In this region, the differential current is less than the restraining current, and the relay will not trip. This is to prevent the relay from tripping on external faults, where the differential current may be high due to CT saturation or other factors.

OPERATING REGION

The operating region is the area above the curve. In this region, the differential current is greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

The dual-slope characteristic is shown in the diagram below:

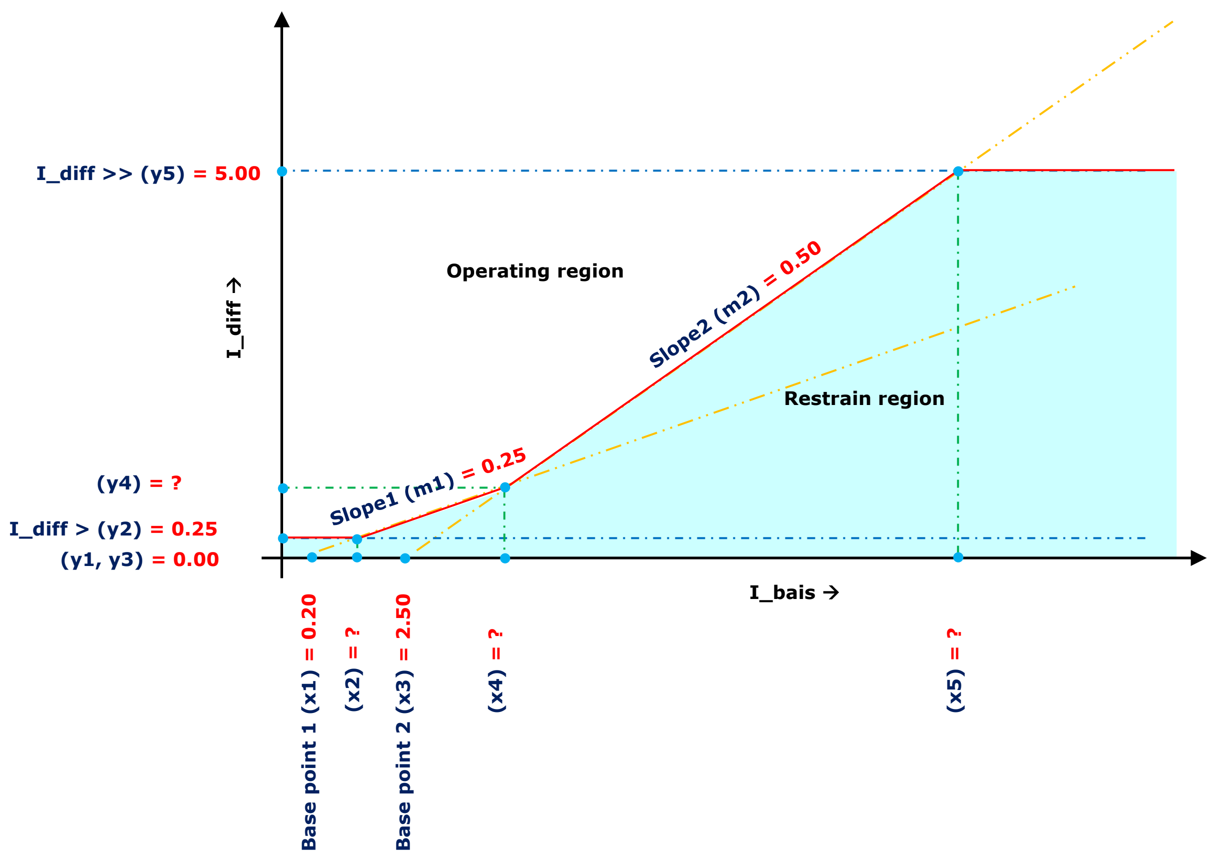


Diagram1: 7UT6x Transformer Differential Relay dual-slope characteristic

SLOPE POINTS CALCULATION

From the differential slope curve, the following values are known:

m1 = 0.25

m2 = 0.50

y1,y3 = 0.0

x1 = 0.20

x3 = 2.50

y2 = 0.25

y5 = 5.00

We need to determine x2, x4, x5 and y4.

Let us find the value of x2 from the line1 (x1, y1) to (x2, y2) with the slope m1.

x1 = 0.20, y1 = 0.0, y2 = 0.25, x2 = ?, m1 = 0.25

Line formula, y = mx.

- ⇨ (y2 – y1) = m1 * (x2 – x1)
- ⇨ (0.25 – 0.00) = 0.25 * (x2 – 0.20)
- ⇨ 0.25 = 0.25 x2 – 0.05
- ⇨ x2 = 0.3 / 0.25

x2 = 1.2

Let us find the value of x5 from the line2 (x3, y3) to (x5, y5) with the slope m2.

x3 = 2.50, y3 = 0.0, y5 = 5.0, x5 = ?, m2 = 0.50

Line formula, y = mx.

- ⇨ (y5 – y3) = m2 * (x5 – x3)

- ⇨ (5.0 – 0.0) = 0.5 * (x5 – 2.5)
- ⇨ 5.0 = 0.5 x5 – 1.25
- ⇨ 0.5 x5 = 6.25
- ⇨ x5 = 6.25 / 0.5

x5 = 12.5

Let us find the value of x4 & Y4 from the line1 (x1, y1) to (x4, y4) with the slope m1 and line2 (x4, y4) to (x5, y5) with the slope m2 through line intercept method.

From line 1 (x1, y1) to (x4, y4) with the slope m1,

x1 = 2.50, y1 = 0.0, x4 = ?, y4 = ?, m1 = 0.25

Line formula, y = mx.

- ⇨ (y4 – y1) = m1 * (x4 – x1)
- ⇨ (y4 – 0.0) = 0.25 * (x4 – 0.2)
- ⇨ y4 = 0.25 * x4 – 0.05 ………… Equation (1)

From line 2 (x4, y4) to (x5, y5) with the slope m2,

x4 = ?, y4 = ?, x5 = 12.5, y5 = 5.0, m2 = 0.5

Line formula, y = mx.

- ⇨ (y5 – y4) = m2 * (x5 – x4)
- ⇨ (5.0 – y4) = 0.5 * (12.5 – x4)
- ⇨ - y4 = 6.25 – 5.0 - 0.5 * x4
- ⇨ - y4 = 1.25 - 0.5 * x4 ………… Equation (2)

Solve equation (1) and equation (2),

$$\begin{array}{rl} y4 = & 0.25 * x4 - 0.05 \\ - y4 = & - 0.50 * x4 + 1.25 \\ \hline 0 = & - 0.25 * x4 + 1.2 \end{array}$$

⇨ 0.25 * x4 = 1.2

⇨ x4 = 1.2 / 0.25

x4 = 4.8

Substitute x4 in equation (1) or equation (2),

Equation (1) → y4 = 0.25 * x4 – 0.05

⇨ y4 = 0.25 * 4.8 – 0.05

y4 = 1.15

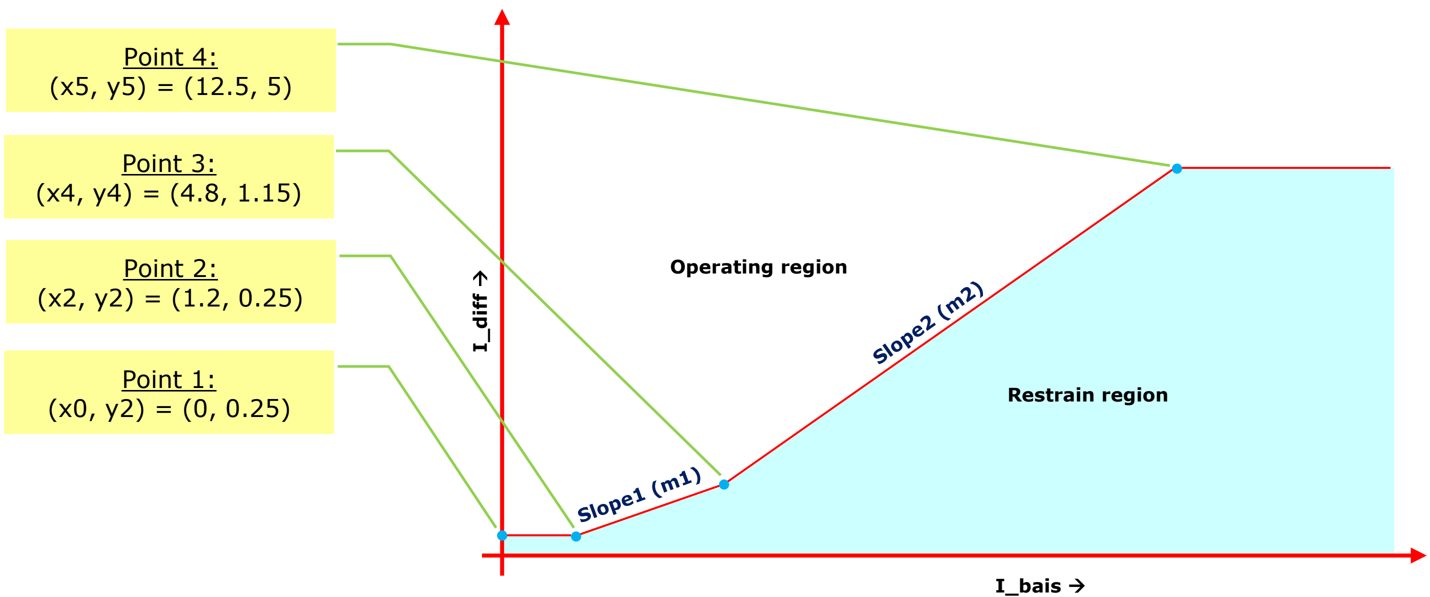


Diagram2: Final curve of 7UT6x Transformer diff. relay

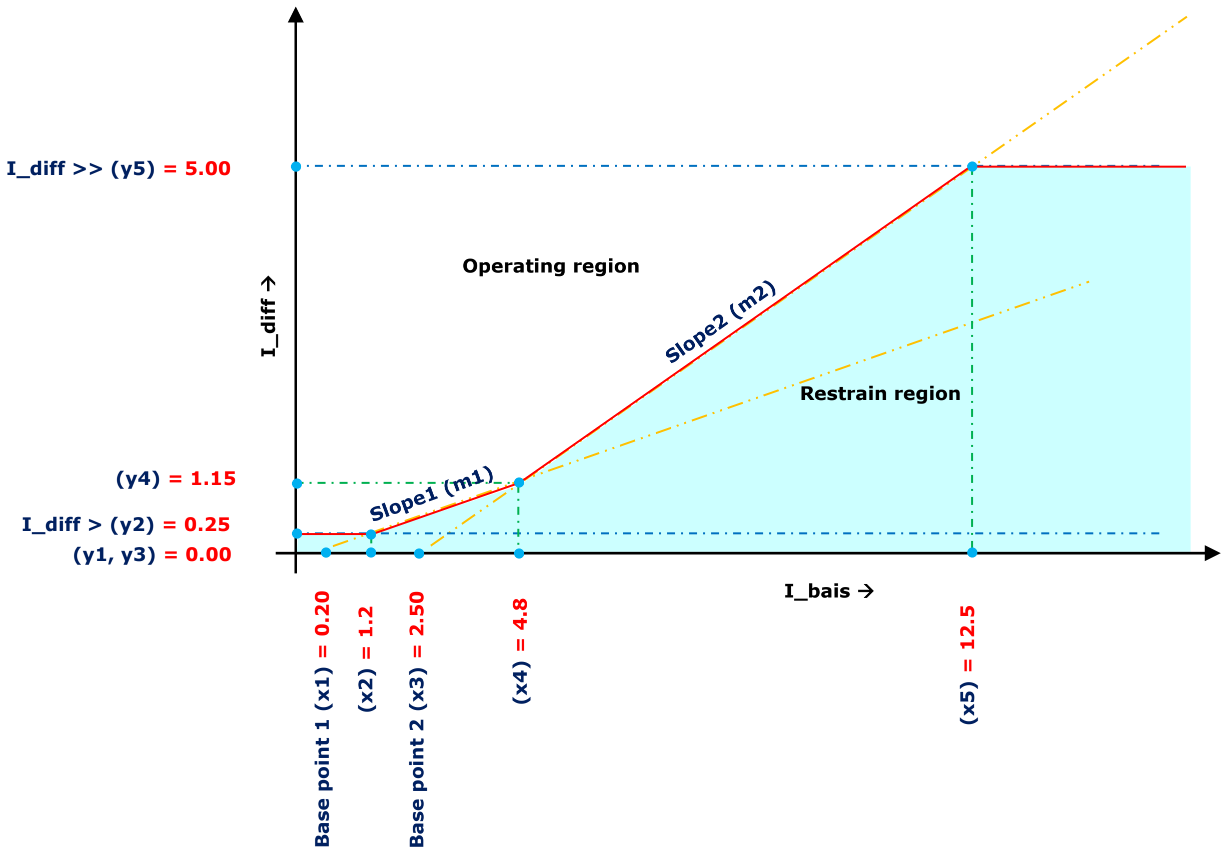


Diagram3: Final curve of 7UT6x Transformer diff. relay (after finding all unknown values)

PROTECTING TRANSFORMERS FROM INTERNAL FAULTS

The differential slope curve used to protect transformers from internal faults. If a fault occurs inside the transformer, the differential current will be greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

EXAMPLE

Consider a power transformer 30MVA, 132/11kV Yd1, having CTs on primary 200/1 and on secondary 1800/1A. Relay having the previously discussed setting.

$V_{L\text{-}L(hv)}$ = 132kV

$V_{L\text{-}L(lv)}$ = 11kV

P = 30MVA

Full load current calculation: (HV side)

P $= \sqrt{3} * V_{L-L(hv)} * I_{hv}$

I_{hv} $= P / (\sqrt{3} * V_{L-L(hv)})$

$= 30,000,000 / (1.732 * 132,000)$

$= 131.22A$

Full load current calculation: (LV side)

P $= \sqrt{3} * V_{L-L(lv)} * I_{lv}$

I_{lv} $= P / (\sqrt{3} * V_{L-L(lv)})$

$= 30,000,000 / (1.732 * 11,000)$

$= 1574.59A$

Matching factor calculation:

CT Matching Factor is basically a multiplication factor by which secondary current of CTs on HV side and LV side is multiplied to make it equal to rated secondary current. This means, if the rated CT secondary current is 1A, then multiplication of CT secondary current by matching factor will give unity. To get this multiplication factor, a reference current is assumed for HV and LV side separately. This reference current is Full Load current.

As we know that in differential protection, phasor sum of CT secondary current are considered for calculation of differential current. In transformer differential protection, the CT ratio in HV and LV side are different, therefore merely taking the phasor sum will result in some definite differential current which may be more than the low set differential setting and hence will lead to actuation of differential element of relay even under normal operating condition. Therefore, it is very important to match the CT secondary current so that differential current is zero under normal operating condition.

Let us understand this with an example. As we know that full load current on HV is $I_{hv} = 131.22$ and on LV is $I_{lv} = 1574.59$. Transformer is running with full load at normal condition.

Full load current on CT secondary side will be given as ($I_{hv} * CTR_{hv} = 131.22 / 200 = 0.656$) and ($I_{lv} * CTR_{lv} = 1574.59 / 1800 = 0.875$)

Where, CTR_{hv} & CTR_{lv} are the CT ratio of HV CT and LV CT.

Thus the differential current under the considered full load condition,

Idiff $= I_{lv} - I_{hv} = 0.875 - 0.656 = 0.219$

If Idiff> setting is 0.2, then the relay differential element will operate in normal full load operation. To avoid such an occurrence it is important to match the HV and LV side CT secondary current so that their phasor sum may be zero under normal situation. In addition, the rated CT secondary current is 1 A, we need to limit the CT secondary current to 1.

Multiplication of actual CT secondary current by matching factor under various normal operating conditions will limit it to 1.

So what will we do to match? We will introduce a term called Matching Factor (MF). What this Matching Factor will do is that when we multiply the HV and LV side CT secondary current corresponding to full load current by this matching factor, the result will be 1. Let us now calculate this.

HV side, I_{mhv} = CTR_{hv} / I_{hv} = 200 / 131.22 = 1.524

Or I_{mhv} = 1 / $I_{hv(CT\ secondary)}$ = 1 / 0.656 = 1.524

LV side, I_{mlv} = CTR_{lv} / I_{lv} = 1800 / 1574.59 = 1.143

Or I_{mlv} = 1 / $I_{lv(CT\ secondary)}$ = 1 / 0.875 = 1.143

I_{mhv} & I_{mlv} are the HV & LV CT matching factor.

Thus the differential current under the considered full load condition with matching factor,

$I_{diff} = I_{lv} * I_{mlv} - I_{hv} * I_{mhv}$ = 0.875 * 1.143 – 0.656 * 1.524 = 0

The relay differential element will operate because the value is under pickup.

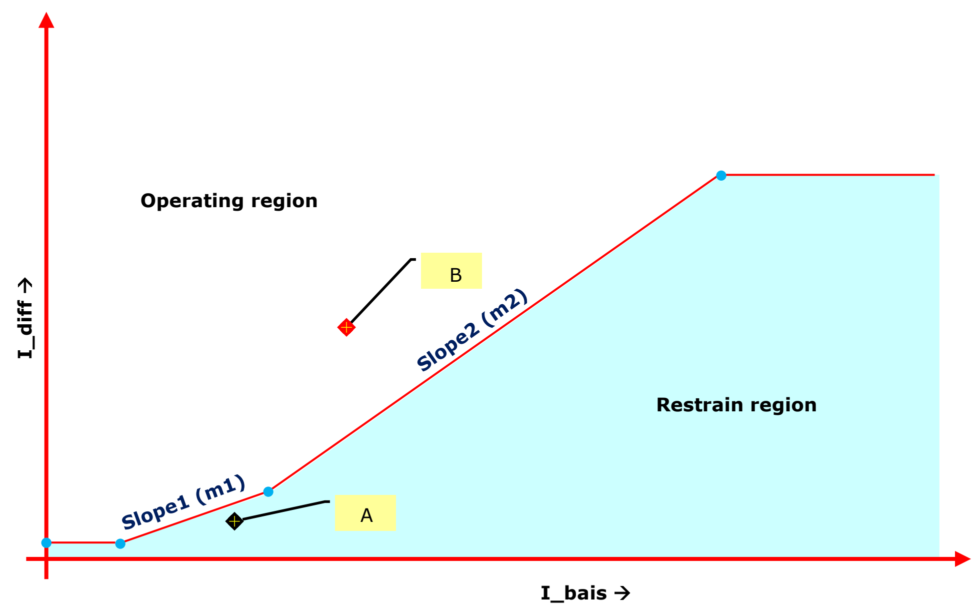


Diagram4: Curve of 7UT6x Transformer diff. relay with calculated points

TESTING BY INJECTING CURRENT IN RESTRAIN AND OPERATING REGION

Point A (Restrain region)

Consider injecting 3 phase HV side current, Ip = 1.5 <0° and LV side current, Is = 1.5 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.5 <(210° - 30°) = 1.5 <180°.

Idiff = |Ip + Is| = |Ip * I_{mhv} + Is * I_{mlv} | …… *Relay will consider with matching factor*

= |(1.5 <0°) * 1.524 + (1.5 <180°) * 1.143|

= |(2.286<0°) + (1.715<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 2.286 *i* * sin(0)] + [1.715 * cos(180) + 1.715 *i* * sin(180)] |

= | [2.286 + 0] + [−1.715 + 0] |

Idiff = |2.286 – 1.715| = 0.571

Ibais = |Ip| + |Is| = |Ip * I_{mhv}| + |Is * I_{mlv} |

= |(1.5 <0°) * 1.524| + |(1.5 <180°) * 1.143|

= |(2.286<0°)| + |(1.715<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 2.286 *i* * sin(0)]| + |[1.715 * cos(180) + 1.715 *i* * sin(180)] |

= | [2.286 + 0]| + |[−1.715 + 0] |

Ibais = | 2.286 | + | -1.715 | = 2.286 + 1.715 = 4.001

Since the point (0.571, 4.001) is in restrain region, relay will not operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN RESTRAIN REGION,

We know that slope1 = 0.25 and slope2 = 0.5,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.25
- if Ibais value is under slope2 line, then k = 0.50

In our condition, slope1 ends 4.8 and the calculated value is under it. So we can take k = 0.25

Calculate k * Ibais = 0.25 * 4.001 = 1.0

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (0.571) which is less than k*Ibais (1.0). So the point is in restrain region. *[Refer diagram4]*

Point B (Operating region)

Consider injecting 3 phase HV side current, Ip = 3.00 <0° and LV side current, Is = 1.0 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.0 <(210° - 30°) = 1.0 <180°.

Idiff = |Ip + Is| = |Ip * I_{mhv} + Is * I_{mlv} | …… *Relay will consider with matching factor*

= |(3.0 <0°) * 1.524 + (1.0 <180°) * 1.143|

= |(4.572<0°) + (1.143<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)] + [1.143 * cos(180) + 1.143 *i* * sin(180)] |

= | [4.572 + 0] + [−1.143 + 0] |

Idiff = |4.572 – 1.143| = 3.429

Ibais = |Ip| + |Is| = |Ip * I_{mhv}| + |Is * I_{mlv} |

= |(3.0 <0°) * 1.524| + |(1.0 <180°) * 1.143|

= |(4.572<0°)| + |(1.143<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)]| + |[1.143 * cos(180) + 1.143 *i* * sin(180)] |

= | [4.572 + 0]| + |[−1.143 + 0] |

Ibais = | 4.572 | + | -1.143 | = 4.572 + 1.143 = 5.715

Since the point (3.429, 5.715) is in operating region, relay will operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN OPERATING REGION,

We know that slope1 = 0.25 and slope2 = 0.5,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.25
- if Ibais value is under slope2 line, then k = 0.50

In our condition, slope1 line ends at Ibais = 4.8 and the calculated value (5.715) is greater 4.8 . So we can take k = 0.5

Calculate k * Ibais = 0.5 * 5.715 = 2.8565

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (3.429) which is greater than k*Ibais (2.857). So the point is in operating region. the relay will trip, disconnecting the transformer from the power system. *[Refer diagram4]*

VECTOR GROUP COMPENSATION / CORRECTION FACTOR

In transformer differential protection, vector group compensation, also known as correction factor, addresses the issue of phase angle shift introduced by different transformer connections.

Here's what you need to know:

1. TRANSFORMER VECTOR GROUPS:

Transformers come in various connection configurations, called vector groups. These groups determine the phase relationship between the high-voltage (HV) and low-voltage (LV) sides. For example, a Dyn1 transformer introduces a 30° phase lag from HV to LV.

2. PHASE SHIFT AND MALOPERATION:

This phase shift can create a differential current even under normal conditions, potentially causing the protection scheme to misinterpret it as a fault and trip unnecessarily. This situation can disrupt power supply and lead to false alarms.

3. COMPENSATION METHODS:

CT CONNECTION: Traditionally, compensation is achieved by wiring the current transformers (CTs) on either the HV or LV side in a specific way to introduce an opposite phase shift of the same magnitude, effectively "canceling out" the transformer's natural shift.

NUMERICAL RELAYS: Modern numerical relays offer internal algorithms that perform mathematical calculations to account for the vector group and adjust the measured currents accordingly. This provides greater flexibility and avoids complex CT wiring configurations.

4. BENEFITS OF COMPENSATION:

ACCURATE FAULT DETECTION: Prevents misoperation due to phase shift, ensuring reliable protection against internal faults.

IMPROVED STABILITY: Reduces nuisance tripping, enhancing the overall stability of the power system.

SIMPLIFIED CONFIGURATION: Numerical compensation eliminates the need for special CT connections, potentially lowering installation and maintenance costs.

5. FACTORS TO CONSIDER:

CORRECT VECTOR GROUP IDENTIFICATION: Choosing the wrong compensation based on an incorrect vector group can still lead to problems.

RELAY SETTINGS: Numerical relays require proper configuration of the vector group and other parameters to function accurately.

CT ACCURACY: Maintaining accurate CT performance is crucial for reliable operation of the scheme.

Remember, vector group compensation is a vital aspect of ensuring accurate and reliable transformer differential protection. Understanding its principle and implementation allows for proper configuration and maintenance of this essential power system safeguard.

CALCULATION WITH CORRECTION FACTOR

Trip point = Idiff_lowset * CT matching factor * correction factor

Type of fault	Reference Winding (Upper voltage)	Even VG-numeral (0,2,4,6,8,10)	Odd VG-numeral (1,3,5,7,9,11)
3 PH	1	1	1
2 PH	1	1	0.866
1 PH With Io	1.5	1.5	1.73
1 PH Without Io	1	1	1.73

Table: Correction factor depending on vector group for 7UT6x

SEIMENS 7UT8X – CALCULATION

The 7UT8x Transformer Differential Relay uses a dual-slope characteristic to distinguish between internal and external faults. The relay settings for this characteristic are as follows:

RELAY SETTING [7UT8X]

Threshold Value	:	0.25	(y1)
Slope 1	:	0.30	(m1)
Slope 2	:	0.70	(m2)
Intersection 1 Irest	:	0.75	(x1)
Intersection 2 Irest	:	4.00	(x2)
I-diff Unrestrained	:	8.00	(y3)

The differential slope curve is a plot of the differential current (I_diff) versus the restraining current (I_bias). The restraining current is calculated based on the currents flowing into and out of the transformer.

The relay settings are as follows:

Slope 1: This is the slope of the first line segment of the curve. It is equal to 0.30

Slope 2: This is the slope of the second line segment of the curve. It is equal to 0.70

Intersection 1 Irest: This is the point on the curve where the first line segment intersects the x-axis with y-axis. It is equal to 0.75

Intersection 2 Irest: This is the point on the curve where the second line segment intersects the first line segment. It is equal to 4.0

Threshold Value: This is the minimum differential current that must be exceeded before the relay will trip. It is equal to 0.25

I-diff Unrestrained: This is the maximum differential current that the relay will tolerate before tripping. It is equal to 8.00

DIFFERENTIAL SLOPE CURVE

The differential slope curve is a characteristic of transformer differential relays that is used to distinguish between internal and external faults. The curve is divided into two regions: the restrain region and the operating region.

RESTRAINT REGION

The restrain region is the area below the curve. In this region, the differential current is less than the restraining current, and the relay will not trip. This is to prevent the relay from tripping on external faults, where the differential current may be high due to CT saturation or other factors.

OPERATING REGION

The operating region is the area above the curve. In this region, the differential current is greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

The dual-slope characteristic is shown in the diagram below:

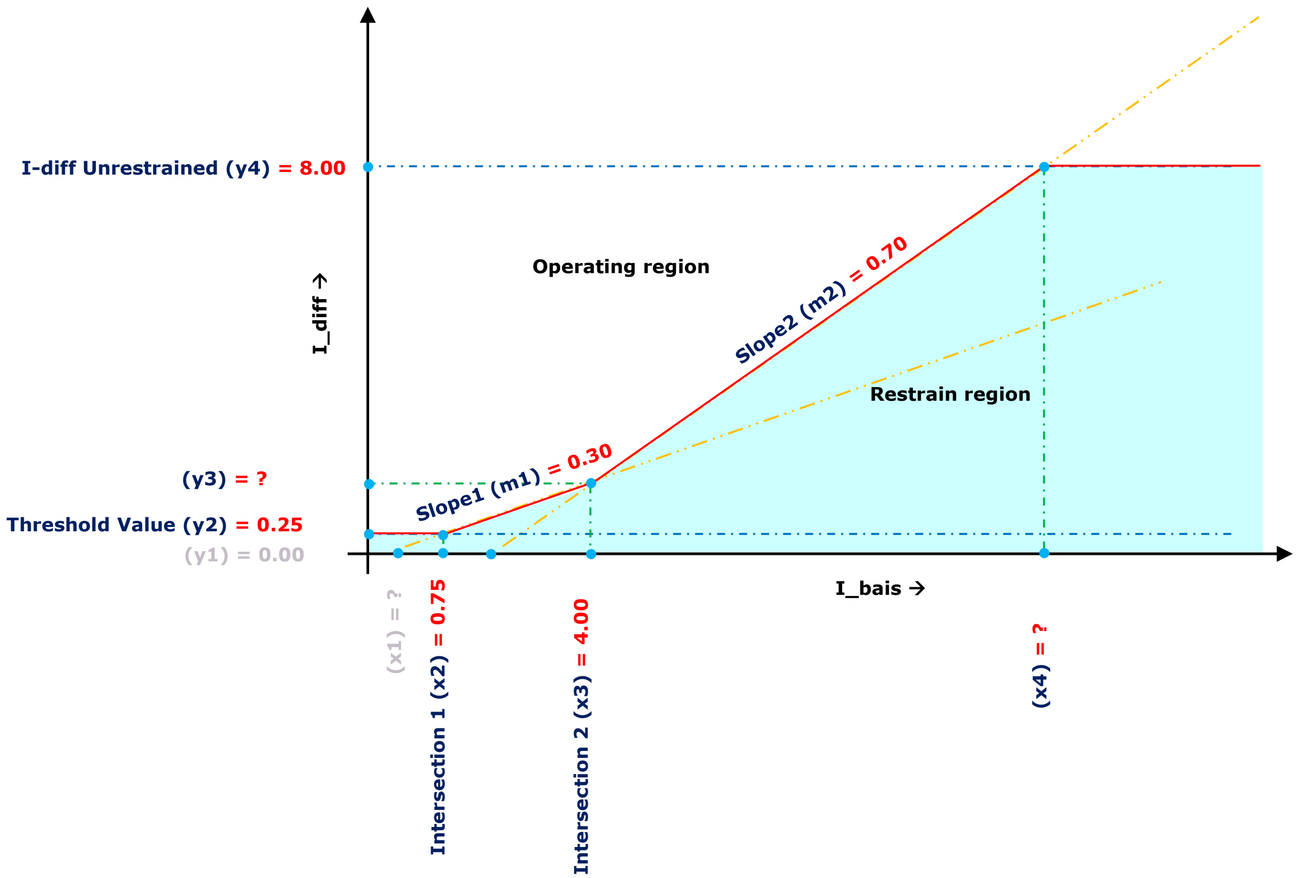


Diagram1: 7UT8x Transformer Differential Relay dual-slope characteristic

SLOPE POINTS CALCULATION

From the differential slope curve, the following values are known:

m1 = 0.30

m2 = 0.70

x2 = 0.75

x3 = 4.00

y2 = 0.25

y4 = 8.00

We need to determine y3 and x4.

Let us find the value of y3 from the line1 (x2, y2) to (x3, y3) with the slope m1.

x2 = 0.75, y2 = 0.25, x3 = 4.00, y3 = ?, m1 = 0.30

Line formula, y = mx.

- ⇨ (y3 – y2) = m1 * (x3 – x2)
- ⇨ (y3 – 0.25) = 0.30 * (4.00 – 0.75)
- ⇨ y3 = 1.2 – 0.225 + 0.25

y3 = 1.225

Let us find the value of x4 from the line2 (x3, y3) to (x4, y4) with the slope m2.

x3 = 4.00, y3 = 1.225, y4 = 8.0, x4 = ?, m2 = 0.70

Line formula, y = mx.

- ⇨ (y4 – y3) = m2 * (x4 – x3)
- ⇨ (8.0 – 1.225) = 0.7 * (x4 – 4.0)
- ⇨ 6.775 = 0.7 x4 – 2.8
- ⇨ 0.7 x4 = 9.575
- ⇨ X4 = 9.575 / 0.7

X4 = 13.6785

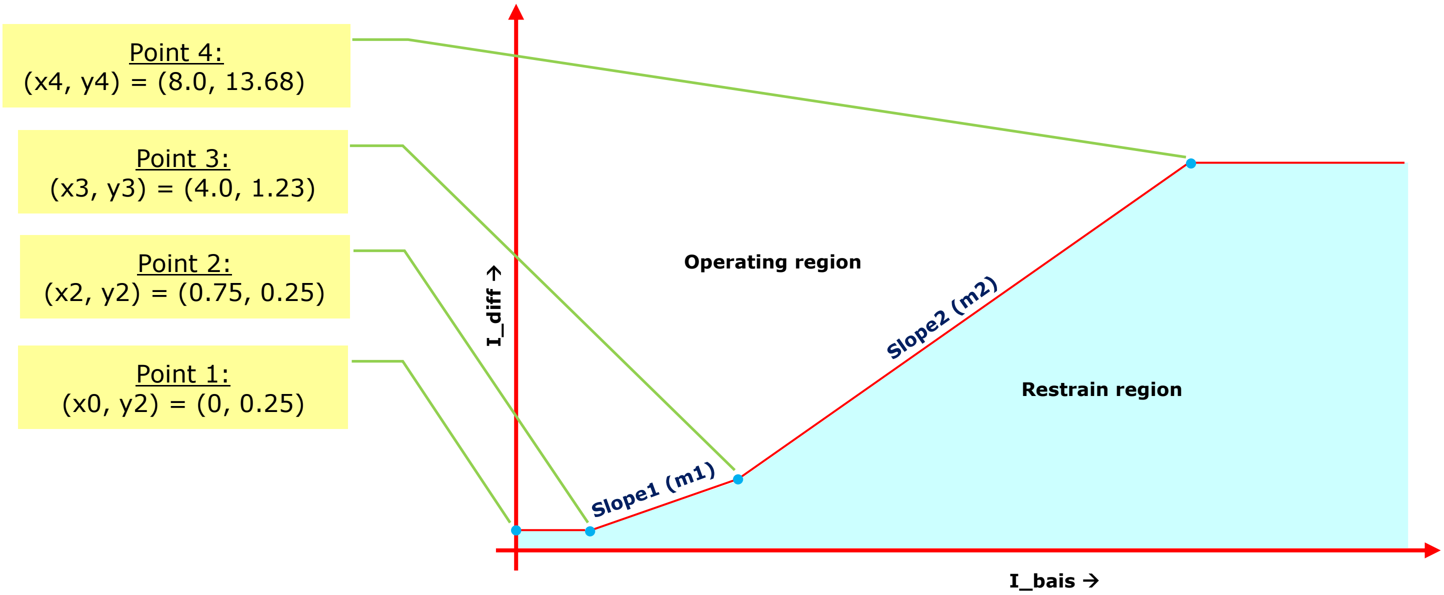


Diagram2: Final curve of 7UT8x Transformer diff. relay

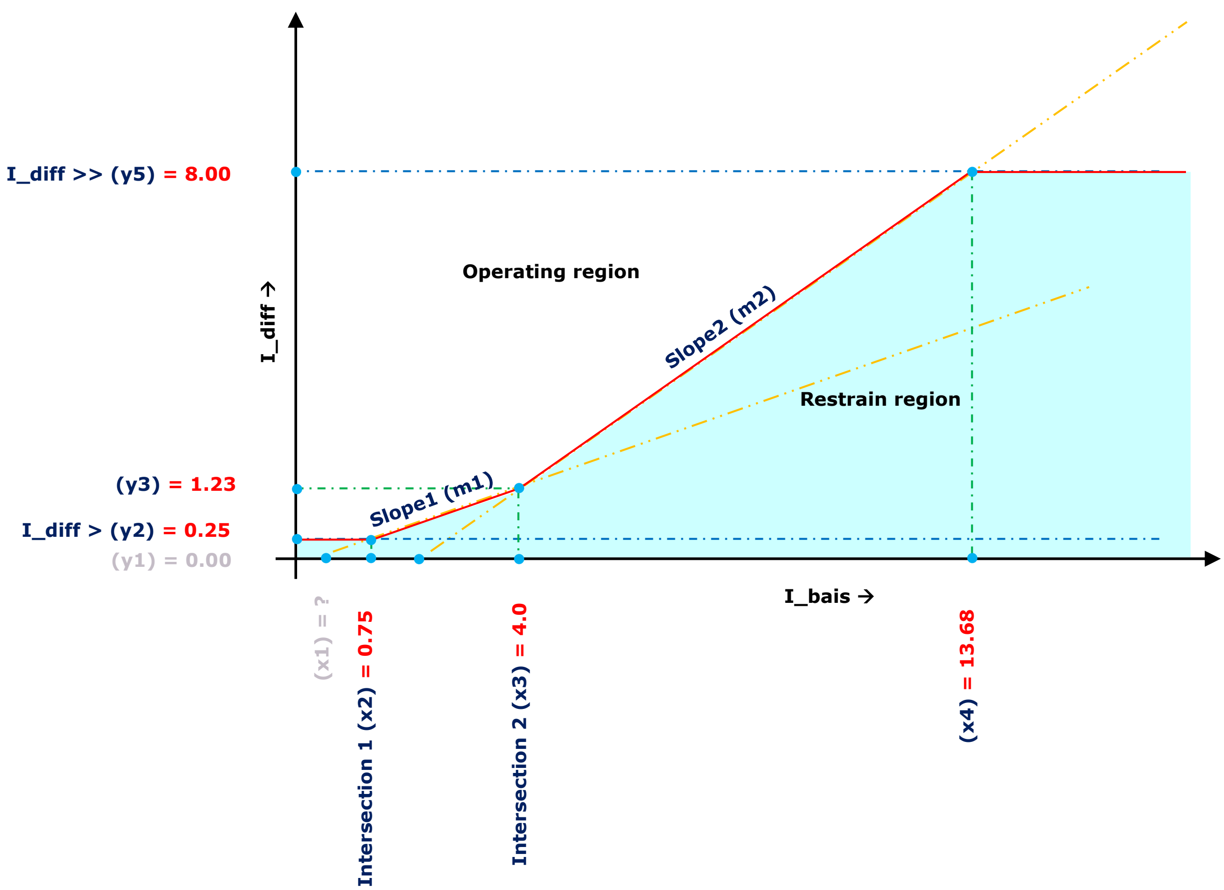


Diagram3: Final curve of 7UT8x Transformer diff. relay (after finding all unknown values)

PROTECTING TRANSFORMERS FROM INTERNAL FAULTS

The differential slope curve used to protect transformers from internal faults. If a fault occurs inside the transformer, the differential current will be greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

EXAMPLE

Consider a power transformer 30MVA, 132/11kV Yd1, having CTs on primary 200/1 and on secondary 1800/1A. Relay having the previously discussed setting.

$V_{L-L(hv)}$ = 132kV

$V_{L-L(lv)}$ = 11kV

P = 30MVA

Full load current calculation: (HV side)

$P = \sqrt{3} * V_{L-L(hv)} * I_{hv}$

$I_{hv} = P / (\sqrt{3} * V_{L-L(hv)})$

$= 30,000,000 / (1.732 * 132,000)$

$= 131.22A$

Full load current calculation: (LV side)

$P = \sqrt{3} * V_{L-L(lv)} * I_{lv}$

$I_{lv} = P / (\sqrt{3} * V_{L-L(lv)})$

$= 30,000,000 / (1.732 * 11,000)$

$= 1574.59A$

Matching factor calculation:

CT Matching Factor is basically a multiplication factor by which secondary current of CTs on HV side and LV side is multiplied to make it equal to rated secondary current. This means, if the rated CT secondary current is 1A, then multiplication of CT secondary current by matching factor will give unity. To get this multiplication factor, a reference current is assumed for HV and LV side separately. This reference current is Full Load current.

As we know that in differential protection, phasor sum of CT secondary current are considered for calculation of differential current. In transformer differential protection, the CT ratio in HV and LV side are different, therefore merely taking the phasor sum will result in some definite differential current which may be more than the low set differential setting and hence will lead to actuation of differential element of relay even under normal operating condition. Therefore, it is very important to match the CT secondary current so that differential current is zero under normal operating condition.

Let us understand this with an example. As we know that full load current on HV is I_{hv} = 131.22 and on LV is I_{lv} = 1574.59 . Transformer is running with full load at normal condition.

Full load current on CT secondary side will be given as ($I_{hv} * CTR_{hv}$ = 131.22 / 200 = 0.656) and ($I_{lv} * CTR_{lv}$ = 1574.59 / 1800 = 0.875)

Where, CTR_{hv} & CTR_{lv} are the CT ratio of HV CT and LV CT.

Thus the differential current under the considered full load condition,

Idiff = $I_{lv} - I_{hv}$ = 0.875 – 0.656 = 0.219

If Idiff> setting is 0.2, then the relay differential element will operate in normal full load operation. To avoid such an occurrence it is important to match the HV and LV side CT secondary current so that their phasor sum may be zero under normal situation. In addition, the rated CT secondary current is 1 A, we need to limit the CT secondary current to 1.

Multiplication of actual CT secondary current by matching factor under various normal operating conditions will limit it to 1.

So what will we do to match? We will introduce a term called Matching Factor (MF). What this Matching Factor will do is that when we multiply the HV and LV side CT secondary current corresponding to full load current by this matching factor, the result will be 1. Let us now calculate this.

HV side, I_{mhv} = CTR_{hv} / I_{hv} = 200 / 131.22 = 1.524

Or I_{mhv} = 1 / $I_{hv(CT\ secondary)}$ = 1 / 0.656 = 1.524

LV side, I_{mlv} = CTR_{lv} / I_{lv} = 1800 / 1574.59 = 1.143

Or I_{mlv} = 1 / $I_{lv(CT\ secondary)}$ = 1 / 0.875 = 1.143

I_{mhv} & I_{mlv} are the HV & LV CT matching factor.

Thus the differential current under the considered full load condition with matching factor,

Idiff = $I_{lv} * I_{mlv} – I_{hv} * I_{mhv}$ = 0.875 * 1.143 – 0.656 * 1.524 = 0

The relay differential element will operate because the value is under pickup.

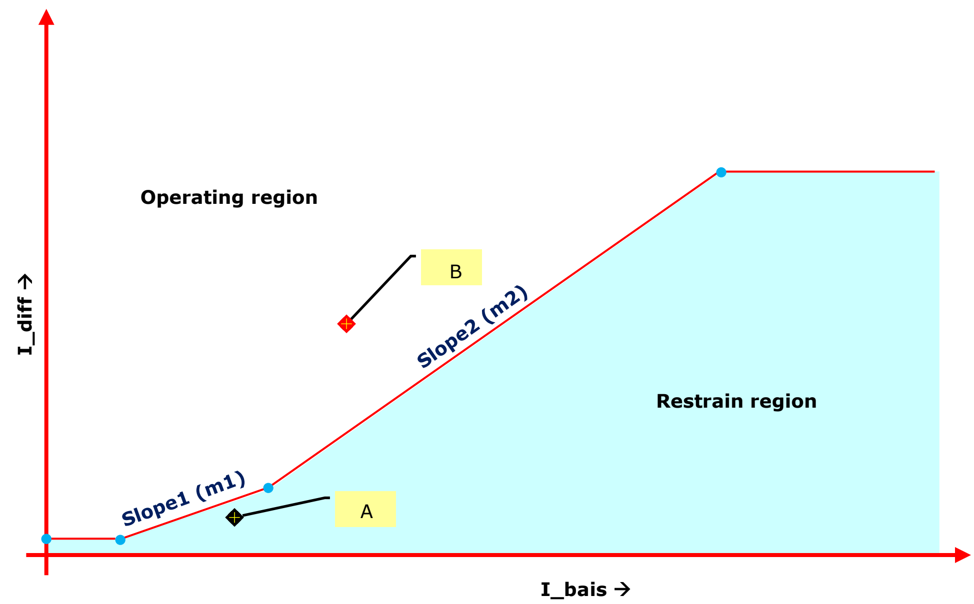


Diagram4: Curve of 7UT8x Transformer diff. relay with calculated points

TESTING BY INJECTING CURRENT IN RESTRAIN AND OPERATING REGION

Point A (Restrain region)

Consider injecting 3 phase HV side current, Ip = 1.5 <0° and LV side current, Is = 1.5 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.5 <(210° - 30°) = 1.5 <180°.

Idiff = |Ip + Is| = |Ip * I_{mhv} + Is * I_{mlv} | …… *Relay will consider with matching factor*

= |(1.5 <0°) * 1.524 + (1.5 <180°) * 1.143|

= |(2.286 <0°) + (1.715 <180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 1.219 *i* * sin(0)] + [1.715 * cos(180) + 1.715 *i* * sin(180)] |

= | [2.286 + 0] + [−1.715 + 0] |

Idiff = |2.286 – 1.715| = 0.5715

Ibais = Max (|Ip|, |Is|) = Max (|Ip * I_{mhv}| + |Is * I_{mlv} |)

= Max { |(1.5 <0°) * 1.524|, |(1.5 <180°) * 1.143| }

= Max { |(2.286 <0°)|, |(1.715<180°)| } = |(2.286 <0°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 1.715 *i* * sin(0)]|

= | [2.286 + 0]|

Ibais = | 2.286 | = 2.286

Since the point (2.286, 0.572) is in restrain region, relay will not operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN RESTRAIN REGION,

We know that slope1 = 0.3 and slope2 = 0.7,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.30
- if Ibais value is under slope2 line, then k = 0.70

In our condition, slope1 ends 4.0 and the calculated value is under it. So we can take k = 0.30

Calculate k * Ibais = 0.30 * 2.286 = 0.6858

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (0.5715) which is less than k*Ibais (0.6858). So the point is in restrain region. *[Refer diagram4]*

Point B (Operating region)

Consider injecting 3 phase HV side current, Ip = 3.00 <0° and LV side current, Is = 1.0 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.0 <(210° - 30°) = 1.0 <180°.

Idiff = |Ip + Is| = |Ip * Imhv + Is * Imlv | *…… Relay will consider with matching factor*

= |(3.0 <0°) * 1.524 + (1.0 <180°) * 1.143|

= |(4.572<0°) + (1.143<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)] + [1.143 * cos(180) + 1.143 *i* * sin(180)] |

= | [4.572 + 0] + [−1.143 + 0] |

Idiff = |4.572 – 1.143| = 3.429

Ibais = Max { |Ip|, |Is| } = Max{ |Ip * I_{mhv}|, |Is * I_{mlv} | }

= Max { |(3.0 <0°) * 1.524|, |(1.0 <180°) * 1.143| }

= Max { |(4.572<0°)|, |(1.143<180°)| } = |(4.572<0°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)]|

= | [4.572 + 0]|

Ibais = | 4.572 | = 4.572

Since the point (4.572, 3.429) is in operating region, relay will operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN OPERATING REGION,

We know that slope1 = 0.3 and slope2 = 0.7,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.30
- if Ibais value is under slope2 line, then k = 0.70

In our condition, slope1 line ends at Ibais = 4.0 and the calculated value (4.572) is greater 4.0 . So we can take k = 0.7

Calculate k * Ibais = 0.7 * 4.572 = 3.2004

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (3.429) which is greater than k*Ibais (3.2). So the point is in operating region. the relay will trip, disconnecting the transformer from the power system. *[Refer diagram4]*

VECTOR GROUP COMPENSATION / CORRECTION FACTOR

In transformer differential protection, vector group compensation, also known as correction factor, addresses the issue of phase angle shift introduced by different transformer connections.

Here's what you need to know:

1. TRANSFORMER VECTOR GROUPS:

Transformers come in various connection configurations, called vector groups. These groups determine the phase relationship between the high-voltage (HV) and low-voltage (LV) sides. For example, a Dyn1 transformer introduces a 30° phase lag from HV to LV.

2. PHASE SHIFT AND MALOPERATION:

This phase shift can create a differential current even under normal conditions, potentially causing the protection scheme to misinterpret it as a fault and trip unnecessarily. This situation can disrupt power supply and lead to false alarms.

3. COMPENSATION METHODS:

CT CONNECTION: Traditionally, compensation is achieved by wiring the current transformers (CTs) on either the HV or LV side in a specific way to introduce an opposite phase shift of the same magnitude, effectively "canceling out" the transformer's natural shift.

NUMERICAL RELAYS: Modern numerical relays offer internal algorithms that perform mathematical calculations to account for the vector group and adjust the measured currents accordingly. This provides greater flexibility and avoids complex CT wiring configurations.

4. BENEFITS OF COMPENSATION:

ACCURATE FAULT DETECTION: Prevents misoperation due to phase shift, ensuring reliable protection against internal faults.

IMPROVED STABILITY: Reduces nuisance tripping, enhancing the overall stability of the power system.

SIMPLIFIED CONFIGURATION: Numerical compensation eliminates the need for special CT connections, potentially lowering installation and maintenance costs.

5. FACTORS TO CONSIDER:

CORRECT VECTOR GROUP IDENTIFICATION: Choosing the wrong compensation based on an incorrect vector group can still lead to problems.

RELAY SETTINGS: Numerical relays require proper configuration of the vector group and other parameters to function accurately.

CT ACCURACY: Maintaining accurate CT performance is crucial for reliable operation of the scheme.

Remember, vector group compensation is a vital aspect of ensuring accurate and reliable transformer differential protection. Understanding its principle and implementation allows for proper configuration and maintenance of this essential power system safeguard.

CALCULATION WITH CORRECTION FACTOR

Trip point = Idiff_lowset * correction factor

Type of fault	Reference Winding (Upper voltage)	Even VG-numeral (0,2,4,6,8,10)	Odd VG-numeral (1,3,5,7,9,11)
3 PH	1	1	1
2 PH	1	1	0.866
1 PH With Io	1.5	1.5	1.73
1 PH Without Io	1	1	1.1

Table: Correction factor depending on vector group for 7UT8x

MICOM P6XX – CALCULATION

The P6xx Transformer Differential Relay uses a dual-slope characteristic to distinguish between internal and external faults. The relay settings for this characteristic are as follows:

RELAY SETTING [P6XX]

Intersection 1, Is1	:	0.25	(y1)
Slope 1	:	0.30	(m1)
Slope 2	:	0.50	(m2)
Intersection 2, Is2	:	4.00	(x1)
High Set 1, Is-HS1	:	6.00	-
High Set 2, Is-HS2	:	8.00	(y3)

The differential slope curve is a plot of the differential current (I_diff) versus the restraining current (I_bias). The restraining current is calculated based on the currents flowing into and out of the transformer.

The relay settings are as follows:

Slope 1: This is the slope of the first line segment of the curve. It is equal to 0.30

Slope 2: This is the slope of the second line segment of the curve. It is equal to 0.50

Intersection 2, Is2: This is the point on the curve where the first line segment intersects the x-axis with y-axis 0.2.

Intersection 1, Is1: This is the minimum differential current that must be exceeded before the relay will trip. It is equal to 0.25

High Set 2, Is-HS2: This is the maximum differential current that the relay will tolerate before tripping. It is equal to 8.00

DIFFERENTIAL SLOPE CURVE

The differential slope curve is a characteristic of transformer differential relays that is used to distinguish between internal and external faults. The curve is divided into two regions: the restrain region and the operating region.

RESTRAINT REGION

The restrain region is the area below the curve. In this region, the differential current is less than the restraining current, and the relay will not trip. This is to prevent the relay from tripping on external faults, where the differential current may be high due to CT saturation or other factors.

OPERATING REGION

The operating region is the area above the curve. In this region, the differential current is greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

The dual-slope characteristic is shown in the diagram below:

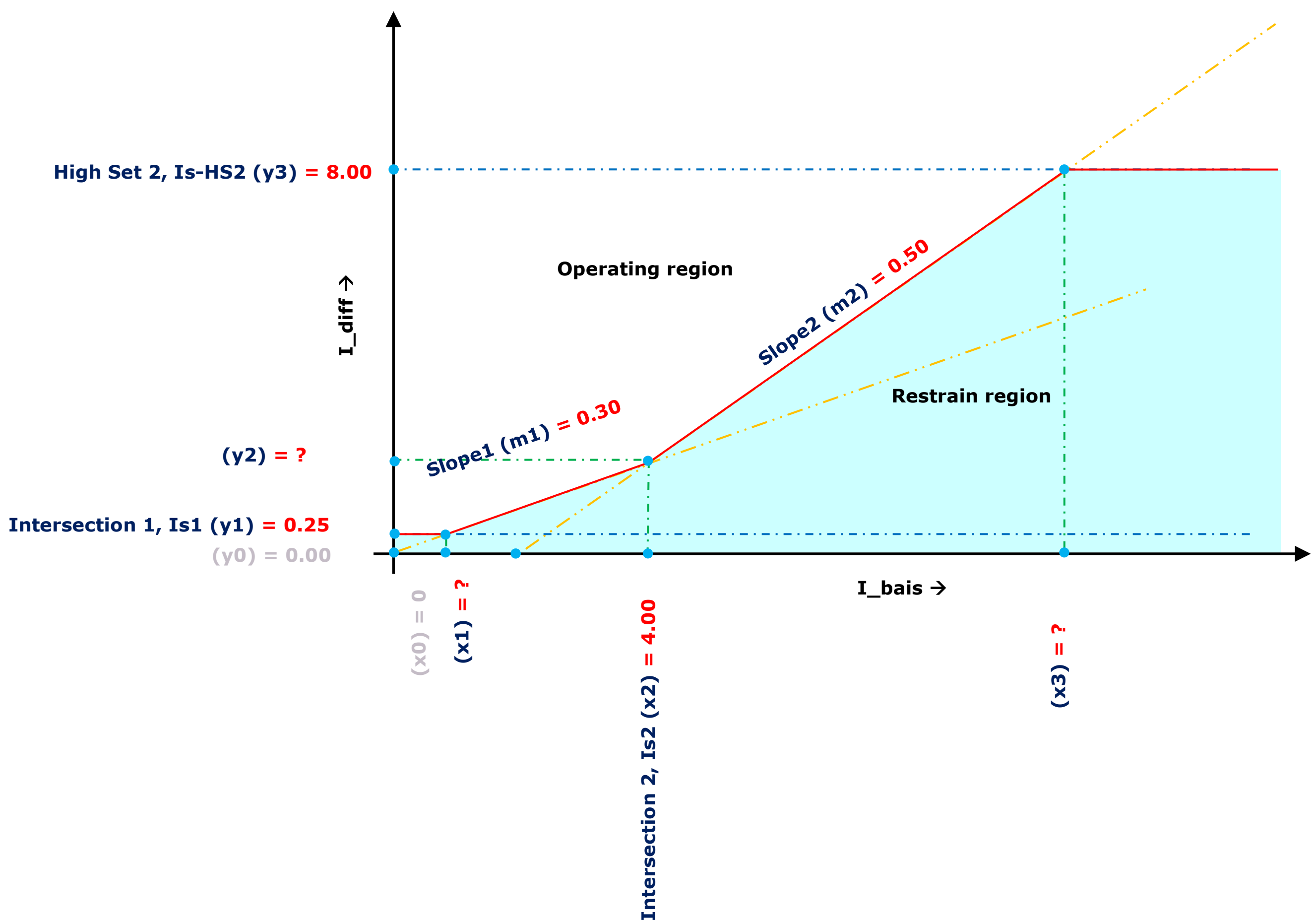


Diagram1: P6xx Transformer Differential Relay dual-slope characteristic

SLOPE POINTS CALCULATION

From the differential slope curve, the following values are known:

m1 = 0.30

m2 = 0.50

x2 = 4.00

y1 = 0.25

y3 = 8.00

We need to determine x1, y2 and x3.

Let us find the value of x1 from the line1 (x1, y1) to (x0, y0) with the slope m1. Consider x1 and y1 as 0.

x0 = 0, y0 = 0, x1 = ?, y1 = 0.25, m1 = 0.30

Line formula, y = mx.

⇨ (y1 – y0) = m1 * (x1 – x0)

⇨ (0.25 – 0) = 0.30 * (x1 – 0)

⇨ 0.25 = 0.3 * x1

x1 = 0.8333

Let us find the value of y2 from the line2 (x1, y1) to (x2, y2) with the slope m1.

x1 = 0.8333, y1 = 0.25, y2 = ?, x2 = 4.0, m1 = 0.30

Line formula, y = mx.

⇨ (y2 – y1) = m1 * (x2 – x1)

⇨ (y2 – 0.25) = 0.3 * (4.0 – 0.8333)

⇨ y2 = 1.2 – 0.2499 + 0.25

y2 = 1.2

Let us find the value of x3 from the line2 (x2, y2) to (x3, y3) with the slope m2.

x2 = 4.0, y2 = 1.2, y3 = 8.0, x3 = ?, m2 = 0.5

Line formula, y = mx.

⇨ (y3 – y2) = m2 * (x3 – x2)

⇨ (8.0 – 1.2) = 0.5 * (x3 – 4.0)

⇨ 6.8 = 0.5 * x3 – 2.0

x3 = 17.60

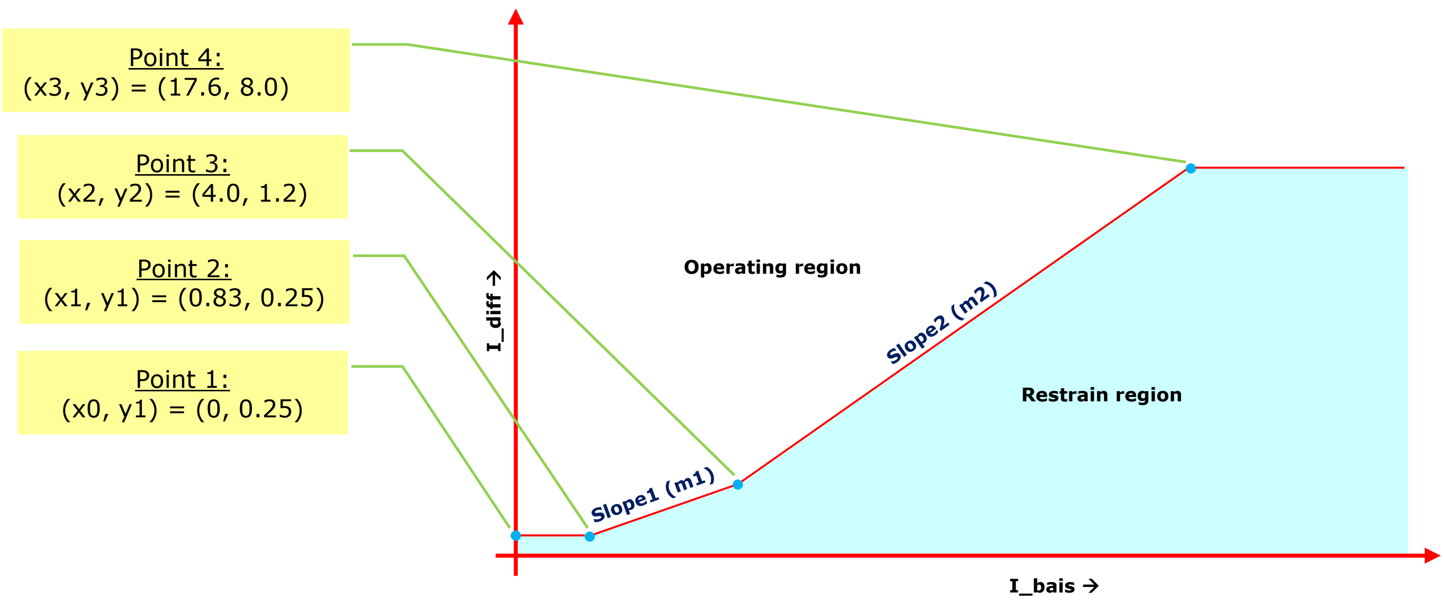


Diagram2: Final curve of 7UT8x Transformer diff. relay

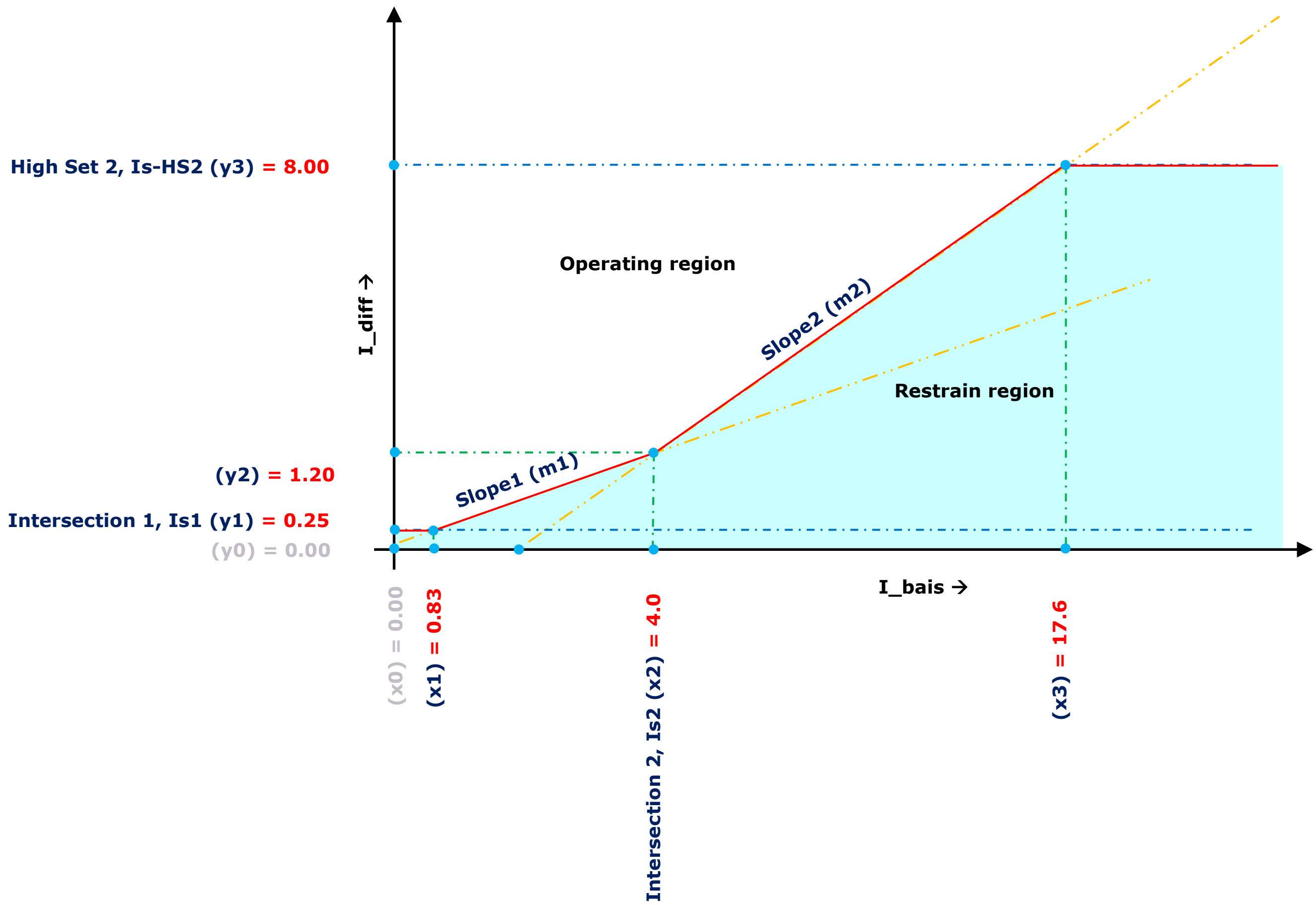


Diagram3: Final curve of 7UT8x Transformer diff. relay (after finding all unknown values)

PROTECTING TRANSFORMERS FROM INTERNAL FAULTS

The differential slope curve used to protect transformers from internal faults. If a fault occurs inside the transformer, the differential current will be greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

EXAMPLE

Consider a power transformer 30MVA, 132/11kV Yd1, having CTs on primary 200/1 and on secondary 1800/1A. Relay having the previously discussed setting.

$V_{L-L(hv)}$ = 132kV

$V_{L-L(lv)}$ = 11kV

P = 30MVA

Full load current calculation: (HV side)

$P = \sqrt{3} * V_{L-L(hv)} * I_{hv}$

$I_{hv} = P / (\sqrt{3} * V_{L-L(hv)})$

$= 30,000,000 / (1.732 * 132,000)$

$= 131.22A$

Full load current calculation: (LV side)

$P = \sqrt{3} * V_{L-L(lv)} * I_{lv}$

$I_{lv} = P / (\sqrt{3} * V_{L-L(lv)})$

$= 30,000,000 / (1.732 * 11,000)$

$= 1574.59A$

Matching factor calculation:

CT Matching Factor is basically a multiplication factor by which secondary current of CTs on HV side and LV side is multiplied to make it equal to rated secondary current. This means, if the rated CT secondary current is 1A, then multiplication of CT secondary current by matching factor will give unity. To get this multiplication factor, a reference current is assumed for HV and LV side separately. This reference current is Full Load current.

As we know that in differential protection, phasor sum of CT secondary current are considered for calculation of differential current. In transformer differential protection, the CT ratio in HV and LV side are different, therefore merely taking the phasor sum will result in some definite differential current which may be more than the low set differential setting and hence will lead to actuation of differential element of relay even under normal operating condition. Therefore, it is very important to match the CT secondary current so that differential current is zero under normal operating condition.

Let us understand this with an example. As we know that full load current on HV is I_{hv} = 131.22 and on LV is I_{lv} = 1574.59 . Transformer is running with full load at normal condition.

Full load current on CT secondary side will be given as ($I_{hv} * CTR_{hv}$ = 131.22 / 200 = 0.656) and ($I_{lv} * CTR_{lv}$ = 1574.59 / 1800 = 0.875)

Where, CTR_{hv} & CTR_{lv} are the CT ratio of HV CT and LV CT.

Thus the differential current under the considered full load condition,

$I_{diff} = I_{lv} - I_{hv} = 0.875 – 0.656 = 0.219$

If Idiff> setting is 0.2, then the relay differential element will operate in normal full load operation. To avoid such an occurrence it is important to match the HV and LV side CT secondary current so that their phasor sum may be zero under normal situation. In addition, the rated CT secondary current is 1 A, we need to limit the CT secondary current to 1.

Multiplication of actual CT secondary current by matching factor under various normal operating conditions will limit it to 1.

So what will we do to match? We will introduce a term called Matching Factor (MF). What this Matching Factor will do is that when we multiply the HV and LV side CT secondary current corresponding to full load current by this matching factor, the result will be 1. Let us now calculate this.

HV side, I_{mhv} = CTR_{hv} / I_{hv} = 200 / 131.22 = 1.524

Or I_{mhv} = 1 / I_{hv}(CT secondary) = 1 / 0.656 = 1.524

LV side, I_{mlv} = CTR_{lv} / I_{lv} = 1800 / 1574.59 = 1.143

Or I_{mlv} = 1 / I_{lv}(CT secondary) = 1 / 0.875 = 1.143

I_{mhv} & I_{mlv} are the HV & LV CT matching factor.

Thus the differential current under the considered full load condition with matching factor,

Idiff = $I_{lv} * I_{mlv} - I_{hv} * I_{mhv}$ = 0.875 * 1.143 – 0.656 * 1.524 = 0

The relay differential element will operate because the value is under pickup.

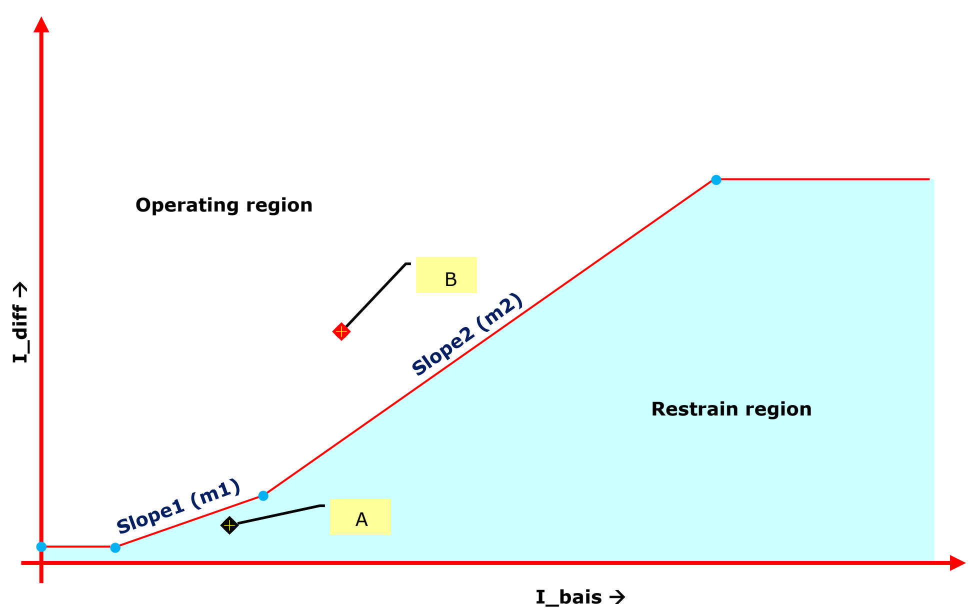


Diagram4: Curve of 7UT8x Transformer diff. relay with calculated points

TESTING BY INJECTING CURRENT IN RESTRAIN AND OPERATING REGION

Point A (Restrain region)

Consider injecting 3 phase HV side current, Ip = 1.5 <0° and LV side current, Is = 1.5 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.5 <(210° - 30°) = 1.5 <180°.

Idiff = |Ip + Is| = |Ip * I_{mhv} + Is * I_{mlv} | …… *Relay will consider with matching factor*

= |(1.5 <0°) * 1.524 + (1.5 <180°) * 1.143|

= |(2.286<0°) + (1.715<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 2.286 *i* * sin(0)] + [1.715 * cos(180) + 1.715 *i* * sin(180)] |

= | [2.286 + 0] + [−1.715 + 0] |

Idiff = |2.286 – 1.715| = 0.571

Ibais = { |Ip| + |Is| } / 2 = { |Ip * I_{mhv}| + |Is * I_{mlv} | } / 2

= { |(1.5 <0°) * 1.524| + |(1.5 <180°) * 1.143| } / 2

= { |(2.286<0°)| + |(1.715<180°)| } / 2

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= { | [2.286 * cos(0) + 2.286 *i* * sin(0)]| + |[1.715 * cos(180) + 1.715 *i* * sin(180)] | } / 2

= { | [2.286 + 0]| + |[−1.715 + 0] | } / 2

Ibais = { | 2.286 | + | -1.715 | } / 2 = {2.286 + 1.715} / 2 = 2.0

Since the point (0.571, 2.0) is in restrain region, relay will not operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN RESTRAIN REGION,

We know that slope1 = 0.3 and slope2 = 0.5,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.3
- if Ibais value is under slope2 line, then k = 0.5

In our condition, slope1 ends 4.0 and the calculated value is under it. So we can take k = 0.3

Calculate k * Ibais = 0.3 * 2.0 = 0.6

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (0.571) which is less than k*Ibais (0.6). So the point is in restrain region. *[Refer diagram4]*

Point B (Operating region)

Consider injecting 3 phase HV side current, Ip = 4.00 <0° and LV side current, Is = 3.0 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 3.0 <(210° - 30°) = 3.0 <180°.

Idiff = |Ip + Is| = |Ip * Imhv + Is * Imlv | …… *Relay will consider with matching factor*

= |(4.0 <0°) * 1.524 + (3.0 <180°) * 1.143|

= |(6.096 <0°) + (3.429 <180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 6.096; θ1 = 0°; r2 = 3.429; θ2 = 180°;

= | [6.096 * cos(0) + 6.096 *i* * sin(0)] + [3.429 * cos(180) + 3.429 *i* * sin(180)] |

= | [6.096 + 0] + [−3.429+ 0] |

Idiff = |6.096 – 3.429| = 2.667

Ibais = { |Ip| + |Is| } / 2 = { |Ip * Imhv| + |Is * Imlv | } / 2

= { |(4.0 <0°) * 1.524| + |(3.0 <180°) * 1.143| } / 2

= { |(6.096<0°)| + |(3.429<180°)| } / 2

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 6.096; θ1 = 0°; r2 = 3.429; θ2 = 180°;

= { | [6.096 * cos(0) + 6.096 *i* * sin(0)]| + |[3.429 * cos(180) + 3.429 *i* * sin(180)] | } / 2

= { | [6.096 + 0]| + |[−3.429 + 0] | } / 2

Ibais = { | 6.096 | + | -3.429 | } / 2 = {6.096 + 3.429} / 2 = 4.7625

Since the point (4.763, 2.667) is in operating region, relay will operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN OPERATING REGION,

We know that slope1 = 0.3 and slope2 = 0.5,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.3
- if Ibais value is under slope2 line, then k = 0.5

In our condition, slope1 line ends at Ibais = 4.0 and the calculated value (4.763) is greater 4.0 . So we can take k = 0.5

Calculate k * Ibais = 0.5 * 4.763 = 2.3815

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (2.667) which is greater than k*Ibais (2.3815). So the point is in operating region. the relay will trip, disconnecting the transformer from the power system. *[Refer diagram4]*

VECTOR GROUP COMPENSATION / CORRECTION FACTOR

In transformer differential protection, vector group compensation, also known as correction factor, addresses the issue of phase angle shift introduced by different transformer connections.

Here's what you need to know:

1. TRANSFORMER VECTOR GROUPS:

Transformers come in various connection configurations, called vector groups. These groups determine the phase relationship between the high-voltage (HV) and low-voltage (LV) sides. For example, a Dyn1 transformer introduces a 30° phase lag from HV to LV.

2. PHASE SHIFT AND MALOPERATION:

This phase shift can create a differential current even under normal conditions, potentially causing the protection scheme to misinterpret it as a fault and trip unnecessarily. This situation can disrupt power supply and lead to false alarms.

3. COMPENSATION METHODS:

CT CONNECTION: Traditionally, compensation is achieved by wiring the current transformers (CTs) on either the HV or LV side in a specific way to introduce an opposite phase shift of the same magnitude, effectively "canceling out" the transformer's natural shift.

NUMERICAL RELAYS: Modern numerical relays offer internal algorithms that perform mathematical calculations to account for the vector group and adjust the measured currents accordingly. This provides greater flexibility and avoids complex CT wiring configurations.

4. BENEFITS OF COMPENSATION:

ACCURATE FAULT DETECTION: Prevents misoperation due to phase shift, ensuring reliable protection against internal faults.

IMPROVED STABILITY: Reduces nuisance tripping, enhancing the overall stability of the power system.

SIMPLIFIED CONFIGURATION: Numerical compensation eliminates the need for special CT connections, potentially lowering installation and maintenance costs.

5. FACTORS TO CONSIDER:

CORRECT VECTOR GROUP IDENTIFICATION: Choosing the wrong compensation based on an incorrect vector group can still lead to problems.

RELAY SETTINGS: Numerical relays require proper configuration of the vector group and other parameters to function accurately.

CT ACCURACY: Maintaining accurate CT performance is crucial for reliable operation of the scheme.

Remember, vector group compensation is a vital aspect of ensuring accurate and reliable transformer differential protection. Understanding its principle and implementation allows for proper configuration and maintenance of this essential power system safeguard.

CALCULATION WITH CORRECTION FACTOR

Trip point = Idiff_lowset * correction factor

Type of fault	Reference Winding (Upper voltage)	Even VG-numeral (0,2,4,6,8,10)	Odd VG-numeral (1,3,5,7,9,11)
3 PH	1	1	1
2 PH	1	1	0.866
1 PH With Io	1.5	1.5	1.73
1 PH Without Io	1	1	1.732

Table: Correction factor depending on vector group for P6xx

ABB RET615 – CALCULATION

The RET615 Transformer Differential Relay uses a dual-slope characteristic to distinguish between internal and external faults. The relay settings for this characteristic are as follows:

RELAY SETTING [RET615]

Id_Min	:	0.25	(y1)
Slope 1	:	0.30	(m1)
Slope 2	:	0.70	(m2)
End Section 1	:	0.75	(x1)
End Section 2	:	4.00	(x2)
Id_UnRes	:	8.00	(y3)

The differential slope curve is a plot of the differential current (I_diff) versus the restraining current (I_bias). The restraining current is calculated based on the currents flowing into and out of the transformer.

The relay settings are as follows:

Slope 1: This is the slope of the first line segment of the curve. It is equal to 0.30

Slope 2: This is the slope of the second line segment of the curve. It is equal to 0.70

End Section 1: This is the point on the curve where the first line segment intersects the x-axis with y-axis. It is equal to 0.75

End Section 2: This is the point on the curve where the second line segment intersects the first line segment. It is equal to 4.0

Id Min: This is the minimum differential current that must be exceeded before the relay will trip. It is equal to 0.25

Id UnRes: This is the maximum differential current that the relay will tolerate before tripping. It is equal to 8.00

DIFFERENTIAL SLOPE CURVE

The differential slope curve is a characteristic of transformer differential relays that is used to distinguish between internal and external faults. The curve is divided into two regions: the restrain region and the operating region.

RESTRAINT REGION

The restrain region is the area below the curve. In this region, the differential current is less than the restraining current, and the relay will not trip. This is to prevent the relay from tripping on external faults, where the differential current may be high due to CT saturation or other factors.

OPERATING REGION

The operating region is the area above the curve. In this region, the differential current is greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

The dual-slope characteristic is shown in the diagram below:

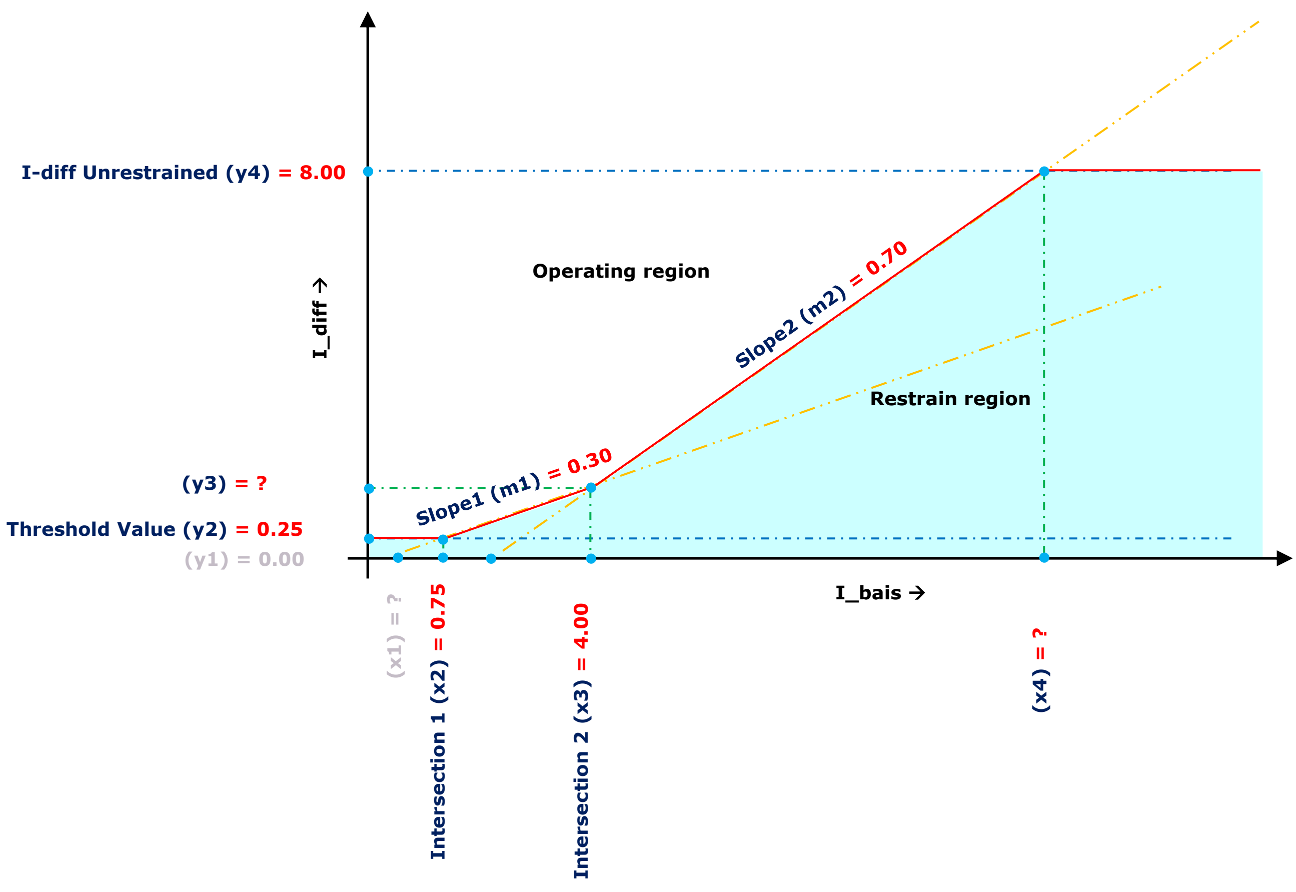


Diagram1: RET615 Transformer Differential Relay dual-slope characteristic

SLOPE POINTS CALCULATION

From the differential slope curve, the following values are known:

$m1 = 0.30$

$m2 = 0.70$

$x2 = 0.75$

$x3 = 4.00$

$y2 = 0.25$

$y4 = 8.00$

We need to determine y3 and x4.

Let us find the value of y3 from the line1 (x2, y2) to (x3, y3) with the slope m1.

x2 = 0.75, y2 = 0.25, x3 = 4.00, y3 = ?, m1 = 0.30

Line formula, $y = mx$.

- ⇨ $(y3 - y2) = m1 * (x3 - x2)$
- ⇨ $(y3 - 0.25) = 0.30 * (4.00 - 0.75)$
- ⇨ $y3 = 1.2 - 0.225 + 0.25$

$y3 = 1.225$

Let us find the value of x4 from the line2 (x3, y3) to (x4, y4) with the slope m2.

x3 = 4.00, y3 = 1.225, y4 = 8.0, x4 = ?, m2 = 0.70

Line formula, $y = mx$.

- ⇨ $(y4 - y3) = m2 * (x4 - x3)$
- ⇨ $(8.0 - 1.225) = 0.7 * (x4 - 4.0)$
- ⇨ $6.775 = 0.7\ x4 - 2.8$
- ⇨ $0.7\ x4 = 9.575$
- ⇨ $X4 = 9.575 / 0.7$

$X4 = 13.6785$

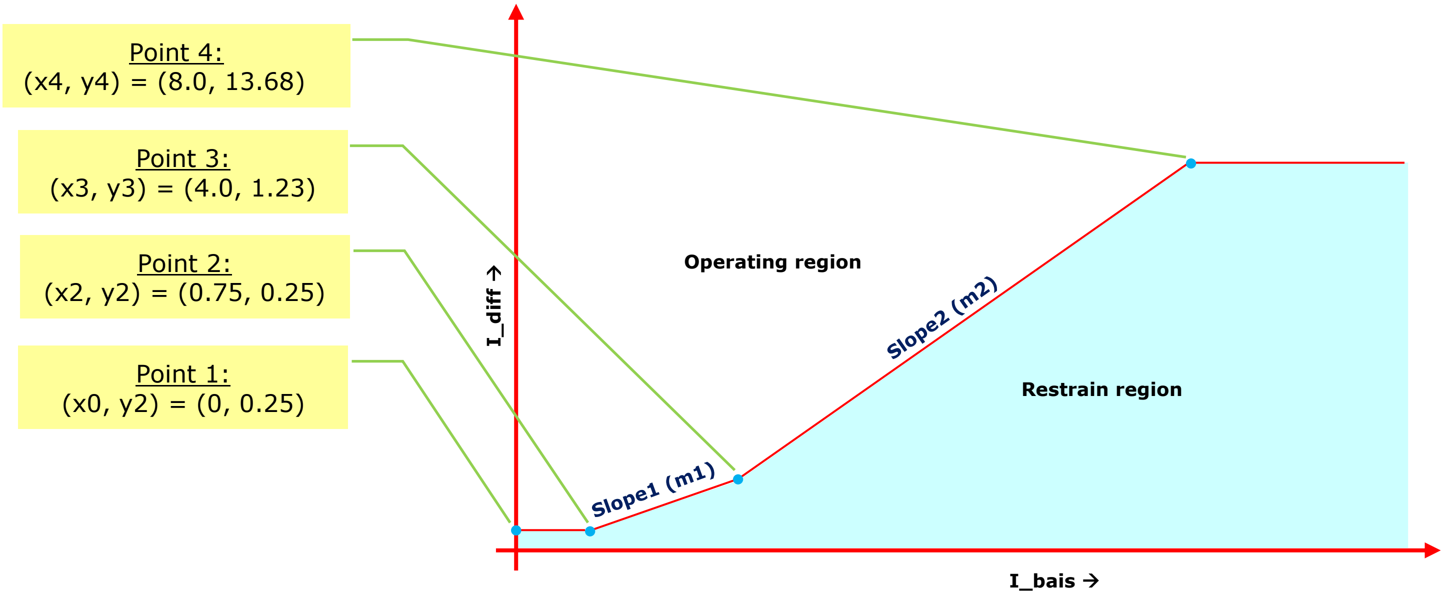


Diagram2: Final curve of RET615 Transformer diff. relay

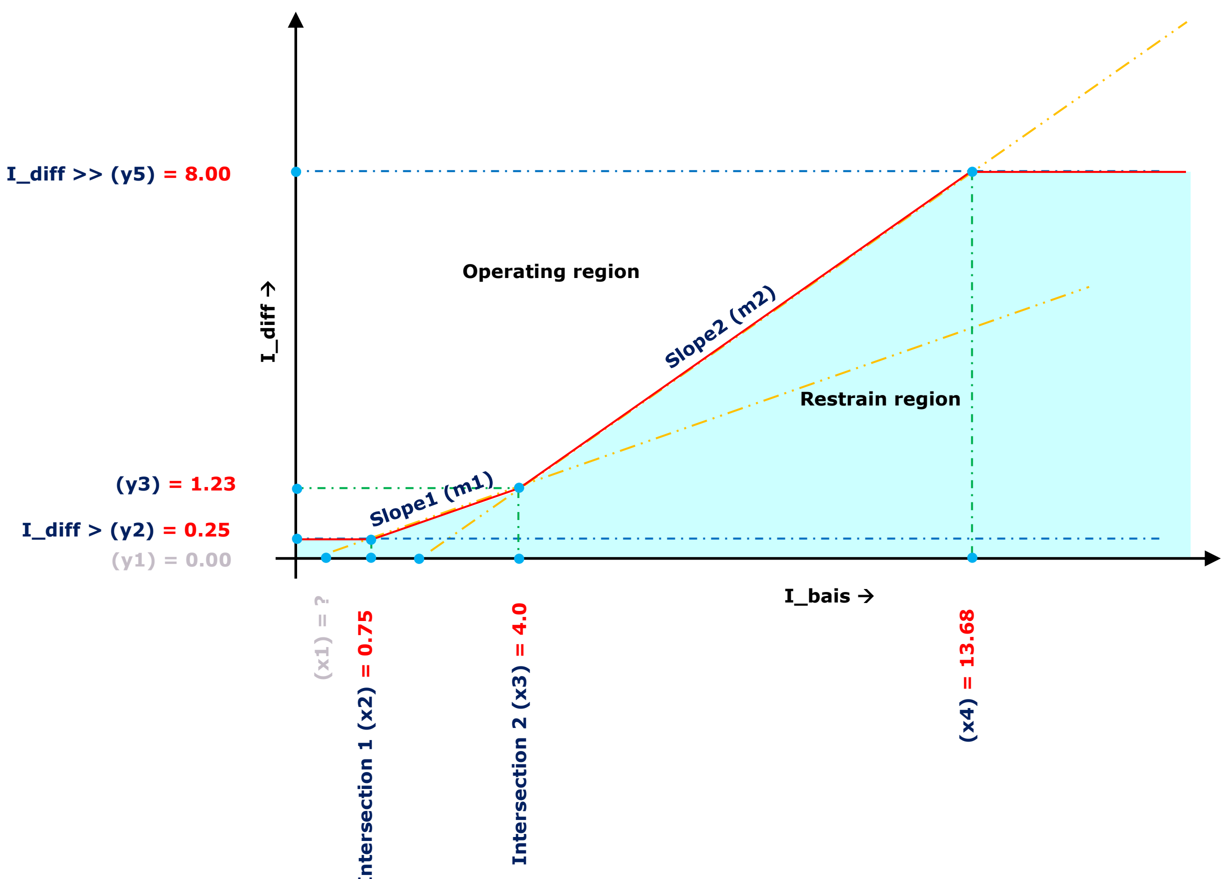


Diagram3: Final curve of RET615 Transformer diff. relay (after finding all unknown values)

PROTECTING TRANSFORMERS FROM INTERNAL FAULTS

The differential slope curve used to protect transformers from internal faults. If a fault occurs inside the transformer, the differential current will be greater than the restraining current, and the relay will trip, disconnecting the transformer from the power system.

EXAMPLE

Consider a power transformer 30MVA, 132/11kV Yd1, having CTs on primary 200/1 and on secondary 1800/1A. Relay having the previously discussed setting.

$V_{L-L(hv)}$ = 132kV

$V_{L-L(lv)}$ = 11kV

P = 30MVA

Full load current calculation: (HV side)

$P = \sqrt{3} * V_{L-L(hv)} * I_{hv}$

$I_{hv} = P / (\sqrt{3} * V_{L-L(hv)})$

$= 30{,}000{,}000 / (1.732 * 132{,}000)$

$= 131.22A$

Full load current calculation: (LV side)

$P = \sqrt{3} * V_{L-L(lv)} * I_{lv}$

$I_{lv} = P / (\sqrt{3} * V_{L-L(lv)})$

$= 30{,}000{,}000 / (1.732 * 11{,}000)$

$= 1574.59A$

Matching factor calculation:

CT Matching Factor is basically a multiplication factor by which secondary current of CTs on HV side and LV side is multiplied to make it equal to rated secondary current. This means, if the rated CT secondary current is 1A, then multiplication of CT secondary current by matching factor will give unity. To get this multiplication factor, a reference current is assumed for HV and LV side separately. This reference current is Full Load current.

As we know that in differential protection, phasor sum of CT secondary current are considered for calculation of differential current. In transformer differential protection, the CT ratio in HV and LV side are different, therefore merely taking the phasor sum will result in some definite differential current which may be more than the low set differential setting and hence will lead to actuation of differential element of relay even under normal operating condition. Therefore, it is very important to match the CT secondary current so that differential current is zero under normal operating condition.

Let us understand this with an example. As we know that full load current on HV is I_{hv} = 131.22 and on LV is I_{lv} = 1574.59 . Transformer is running with full load at normal condition.

Full load current on CT secondary side will be given as ($I_{hv} * CTR_{hv}$ = 131.22 / 200 = 0.656) and ($I_{lv} * CTR_{lv}$ = 1574.59 / 1800 = 0.875)

Where, CTR_{hv} & CTR_{lv} are the CT ratio of HV CT and LV CT.

Thus the differential current under the considered full load condition,

Idiff = $I_{lv} - I_{hv}$ = 0.875 – 0.656 = 0.219

If Idiff> setting is 0.2, then the relay differential element will operate in normal full load operation. To avoid such an occurrence it is important to match the HV and LV side CT secondary current so that their phasor sum may be zero under normal situation. In addition, the rated CT secondary current is 1 A, we need to limit the CT secondary current to 1.

Multiplication of actual CT secondary current by matching factor under various normal operating conditions will limit it to 1.

So what will we do to match? We will introduce a term called Matching Factor (MF). What this Matching Factor will do is that when we multiply the HV and LV side CT secondary current corresponding to full load current by this matching factor, the result will be 1. Let us now calculate this.

HV side, I_{mhv} = CTR_{hv} / I_{hv} = 200 / 131.22 = 1.524

Or I_{mhv} = 1 / $I_{hv(\text{CT secondary})}$ = 1 / 0.656 = 1.524

LV side, I_{mlv} = CTR_{lv} / I_{lv} = 1800 / 1574.59 = 1.143

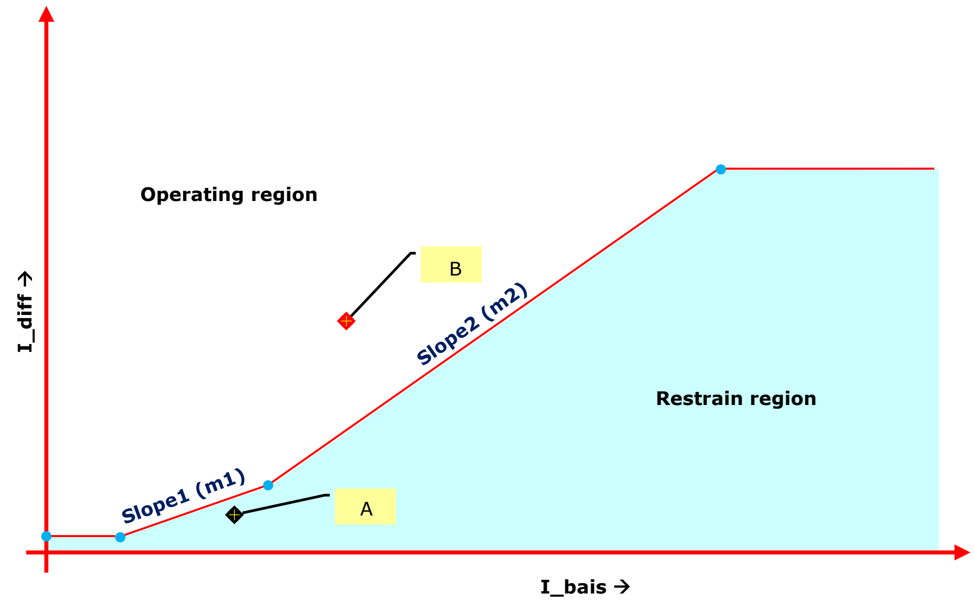
Or I_{mlv} = 1 / $I_{lv(\text{CT secondary})}$ = 1 / 0.875 = 1.143

I_{mhv} & I_{mlv} are the HV & LV CT matching factor.

Thus the differential current under the considered full load condition with matching factor,

Idiff = $I_{lv} * I_{mlv} - I_{hv} * I_{mhv}$ = 0.875 * 1.143 – 0.656 * 1.524 = 0

The relay differential element will operate because the value is under pickup.



TESTING BY INJECTING CURRENT IN RESTRAIN AND OPERATING REGION

Point A (Restrain region)

Consider injecting 3 phase HV side current, Ip = 1.5 <0° and LV side current, Is = 1.5 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.5 <(210° - 30°) = 1.5 <180°.

Idiff = |Ip + Is| = |Ip * I_{mhv} + Is * I_{mlv} | …… *Relay will consider with matching factor*

= |(1.5 <0°) * 1.524 + (1.5 <180°) * 1.143|

= |(2.286 <0°) + (1.715 <180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 1.219 *i* * sin(0)] + [1.715 * cos(180) + 1.715 *i* * sin(180)] |

= | [2.286 + 0] + [−1.715 + 0] |

Idiff = |2.286 – 1.715| = 0.5715

Ibais = Max (|Ip|, |Is|) = Max (|Ip * I_{mhv}| + |Is * I_{mlv} |)

= Max { |(1.5 <0°) * 1.524|, |(1.5 <180°) * 1.143| }

= Max { |(2.286 <0°)|, |(1.715<180°)| } = |(2.286 <0°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 2.286; θ1 = 0°; r2 = 1.715; θ2 = 180°;

= | [2.286 * cos(0) + 1.715 *i* * sin(0)]|

= | [2.286 + 0]|

Ibais = | 2.286 | = 2.286

Since the point (2.286, 0.572) is in restrain region, relay will not operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN RESTRAIN REGION,

We know that slope1 = 0.3 and slope2 = 0.7,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.30
- if Ibais value is under slope2 line, then k = 0.70

In our condition, slope1 ends 4.0 and the calculated value is under it. So we can take k = 0.30

Calculate k * Ibais = 0.30 * 2.286 = 0.6858

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (0.5715) which is less than k*Ibais (0.6858). So the point is in restrain region. *[Refer diagram4]*

Point B (Operating region)

Consider injecting 3 phase HV side current, Ip = 3.00 <0° and LV side current, Is = 1.0 <210° on to the relay's current input. Note that the vector group is Yd1 that is -30° phase shift in LV side with respect to HV. So the relay will consider as, Is = 1.0 <(210° - 30°) = 1.0 <180°.

Idiff = |Ip + Is| = |Ip * Imhv + Is * Imlv | *...... Relay will consider with matching factor*

= |(3.0 <0°) * 1.524 + (1.0 <180°) * 1.143|

= |(4.572<0°) + (1.143<180°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)] + [1.143 * cos(180) + 1.143 *i* * sin(180)] |

= | [4.572 + 0] + [−1.143 + 0] |

Idiff = |4.572 – 1.143| = 3.429

Ibais = Max { |Ip|, |Is| } = Max{ |Ip * I_{mhv}|, |Is * I_{mlv} | }

= Max { |(3.0 <0°) * 1.524|, |(1.0 <180°) * 1.143| }

= Max { |(4.572<0°)|, |(1.143<180°)| } = |(4.572<0°)|

Convert from polar to rectangular form, real = r.cosθ; imag = r.sinθ;

Where r1 = 4.572; θ1 = 0°; r2 = 1.143; θ2 = 180°;

= | [4.572 * cos(0) + 4.572 *i* * sin(0)]|

= | [4.572 + 0]|

Ibais = | 4.572 | = 4.572

Since the point (4.572, 3.429) is in operating region, relay will operate. *[Refer diagram4]*

HOW TO CONFIRM THAT THE POINT IS IN OPERATING REGION,

We know that slope1 = 0.3 and slope2 = 0.7,

Consider k as slope,

- if Ibais value is under slope1 line, then k = 0.30
- if Ibais value is under slope2 line, then k = 0.70

In our condition, slope1 line ends at Ibais = 4.0 and the calculated value (4.572) is greater 4.0 . So we can take k = 0.7

Calculate k * Ibais = 0.7 * 4.572 = 3.2004

Check **condition,** Idiff > k * Ibais

- If true, then the point is in operating region
- If false, then the point is in restrain region

In our condition, Idiff (3.429) which is greater than k*Ibais (3.2). So the point is in <u>operating region</u>. the relay will trip, disconnecting the transformer from the power system. *[Refer diagram4]*

VECTOR GROUP COMPENSATION / CORRECTION FACTOR

In transformer differential protection, vector group compensation, also known as correction factor, addresses the issue of phase angle shift introduced by different transformer connections.

Here's what you need to know:

1. TRANSFORMER VECTOR GROUPS:

Transformers come in various connection configurations, called vector groups. These groups determine the phase relationship between the high-voltage (HV) and low-voltage (LV) sides. For example, a Dyn1 transformer introduces a 30° phase lag from HV to LV.

2. PHASE SHIFT AND MALOPERATION:

This phase shift can create a differential current even under normal conditions, potentially causing the protection scheme to misinterpret it as a fault and trip unnecessarily. This situation can disrupt power supply and lead to false alarms.

3. COMPENSATION METHODS:

CT CONNECTION: Traditionally, compensation is achieved by wiring the current transformers (CTs) on either the HV or LV side in a specific way to introduce an opposite phase shift of the same magnitude, effectively "canceling out" the transformer's natural shift.

NUMERICAL RELAYS: Modern numerical relays offer internal algorithms that perform mathematical calculations to account for the vector group and adjust the measured currents accordingly. This provides greater flexibility and avoids complex CT wiring configurations.

4. BENEFITS OF COMPENSATION:

ACCURATE FAULT DETECTION: Prevents misoperation due to phase shift, ensuring reliable protection against internal faults.

IMPROVED STABILITY: Reduces nuisance tripping, enhancing the overall stability of the power system.

SIMPLIFIED CONFIGURATION: Numerical compensation eliminates the need for special CT connections, potentially lowering installation and maintenance costs.

5. FACTORS TO CONSIDER:

CORRECT VECTOR GROUP IDENTIFICATION: Choosing the wrong compensation based on an incorrect vector group can still lead to problems.

RELAY SETTINGS: Numerical relays require proper configuration of the vector group and other parameters to function accurately.

CT ACCURACY: Maintaining accurate CT performance is crucial for reliable operation of the scheme.

Remember, vector group compensation is a vital aspect of ensuring accurate and reliable transformer differential protection. Understanding its principle and implementation allows for proper configuration and maintenance of this essential power system safeguard.

CALCULATION WITH CORRECTION FACTOR

Trip point = Idiff_lowset * correction factor

Type of fault	Reference Winding (Upper voltage)	Even VG-numeral (0,2,4,6,8,10)	Odd VG-numeral (1,3,5,7,9,11)
3 PH	1	1	1
2 PH	1	1	0.866
1 PH With Io	1.5	1.5	1.73
1 PH Without Io	1	1	1

Table: Correction factor depending on vector group for 7UT8x