Principles of Differential Relaying

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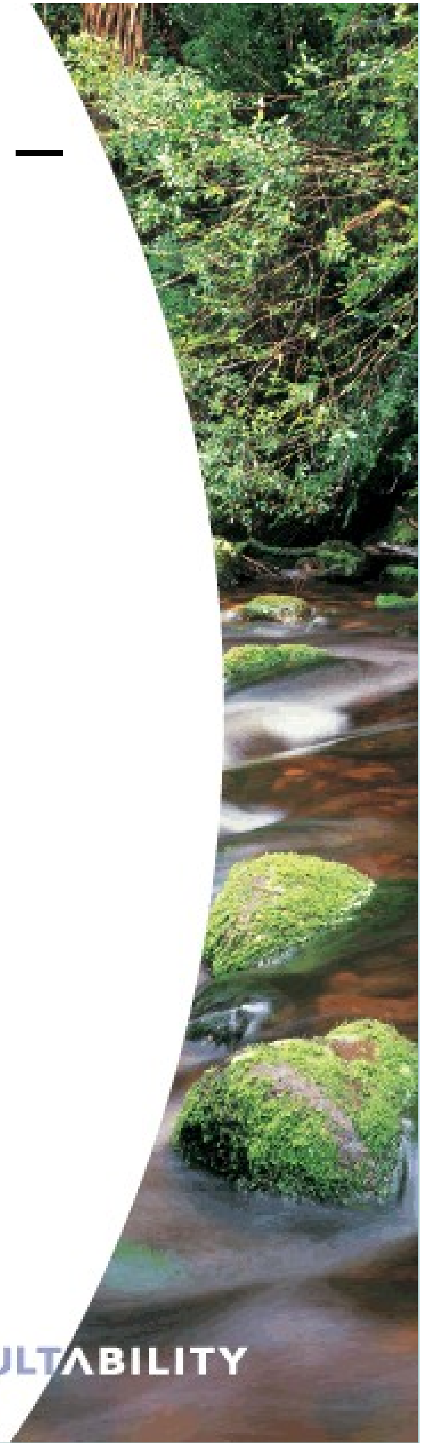
Principles of Differential Relaying – Introduction

- Introduction
- Classification
- Current Balance
- Voltage Balance
- High and Low Impedance Schemes.
- The restraint characteristic
- Low Impedance Diff Settings
- Testing the restraint characteristic.

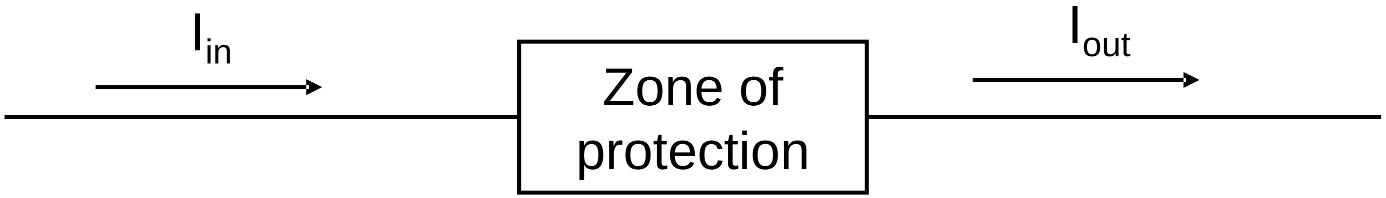


Principles of Differential Relaying – Introduction

- Power systems divided into zones of protection
- E.g. bus, generator, transformer, transmission line, capacitor, motor, etc.
- Protection systems applied to these may be broadly classified as unit and non-unit protection systems.
- Unit systems bounded by CT locations.
- Major advantage of unit over non-unit is selectivity and speed.

Principles of Differential Relaying – Introduction

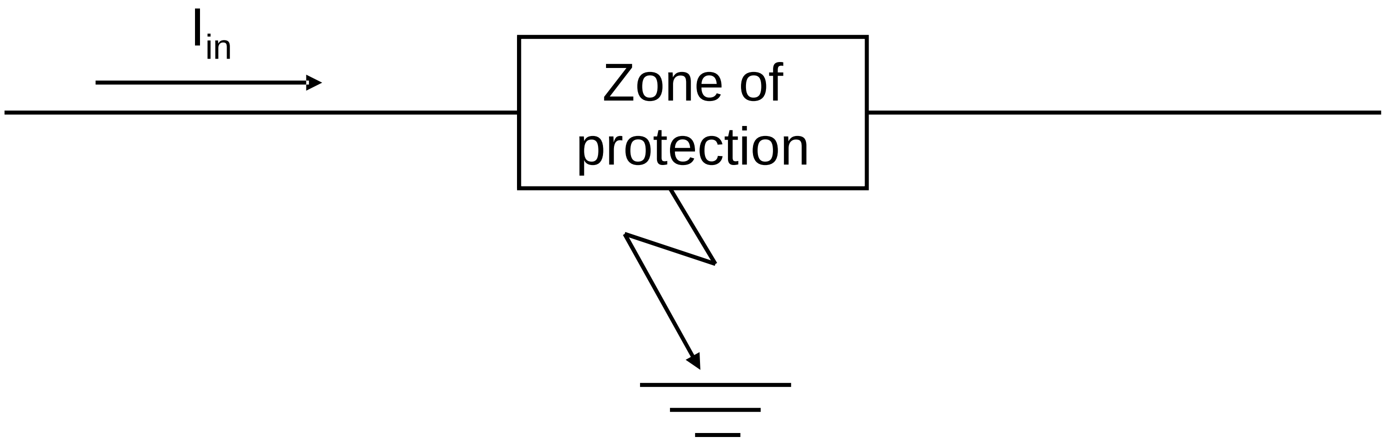
- Differential relaying systems are based on the premise that under normal conditions current in equals current out (no source or sinks).



$$I_{in} = I_{out} \Rightarrow I_{diff} = I_{in} - I_{out} = 0$$

Principles of Differential Relaying – Introduction

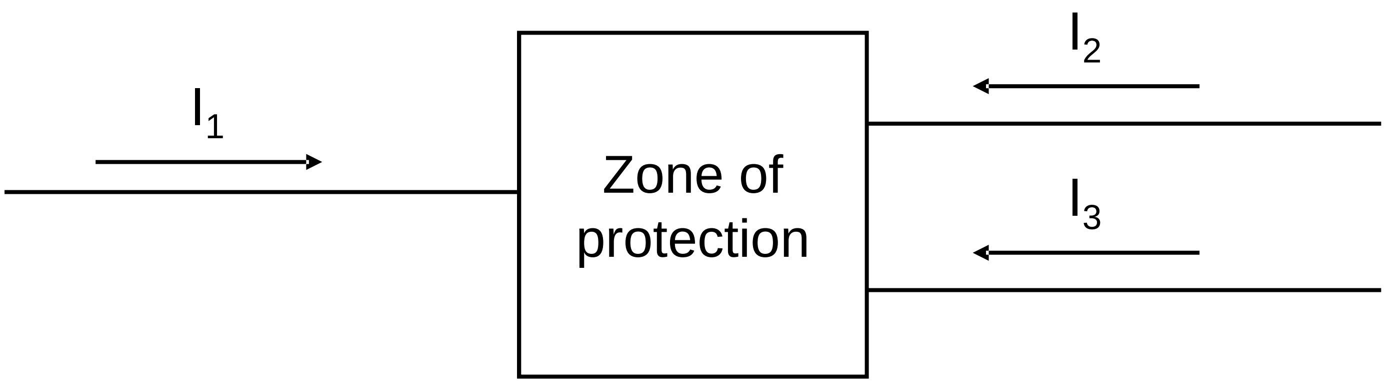
- Inzone fault – current in does not equal current out.



$$I_{in} \neq I_{out} \Rightarrow I_{diff} \neq 0$$

Principles of Differential Relaying – Introduction

- With multi-terminal zones the vectorial sum of the currents at each terminal must equal zero.

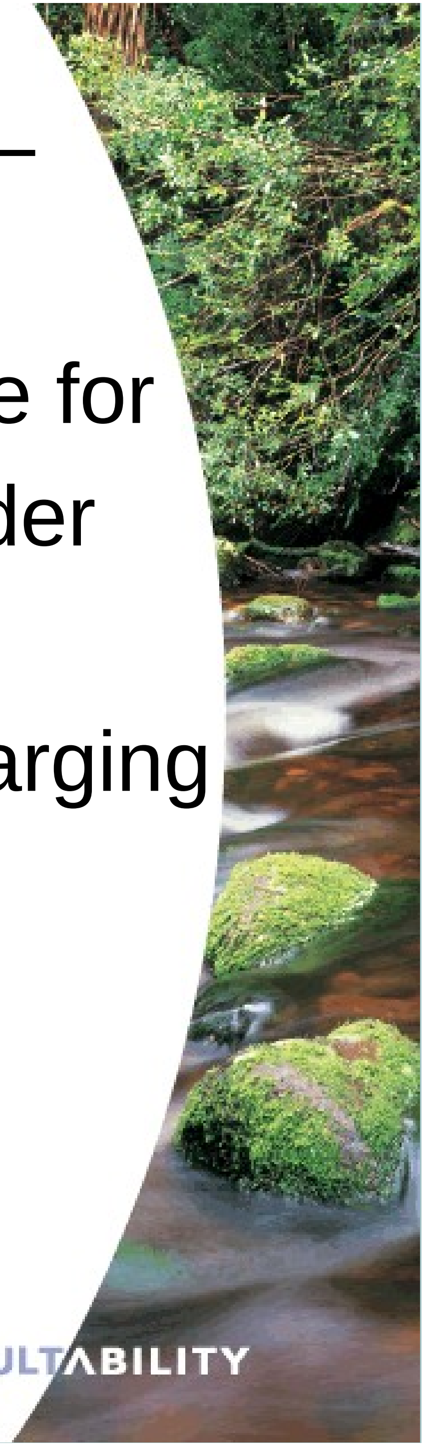


$$I_{in} = I_{out}$$

$$I_1 + I_2 + I_3 = 0$$

Principles of Differential Relaying – Introduction

- In reality provision has to be made for nonzero differential quantities under normal, healthy conditions.
- These could result due to line charging current, CT mismatching, the transformer tapchanger, etc.



Principles of Differential Relaying – Introduction

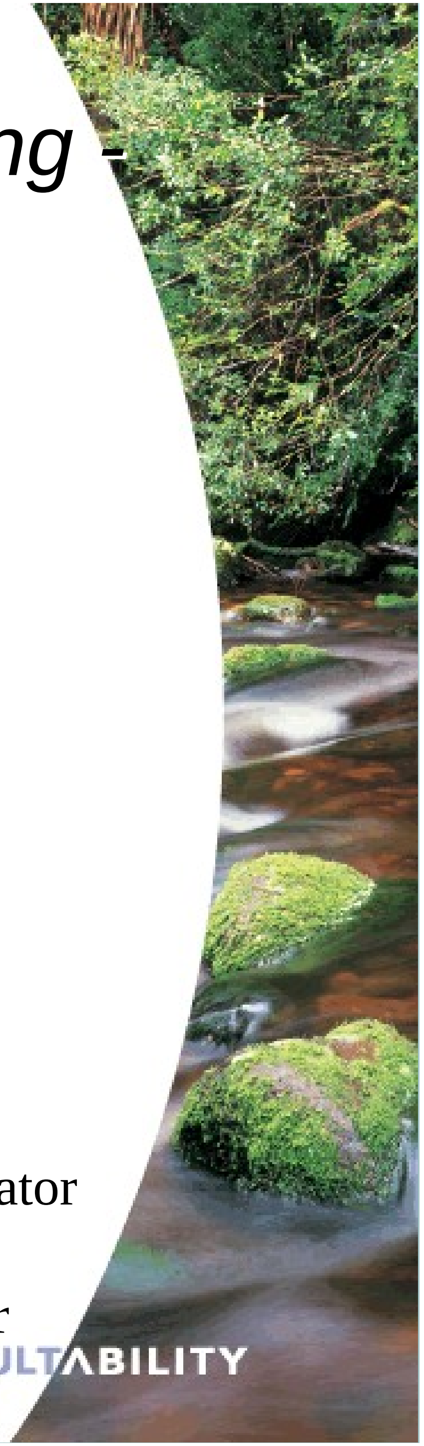
- Provision is thus made for ways to prevent relay operation which could result due to differential current being present under normal system conditions.
- This is classically done by deriving a restraint quantity from the terminal currents (biased differential protection).

Principles of Differential Relaying – Introduction

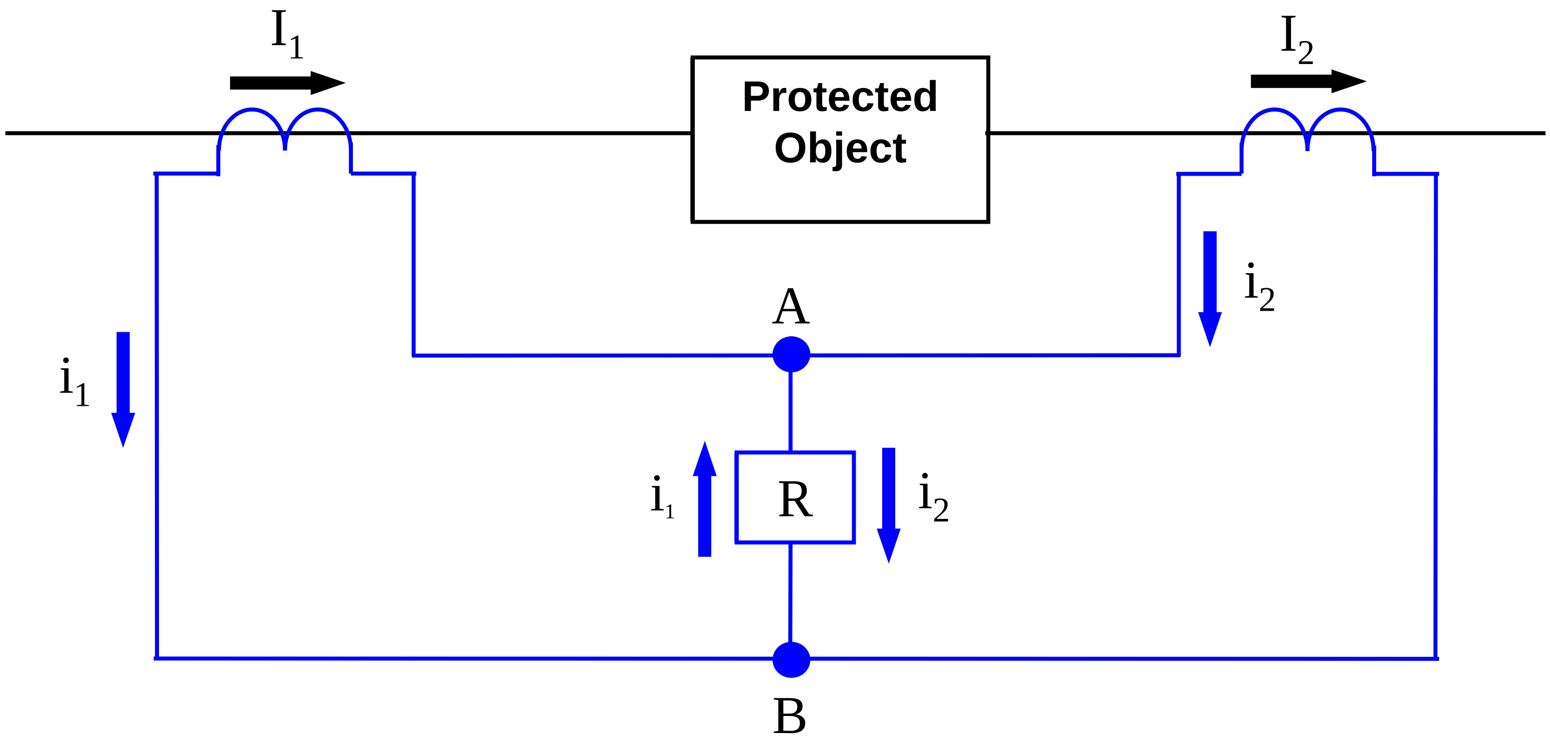
- Alternatively the operating point of the system is increased by the use of a stabilising resistor (unbiased/high impedance diff protection).
- Manufacturers have their own unique ways of deriving the restraining quantities giving rise to many different kinds of restraint characteristics in modern differential relays.

Principles of Differential Relaying - Classification

- Differential Protection
  - Voltage Balance
    - Translay
  - Current Balance
    - High Z (Unbiased diff protection)
      - REF
      - Buszone
      - Generator
      - Motor
    - Low Z
      - Solkor
      - Biased Differential
        - Trfr
        - Generator
        - Motor
        - Feeder



Principles of Differential Relaying – Current Balance



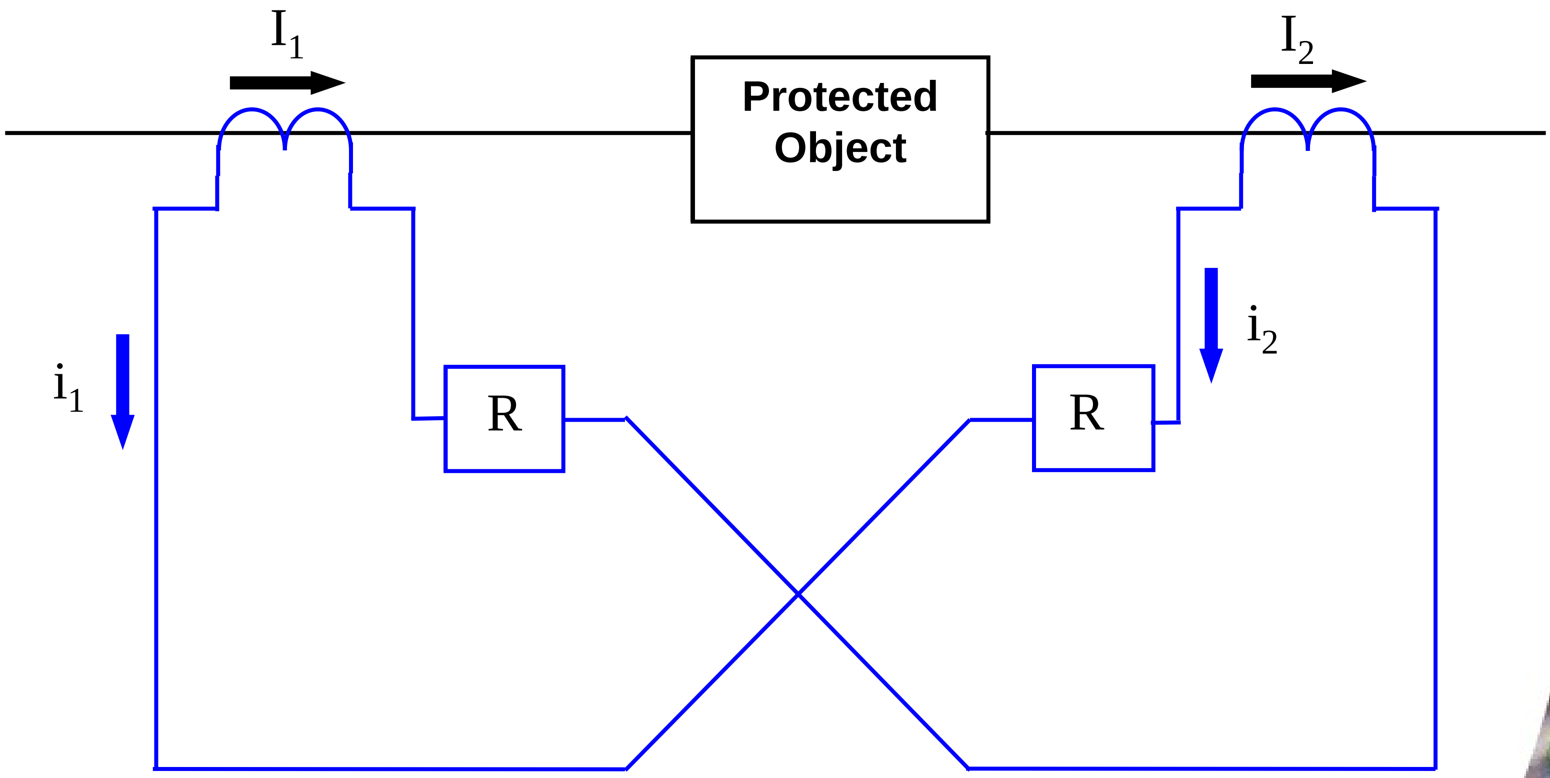
Principles of Differential Relaying – Current Balance

- Normal conditions, $I_1 = I_2$
- By virtue of CT connections I_1 and I_2 add to zero through relay,

$$I_{diff} = \left| I_1 + I_2 \right| = 0$$

- The secondary currents thus appear to circulate in the CT secondaries only – circulating current differential protection.
- No relay current implies, $V_{AB} = 0$, relay at electrical midpoint.

Principles of Differential Relaying – Voltage Balance



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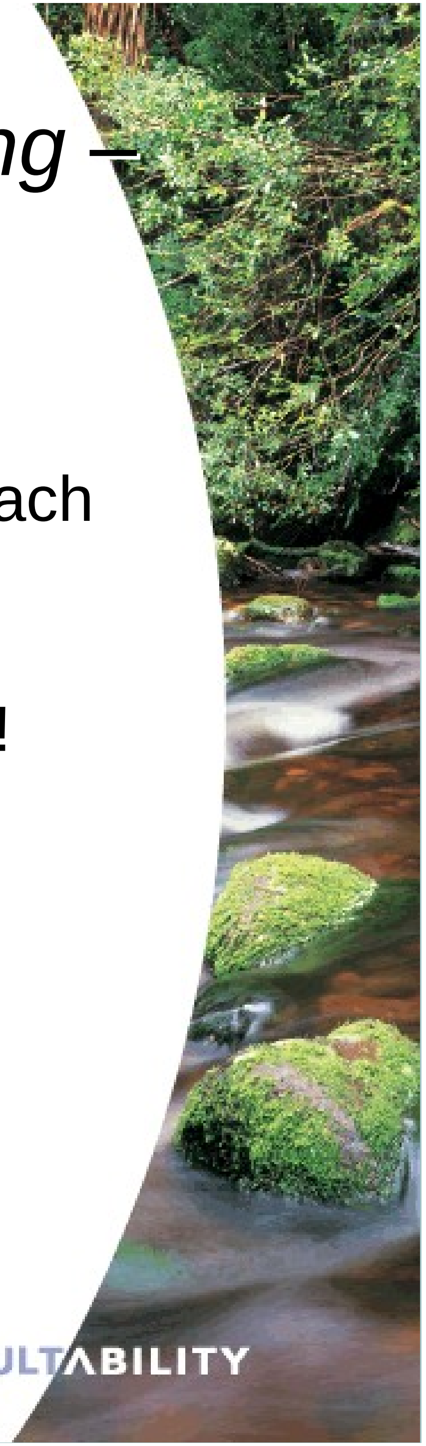
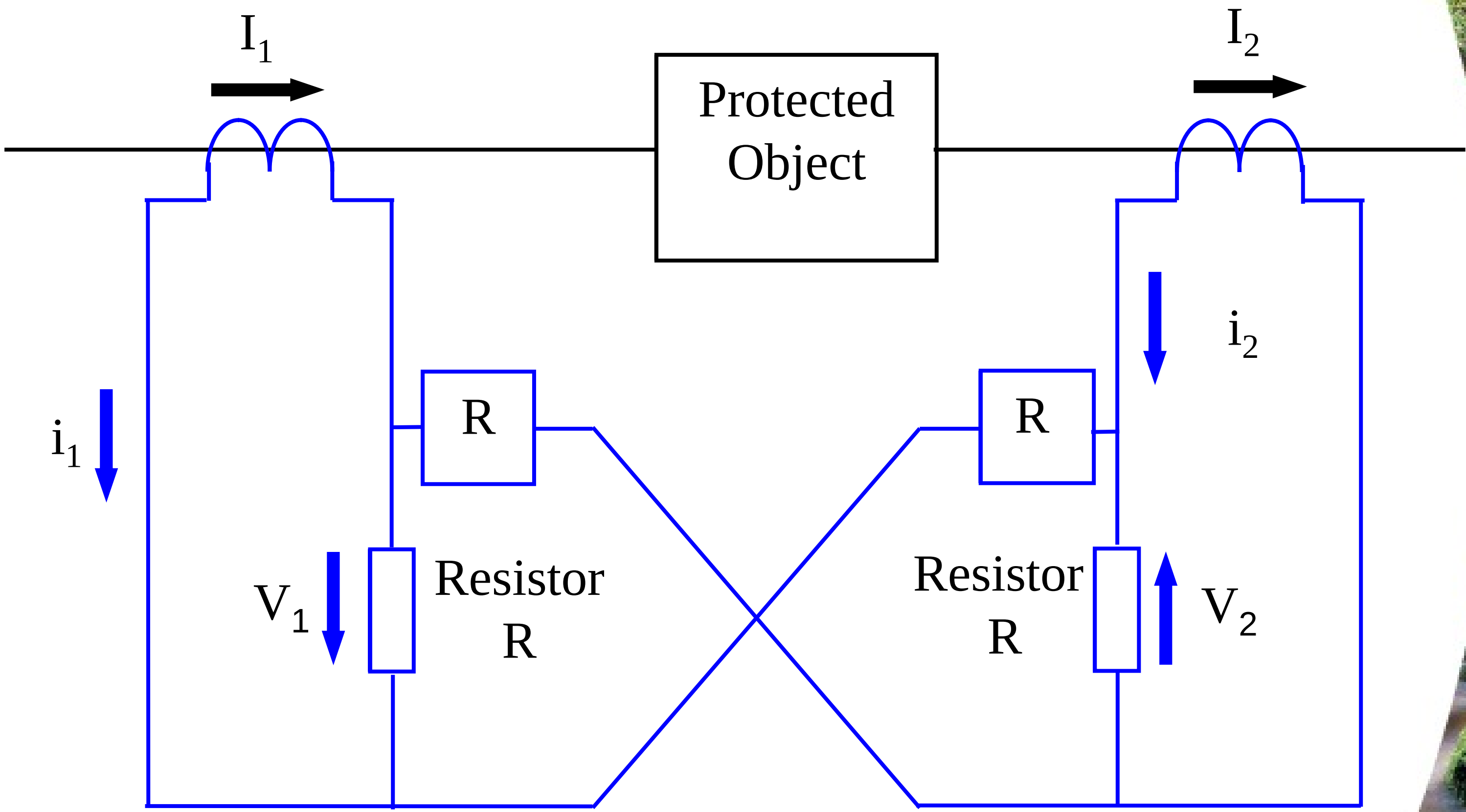
Principles of Differential Relaying – Voltage Balance

- Normal conditions, $I_1 = I_2$ as before.
- By virtue of CT connections I_1 and I_2 oppose each other and thus no CT secondary current.
- Implies that CT's are effectively open-circuited!
- Overcome by loading each CT with a resistor.



Principles of Differential Relaying – Voltage Balance



Principles of Differential Relaying – Current Balance

- Differential Protection
  - Voltage Balance
    - Translay
  - Current Balance
    - ***High Z***
      (Unbiased diff protection)
      - REF
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    - ***Low Z***
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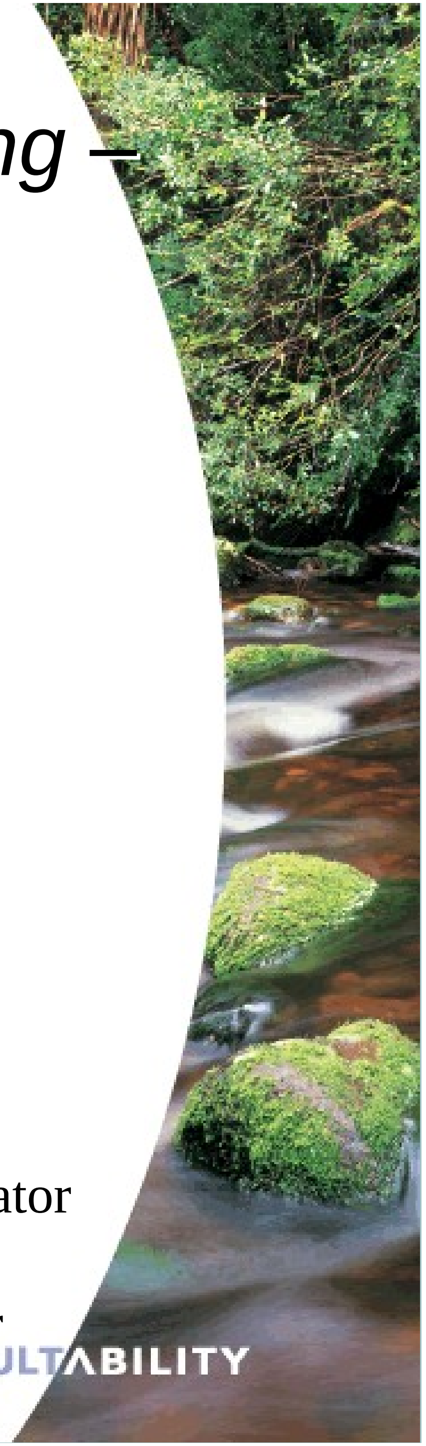
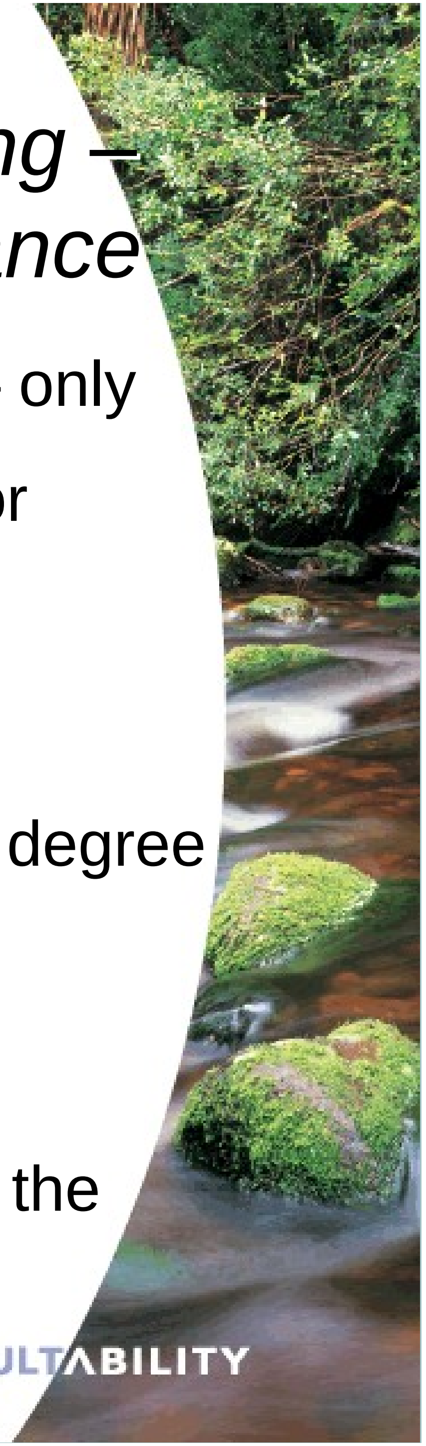


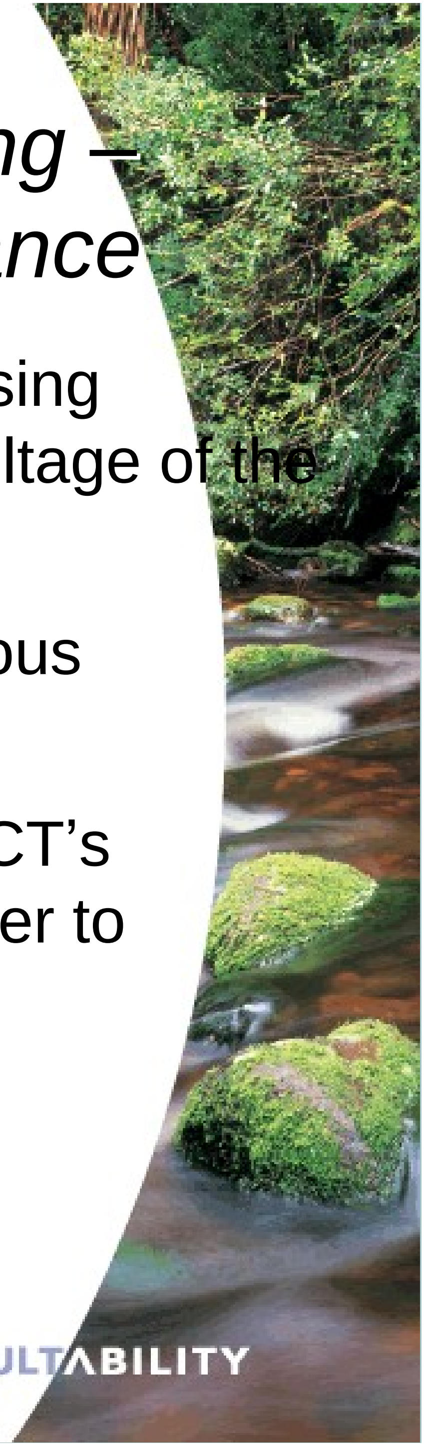
Principles of Differential Relaying – Current Balance – High Impedance

- Also known as unbiased differential protection – only one actuating relay quantity (current) required for operation.
- Examples = REF, generator and busbar diff.
- It is assumed with these schemes that a certain degree of CT saturation is possible under throughfault conditions.
- This leads to a spill current which could operate the relay.

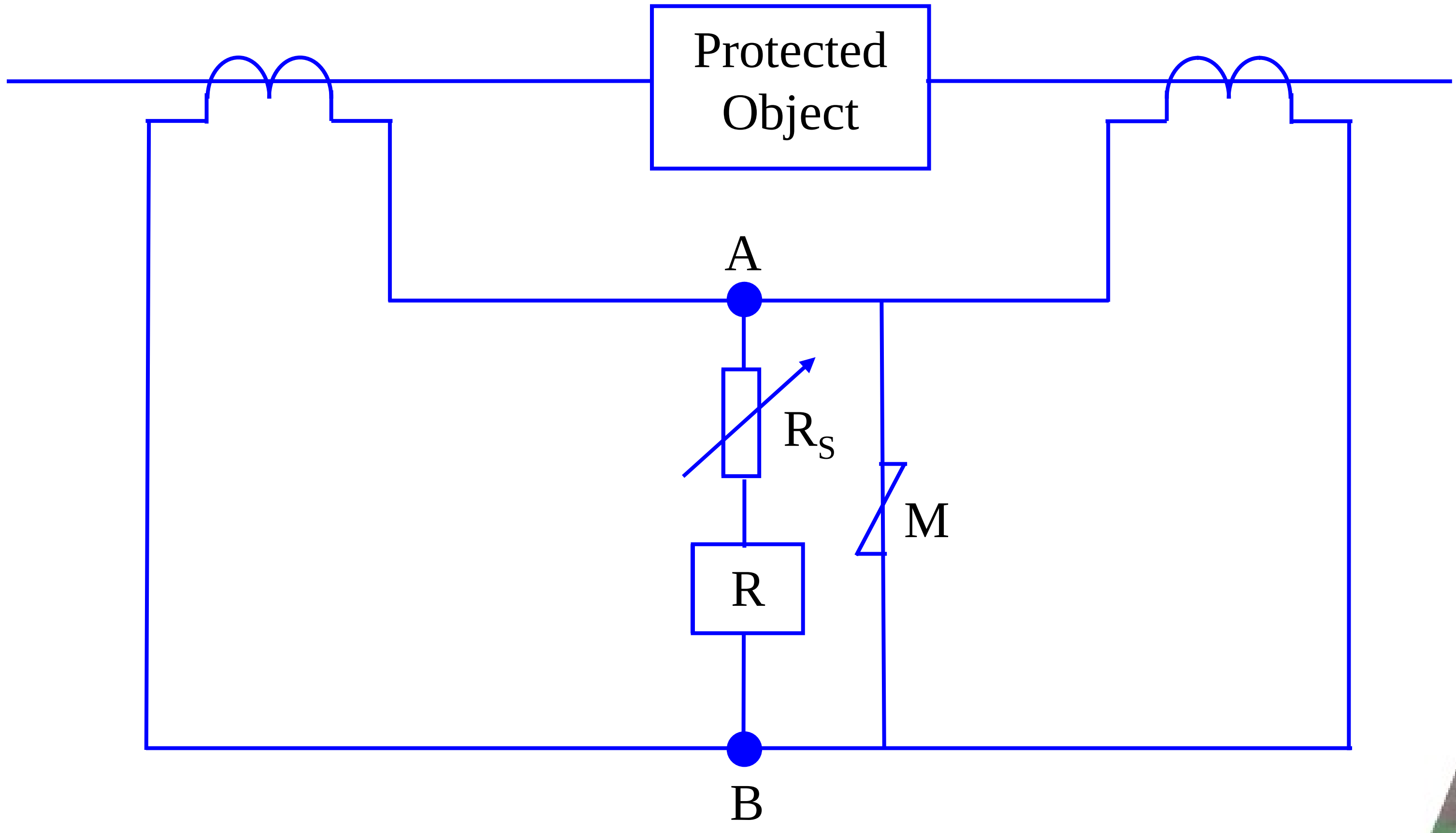


Principles of Differential Relaying – Current Balance – High Impedance

- Stabilisation is achieved by means of a stabilising resistor, R_S, intended to raise the operating voltage of the system.
- Fault current through R_S could lead to dangerous overvoltages – voltage limiters are required.
- Relatively easy to set but it requires identical CT's (identical magnetisation characteristics) in order to minimise the spill current with normal load.

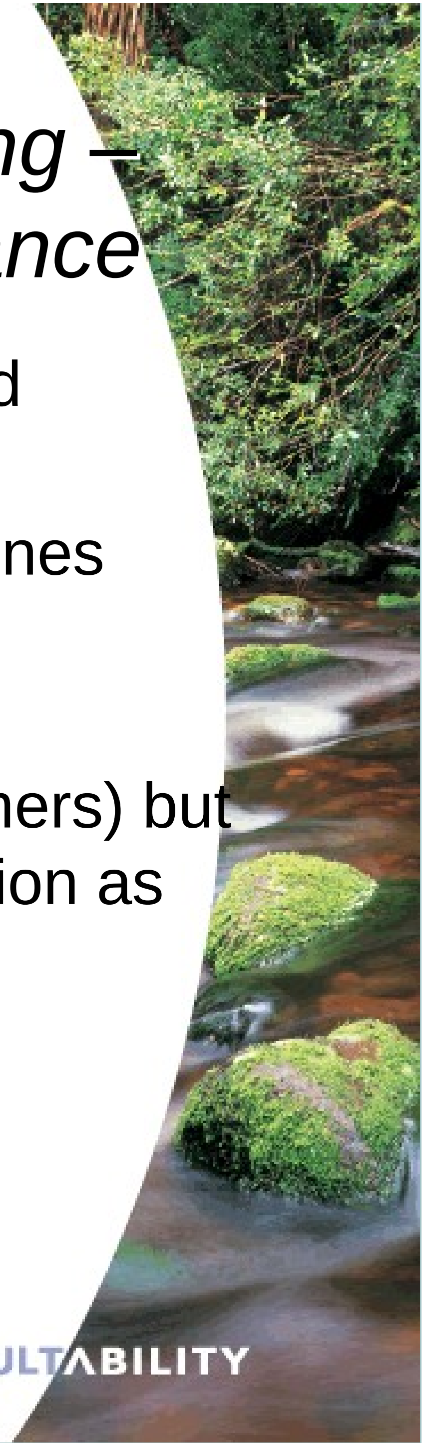


Principles of Differential Relaying – Current Balance – High Impedance



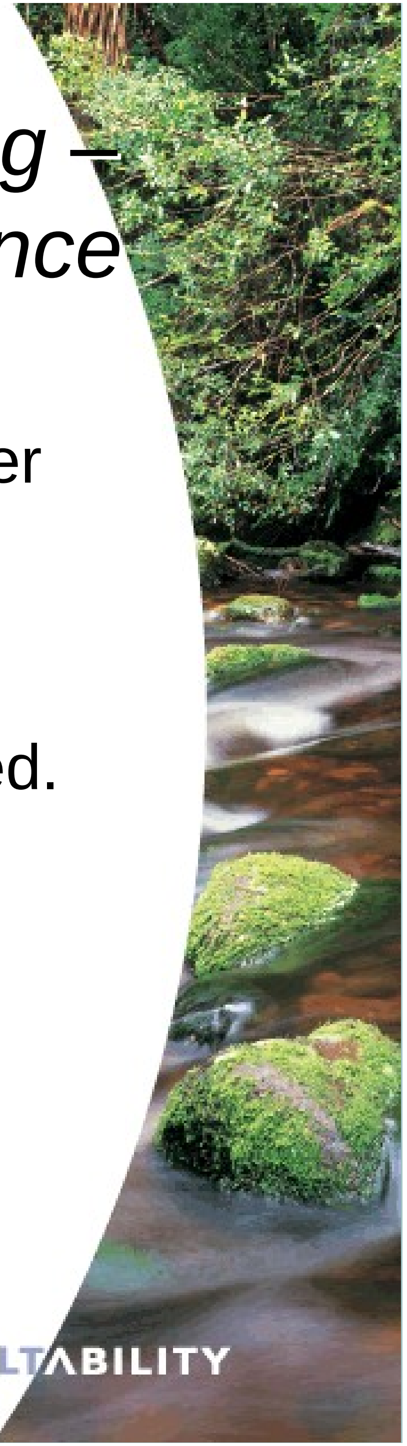
Principles of Differential Relaying – Current Balance – High Impedance

- REF is fast and sensitive (more so than biased differential protection)
- Applied to transformer windings – especially ones which have been impedance earthed.
- Also buszones and generators.
- Typically only used for EF schemes (transformers) but could be triplicated to offer phase fault protection as well – generator, motor, buszone.



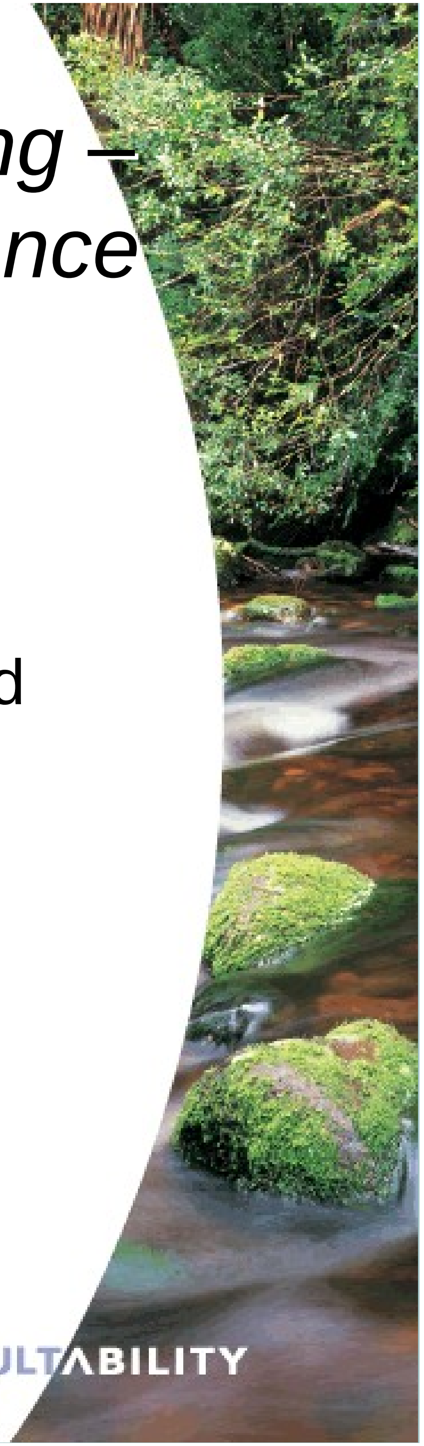
Principles of Differential Relaying – Current Balance – High Impedance

- When setting a high impedance differential scheme the objective is to ensure stability under worst case through fault conditions.
- System studies are required.
- At the same time maximum sensitivity is desired.
- The idea is to determine what stability voltage setting, V_S, is required under worst case throughfault conditions.
- This is done as follows:



Principles of Differential Relaying – Current Balance – High Impedance

- Determine worst case throughfault current.
- Determine which CT is most likely to saturate.
- Assume total saturation.
- Fault current flowing through saturated CT and associated wiring generates a voltage across the relay/R_S combination.
- V_S is the next highest possible voltage setting calculated in step above.
- For relays calibrated in volts this is all that is required. R_S internal to relay.



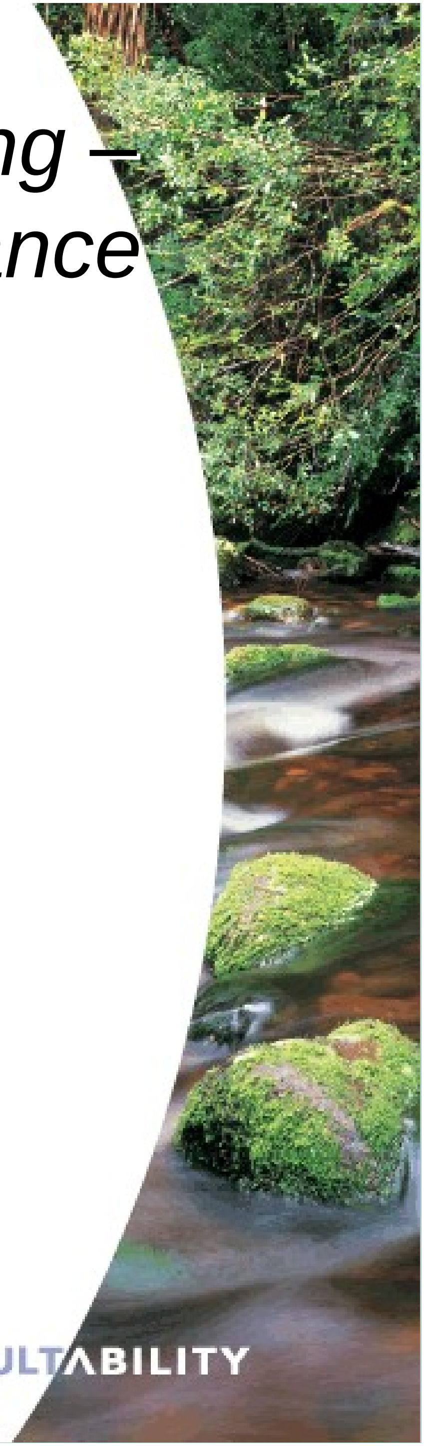
Principles of Differential Relaying – Current Balance – High Impedance

- Some relays have a current settings with external R_S.
- Stability setting is then in essence the determination of R_S.

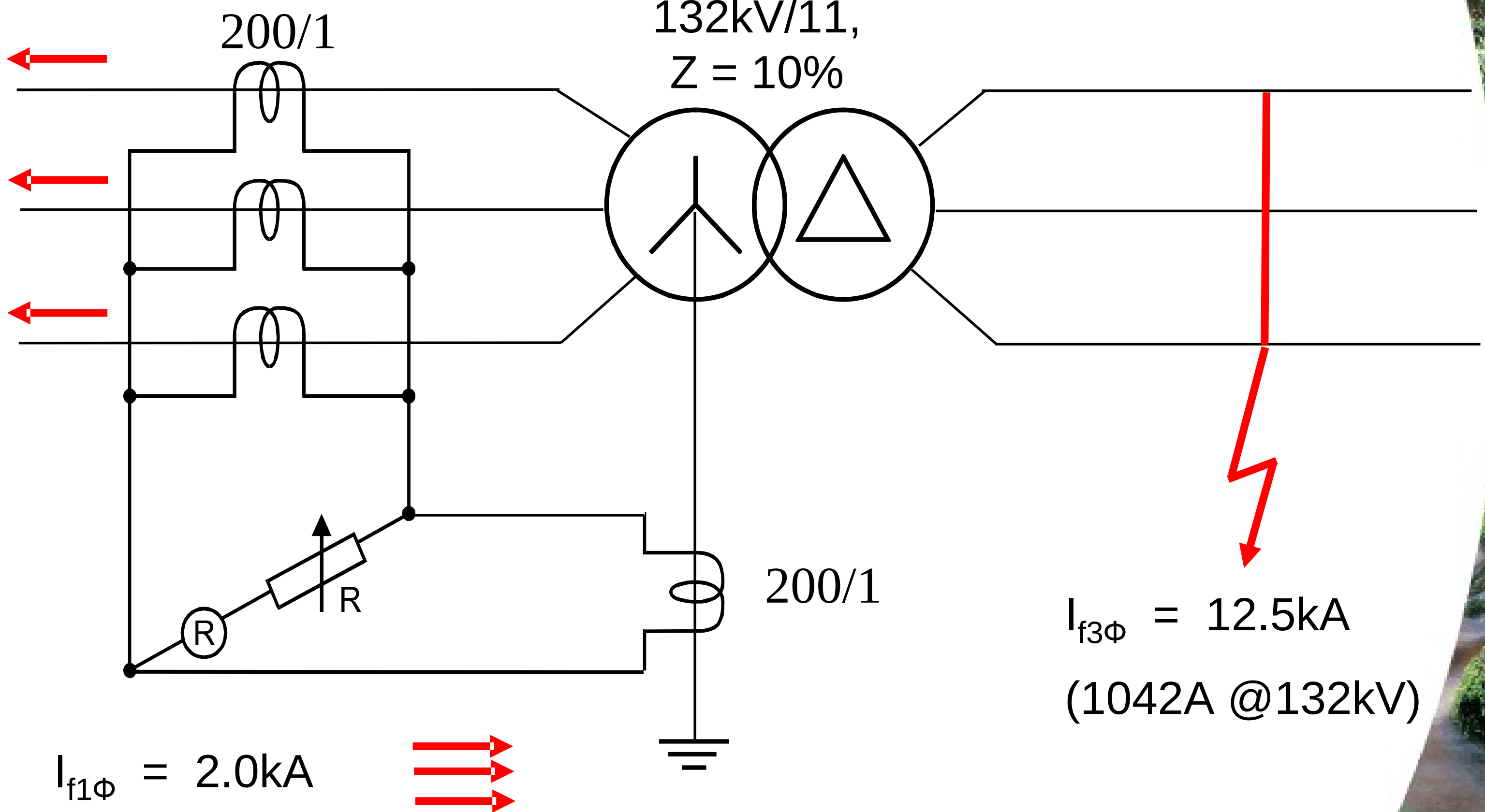
$$R_S = \frac{V_S}{I_{op}}$$

I_{OP} = relay settings current

(Note: relay impedance neglected)



Current Balance – High Impedance – REF Example



$I_{f3\Phi}$ = 12.5kA

(1042A @132kV)

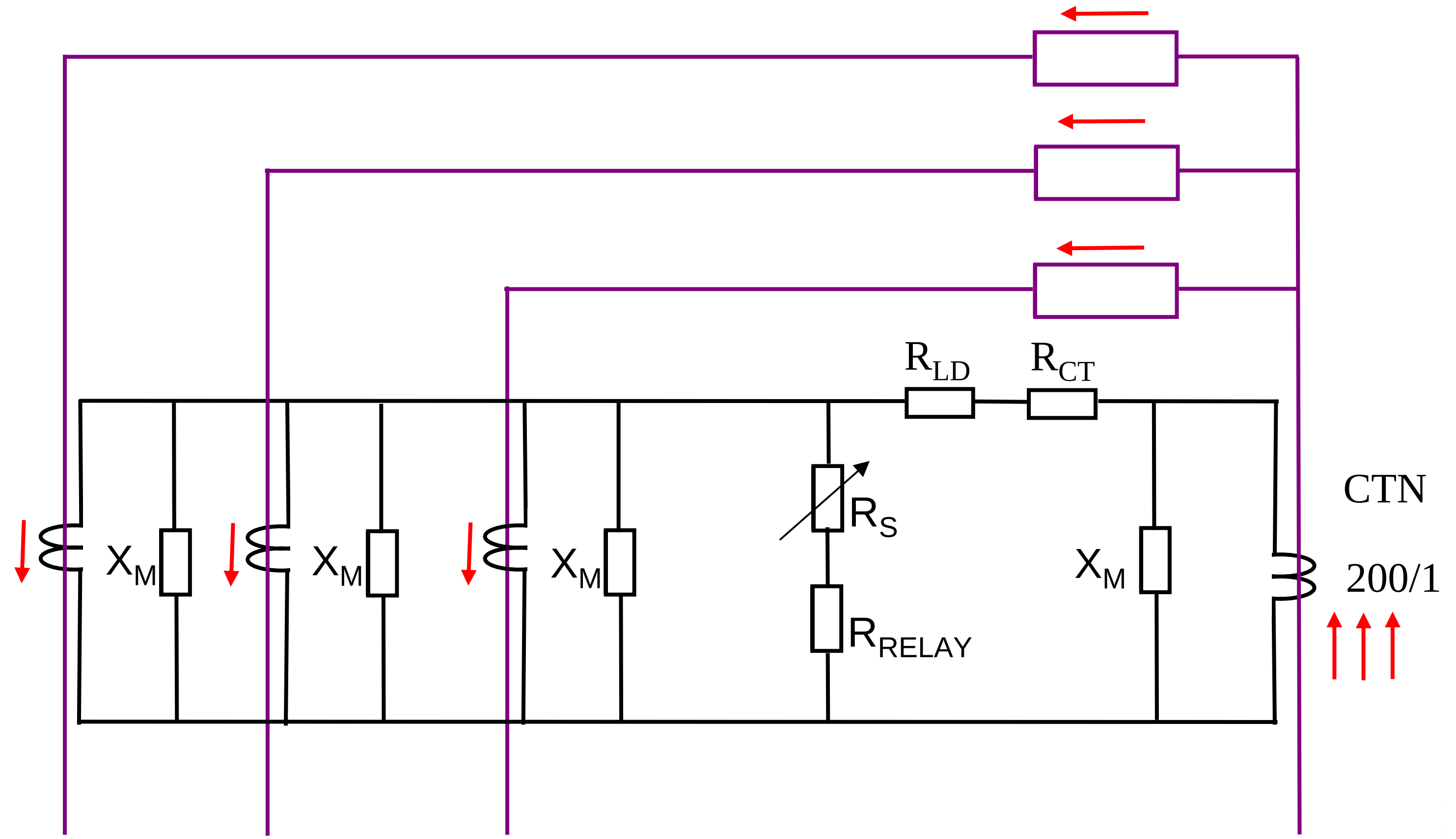
$I_{f1\Phi}$ = 2.0kA

(Upstream line fault)

Current Balance – High Impedance – REF Example

- Worst case throughfault = 132kV upstream line fault
- Neutral CT most likely to saturate – assume total saturation

Current Balance – High Impedance – REF Example



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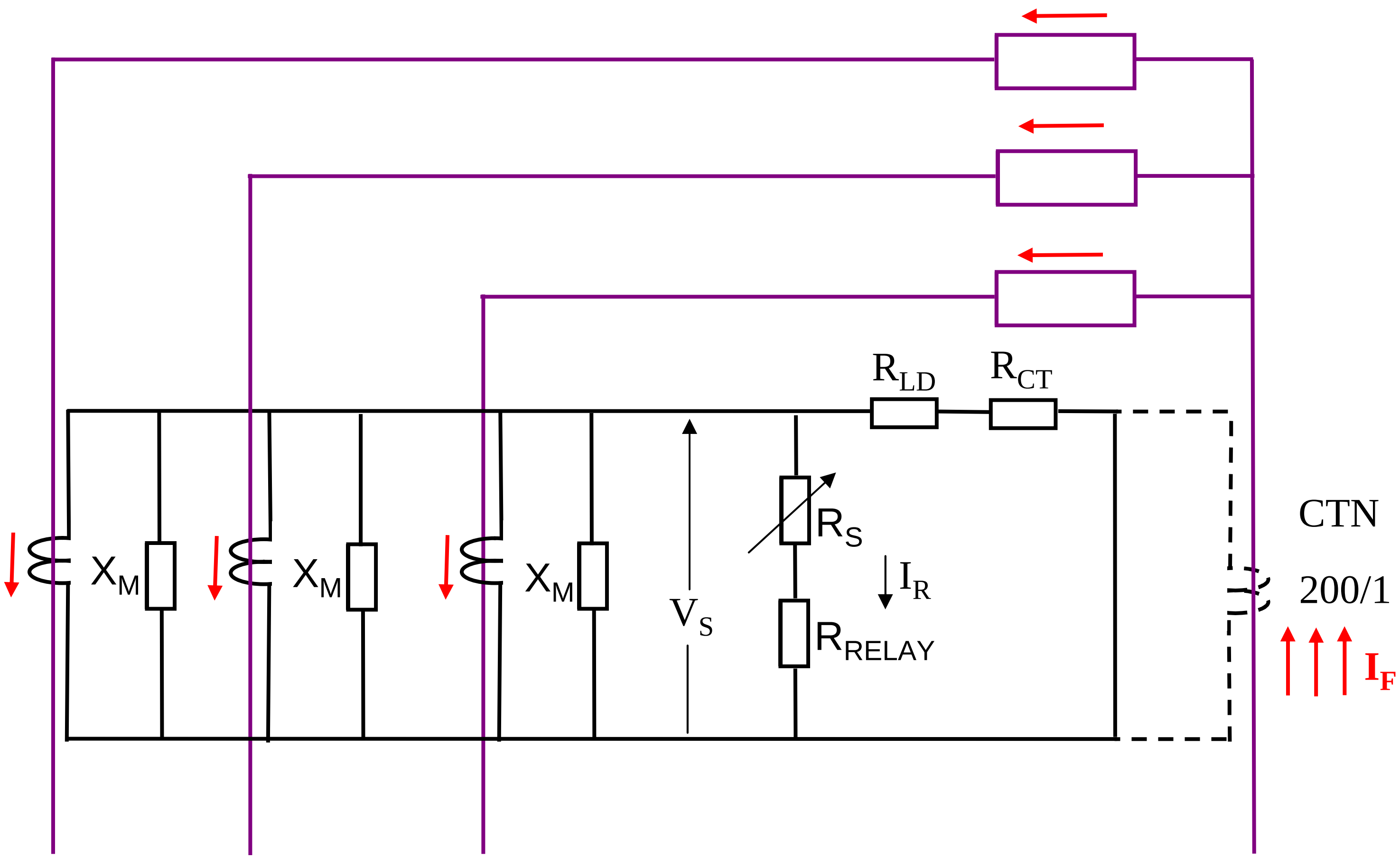
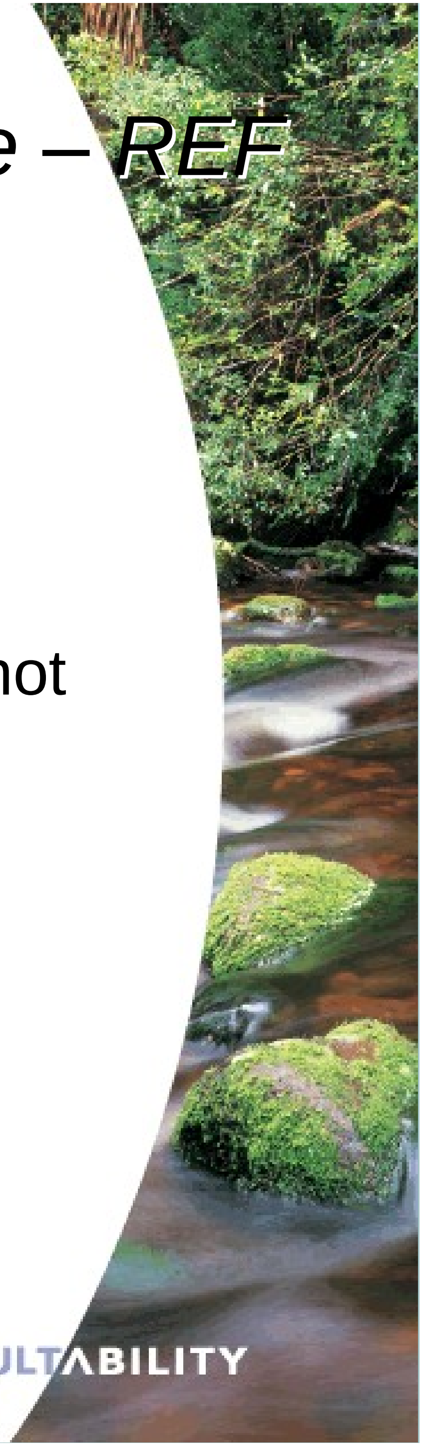
Current Balance – High Impedance – REF Example

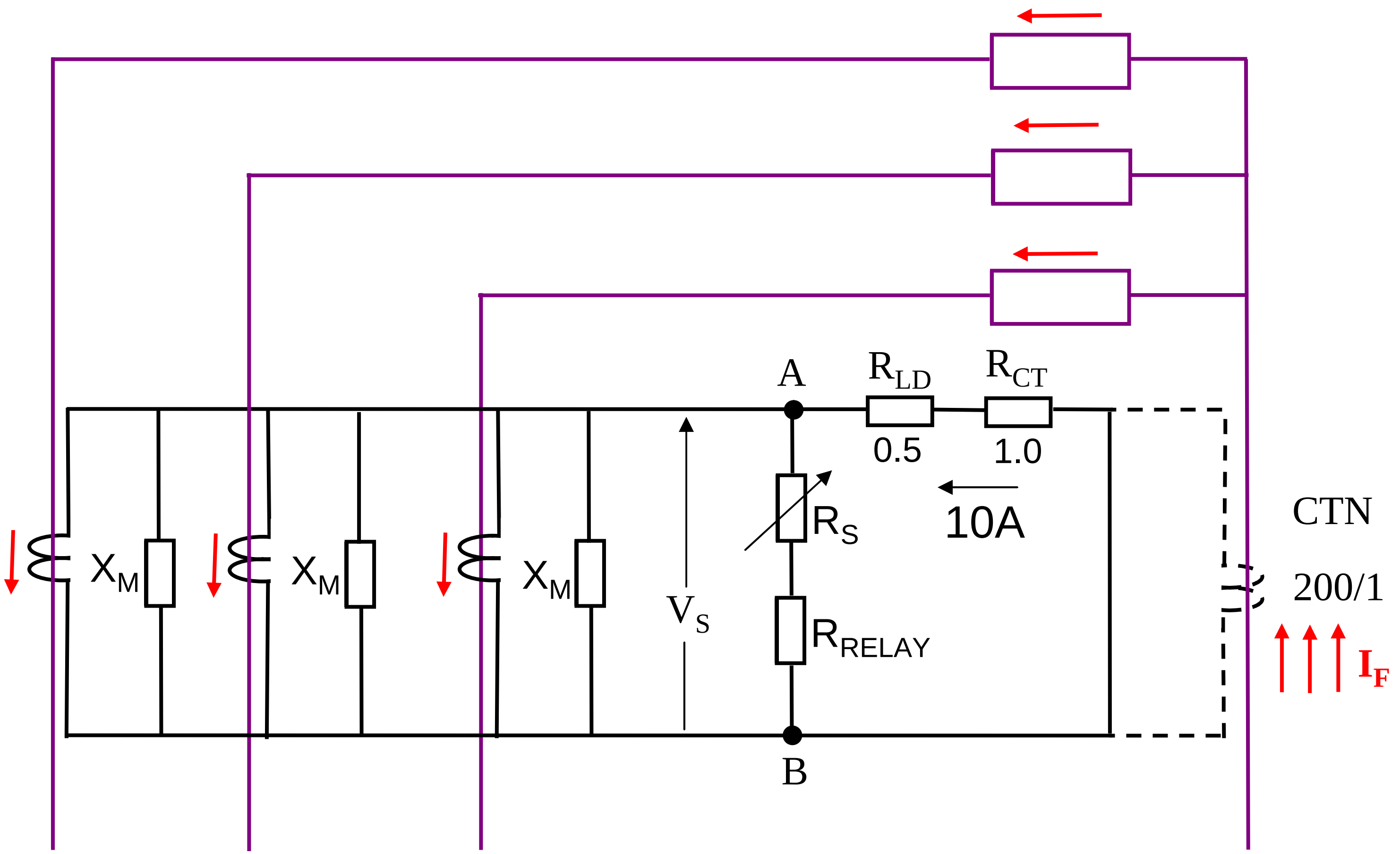


Current Balance – High Impedance – REF Example

- Neutral CT magnetisation impedance goes to zero with full saturation.
- R_{LD} = total loop resistance from relay to CT.
- Use AS 3008.1.1 to calculate R_{LD} if exact value not known. Here assume $R_{LD} = 0.5\Omega$.
- R_{CT} usually obtained from CT spec (The R value in Class PX – AS 60044.1 or Class PL – AS 1675, e.g. 0.05PX150 R0.75)
- If R_{CT} not known can use 5mΩ/turn for 1A and 3mΩ/turn for 5A CT. Thus get $200 \cdot 0.005 = 1\Omega$.



Current Balance – High Impedance – REF Example



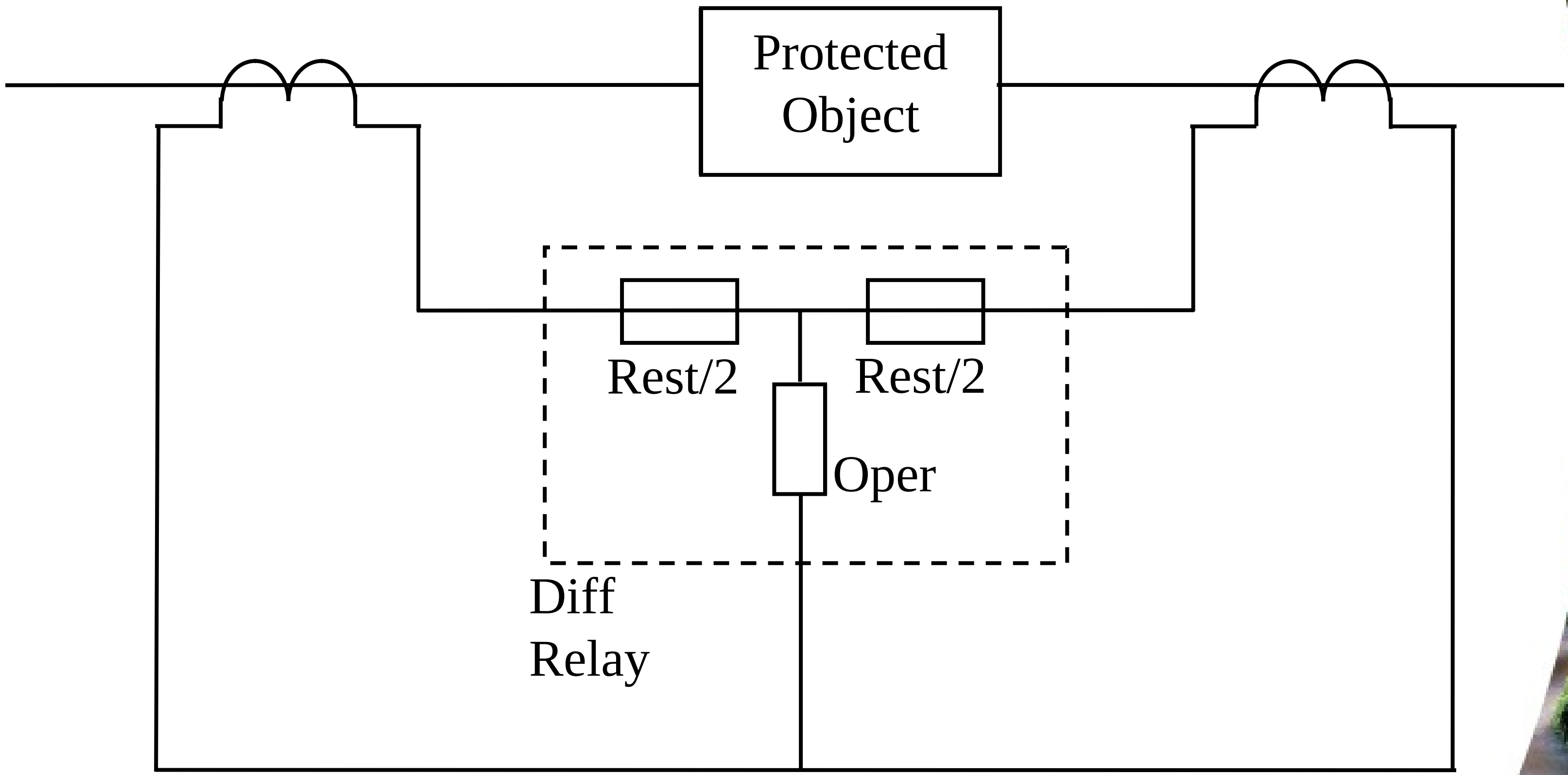
Current Balance – High Impedance – REF Example

- For the given out of zone line fault will have 10A flowing in the neutral CT secondary circuit.
- This will generate a voltage, $V_S = 10 \cdot (0.5 + 1) = 15V$ between points A-B.
- If relay operating current is say 20mA then $R_S = 15V/20mA = 750\Omega$.
- Required CT kneepoint voltage $\geq 2 \cdot V_S = 30V$.

Principles of Differential Relaying – Current Balance – Low Impedance

- Characterised by two actuating quantities – restraint and operate.

Principles of Differential Relaying – Current Balance – Low Impedance



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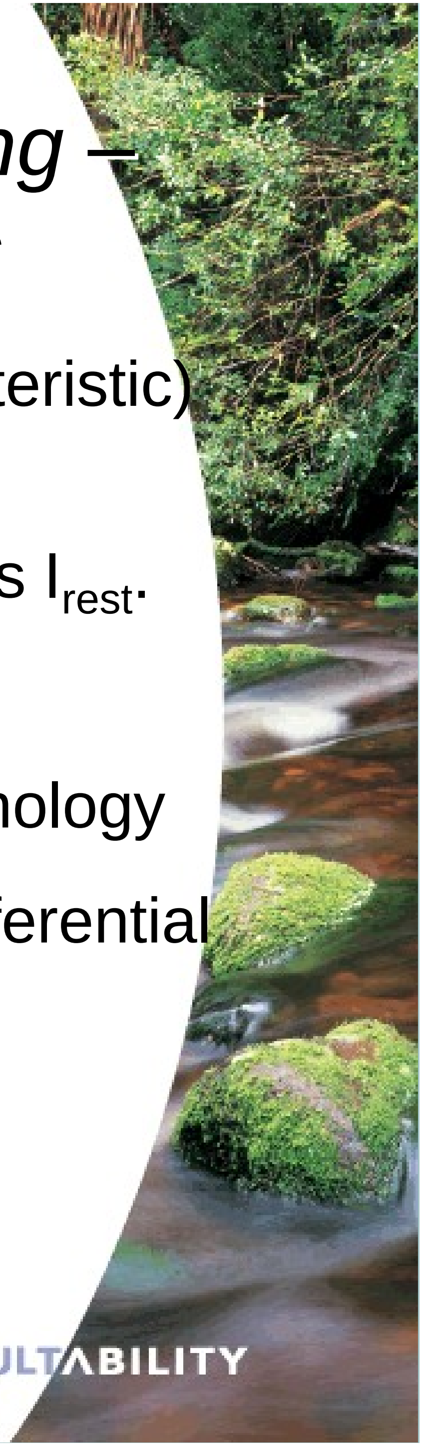
Principles of Differential Relaying – The Restraint Characteristic

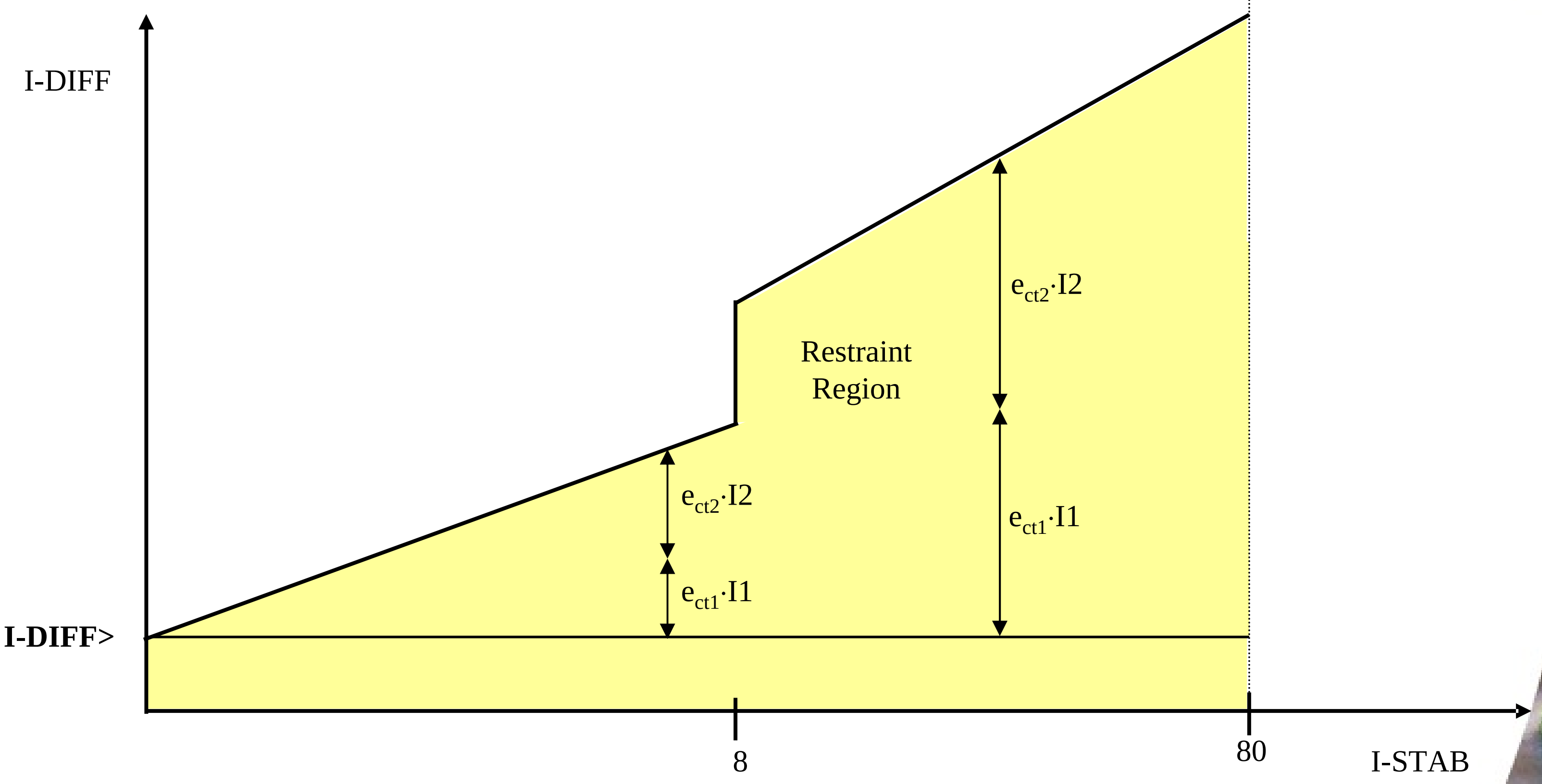
- The restraint characteristic (or stability characteristic) warrants further attention.
- It is most commonly depicted as a plot of I_{diff} vs I_{rest}.
- $I_{rest} = I_{bias} = I_{stab}$
- It is very important to understand all the terminology

  used especially if one deals with a modern differential relay.
- Two very different diagrams –

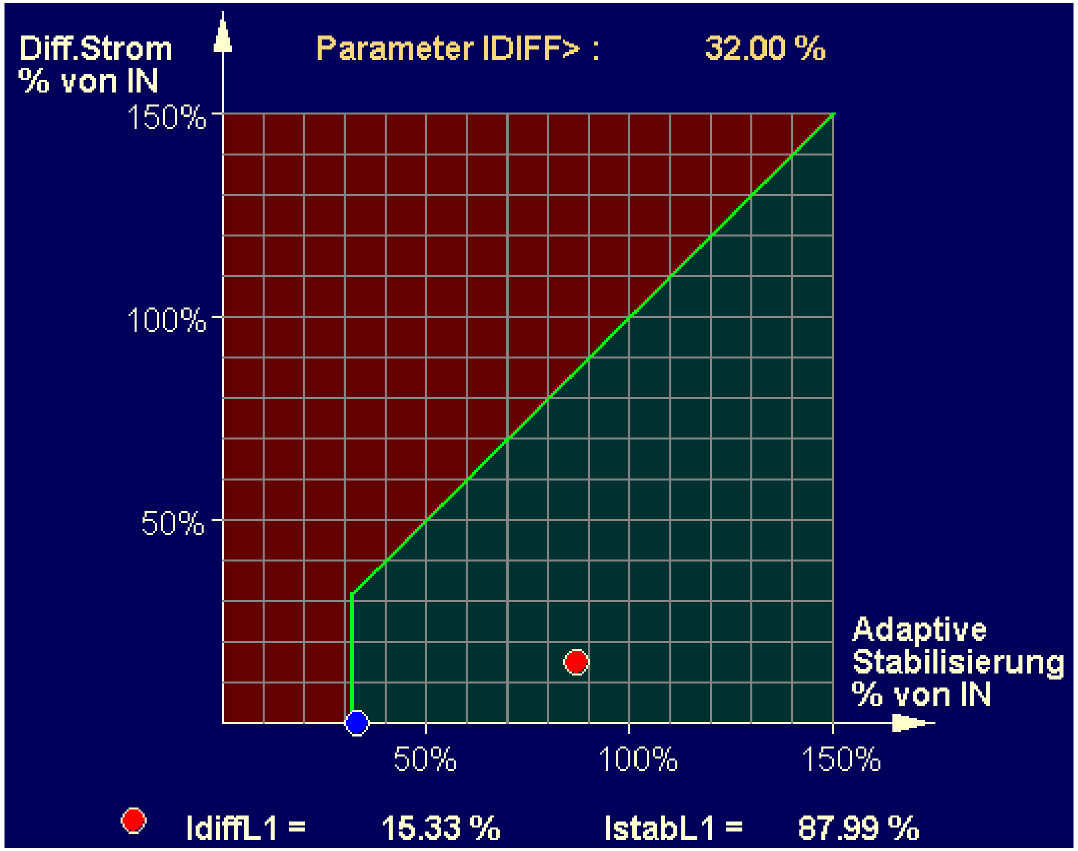
  same axis labelling???



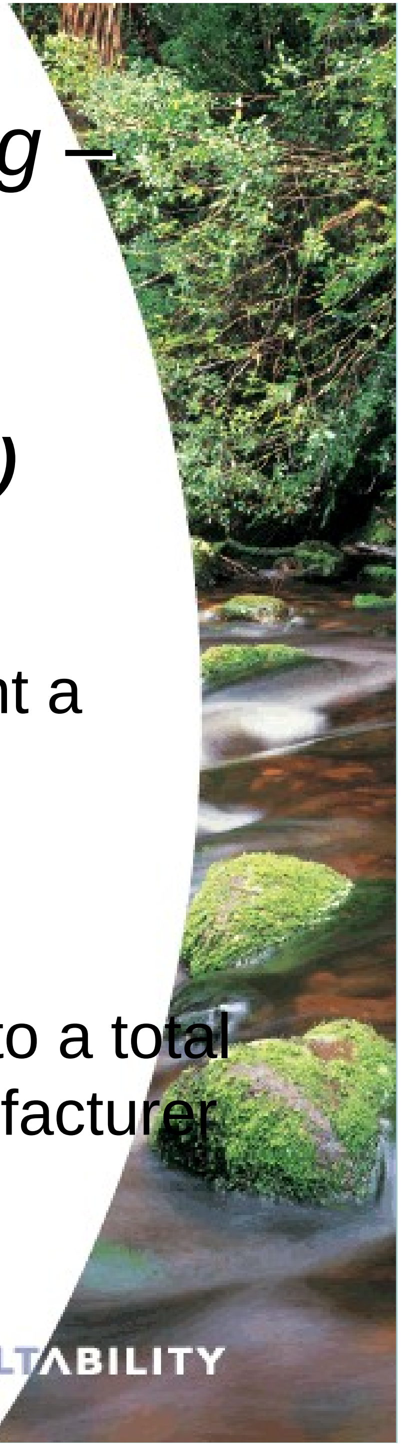
Principles of Differential Relaying – The Restraint Characteristic



Principles of Differential Relaying – The Restraint Characteristic



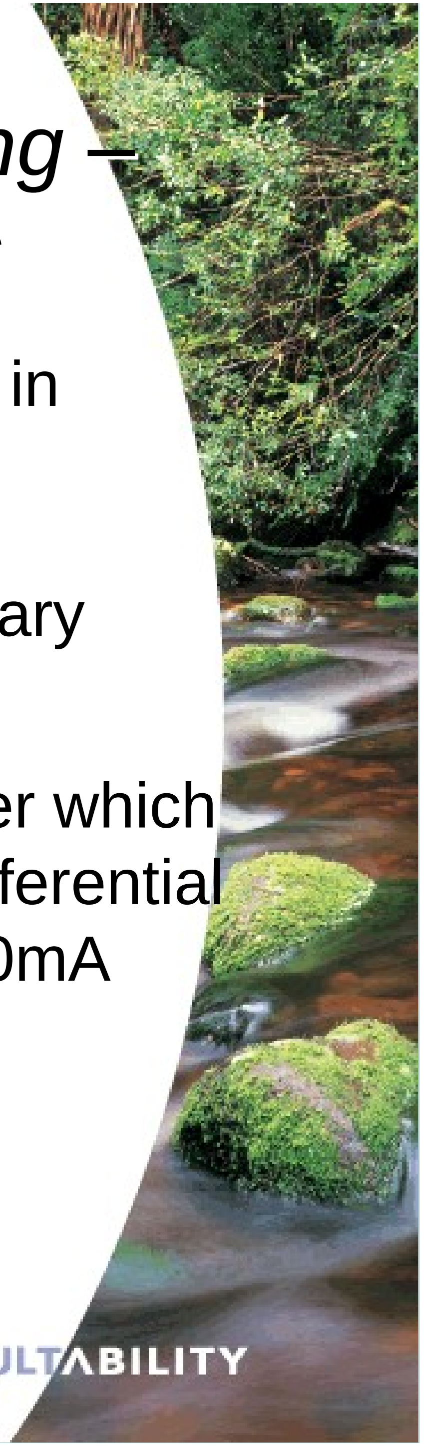
Principles of Differential Relaying – The Restraint Characteristic



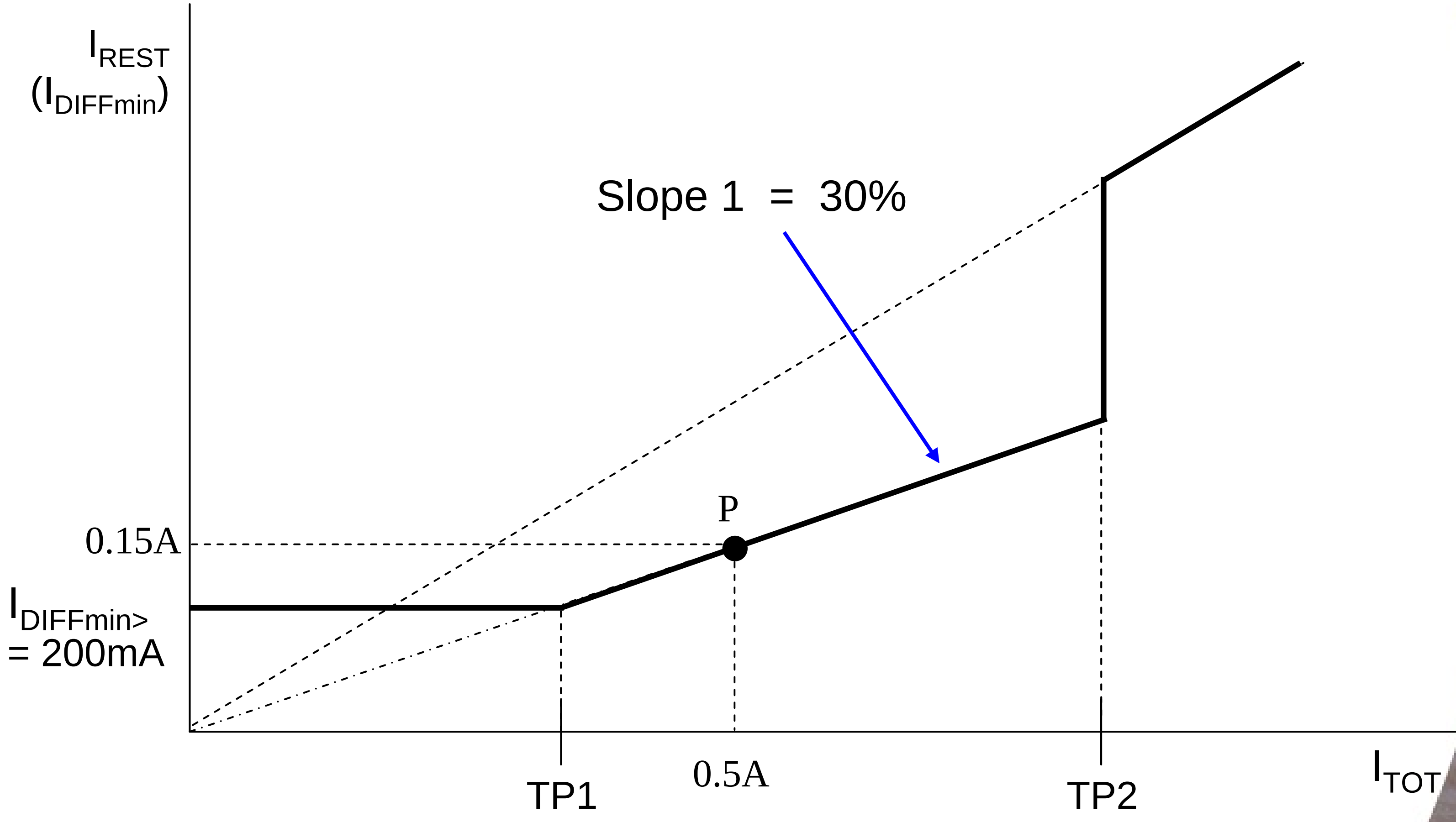
- What needs to be realised is that the first one is properly termed the ***restraint characteristic (RC)*** whilst the latter is an operating characteristic.
- Strictly speaking the RC tells us how much current a relay will use to restrain based on the currents measured at the respective CT locations.
- The currents at the CT locations are combined into a total current, the exact formula varying from one manufacturer to the next.
- Call this current I_{TOT}.

Principles of Differential Relaying – The Restraint Characteristic

- I_{TOT} is commonly called the restraint current but in reality the restraint current is derived from it.
- I_{TOT} is also a measure of the loading of the primary system.
- For example: consider a two winding transformer which has a slope 1 setting of 30% and a minimum differential operating current setting, $I_{DIFFmin}$ = 20% (or 200mA for a 1A relay).



Principles of Differential Relaying – The Restraint Characteristic



Principles of Differential Relaying – The Restraint Characteristic

- The manufacturer says that:

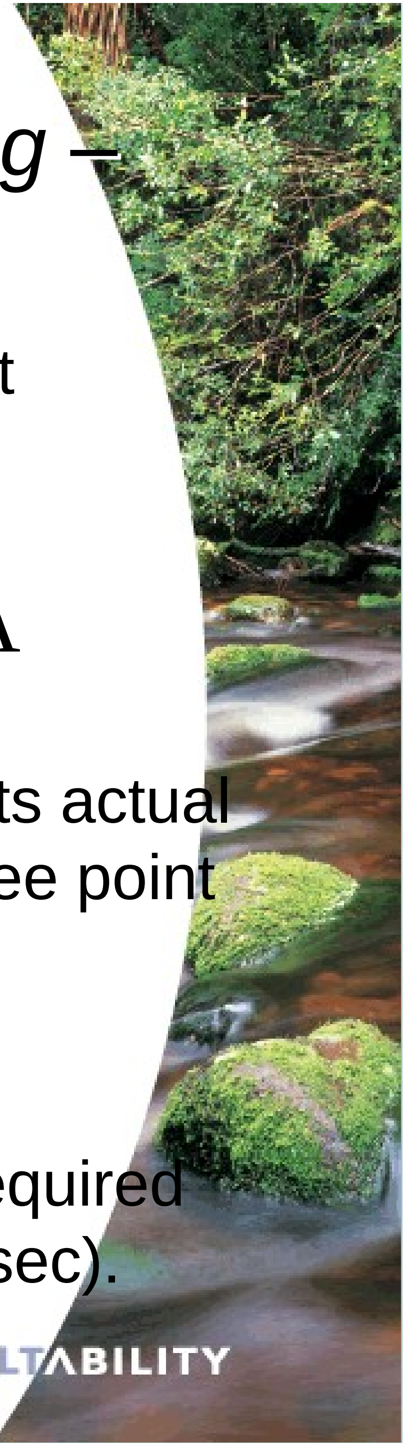
$$I_{rest} = \frac{|I_1| + |I_2|}{2}$$

- What he is really saying is that

$$I_{TOT} = \frac{|I_1| + |I_2|}{2}$$

- I_1 and I_2 are the currents measured at the respective ends.

Principles of Differential Relaying – The Restraint Characteristic



- Suppose further that there is 0.5A (sec) flowing at each end.

$$I_{TOT} = \frac{|I_1| + |I_2|}{2} = \frac{0.5 + 0.5}{2} = 0.5A$$

- The relay will now use 30% of this I_{TOT} to derive its actual restraint current, i.e. I_{rest} = 0.3 x 0.5 = 0.15A (see point P on the restraint characteristic).
- Now if I_{DIFF} > 0.15A relay operation results.
- Alternatively, 0.15A is the minimum diff current required for relay operation if the system loading is 0.5A (sec).

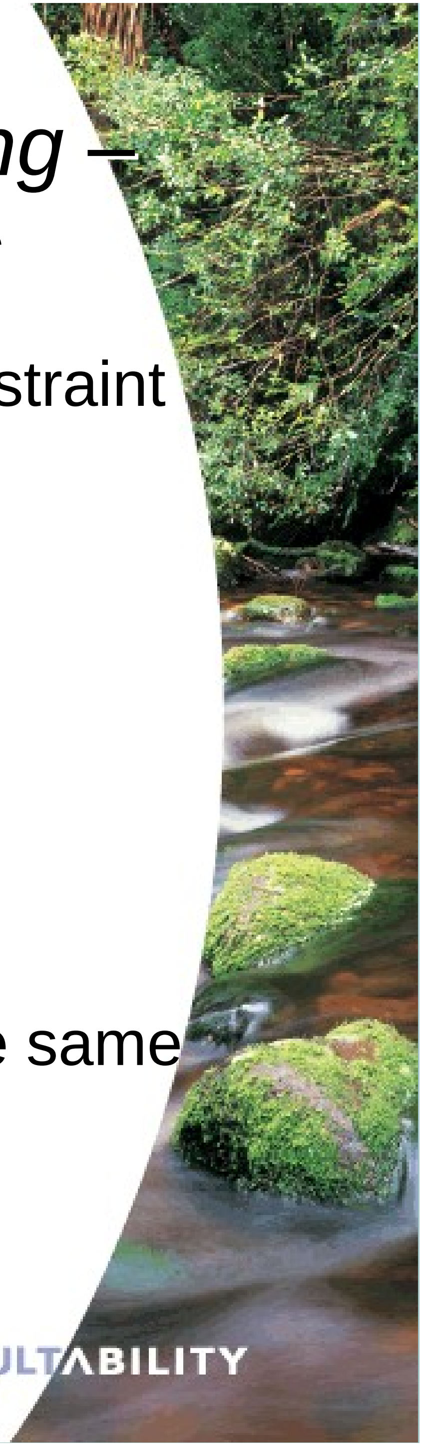
Principles of Differential Relaying – The Restraint Characteristic

- If the relay in question was a 7SD, then the restraint current would be given by:

$$I_{rest} = \mathrm{Idiff} > +0.3 \cdot I_{TOT}$$

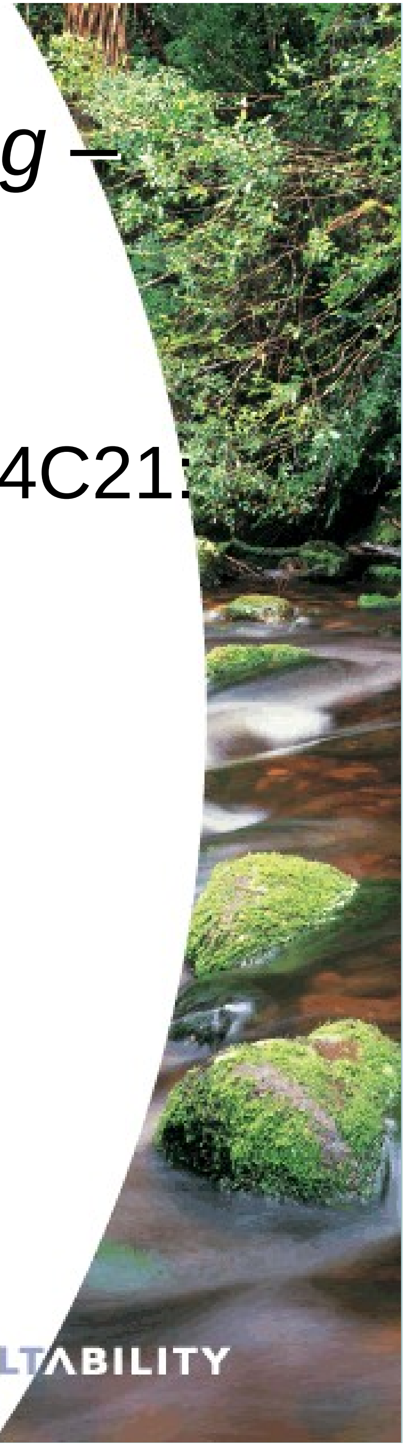
$$= 0.2 + 0.3 \cdot \frac{0.5 + 0.5}{2} = 0.35\mathrm{A}$$

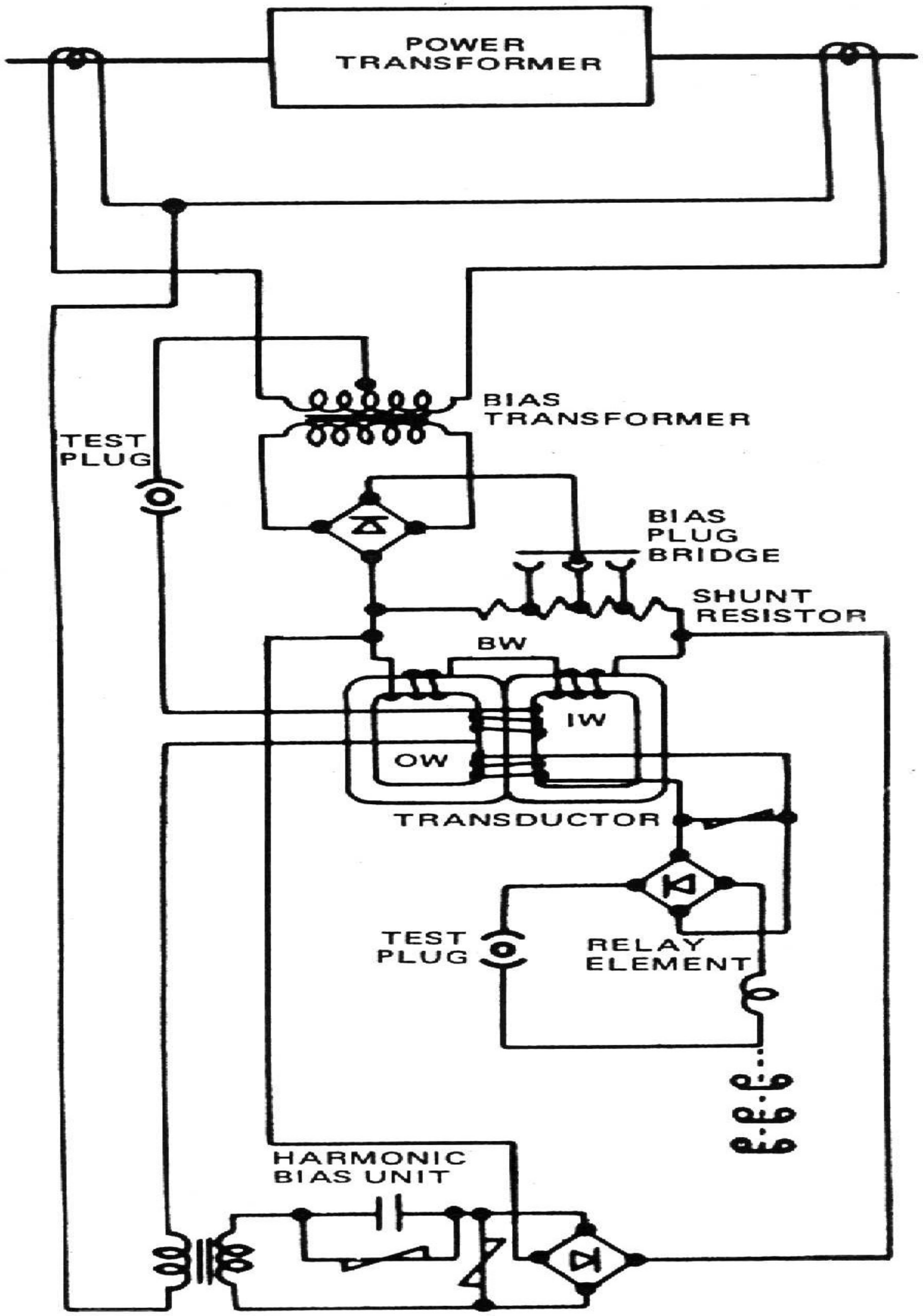
- Thus greater restrain here with the 7SD for the same throughcurrents.



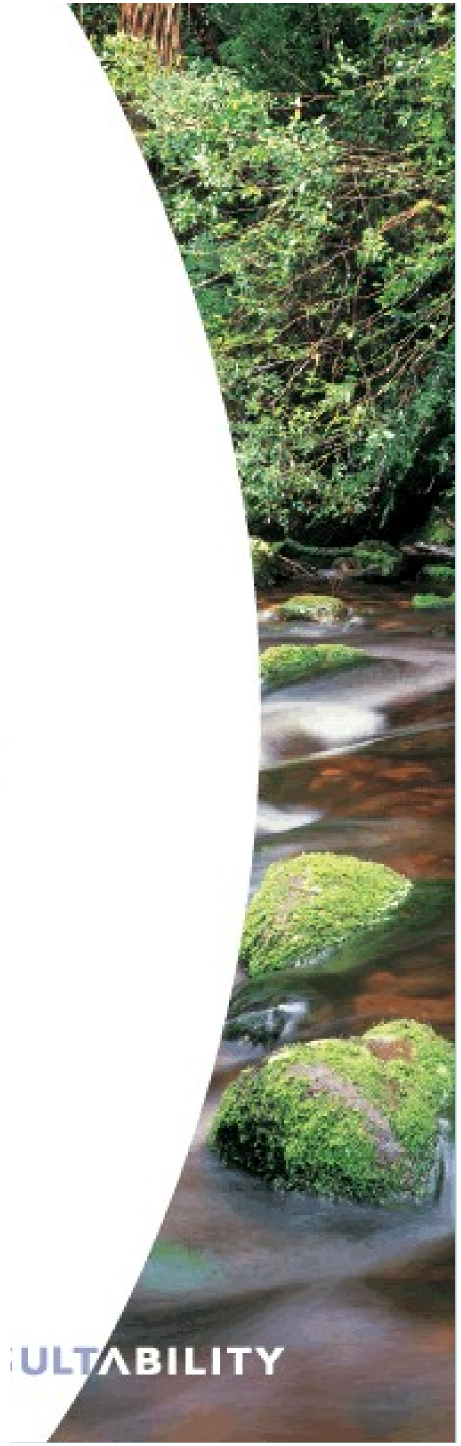
Principles of Differential Relaying – The Restraint Characteristic

- Concept well illustrated by the Reyrolle 4C21:





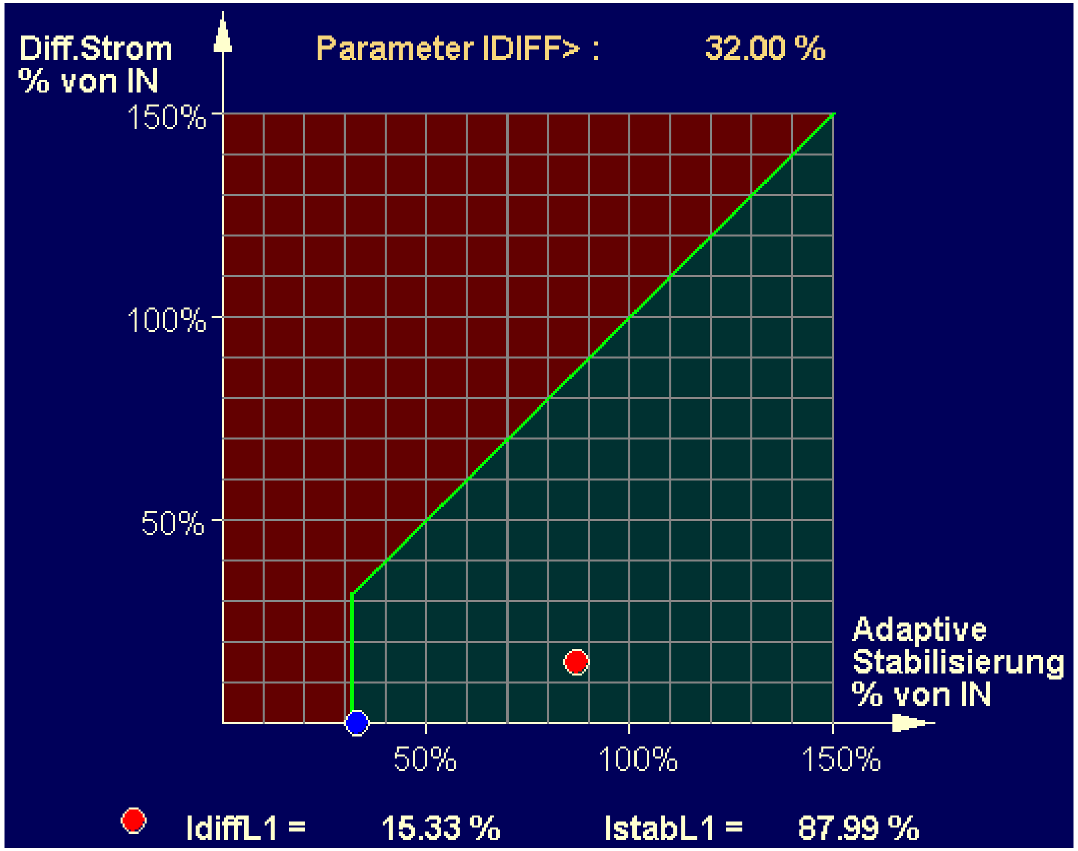
BW: Bias Winding
IW: Input Winding
OW: Output Winding



Principles of Differential Relaying – The Restraint Characteristic

- The 7SD uses the RC to determine how much restraint current is to be applied based on I_{TOT}.
- I_{diff} is now compared to I_{rest} and operating results if $I_{diff} > I_{rest}$ as illustrated by the operating characteristic.
- The characteristic is simple in that operation if $y > x$, no-op if $y < x$ with the boundary defined by $y = x$.
- $y = I_{diff}$, $x = I_{rest}$.

Principles of Differential Relaying – The Restraint Characteristic



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Principles of Differential Relaying – The Restraint Characteristic

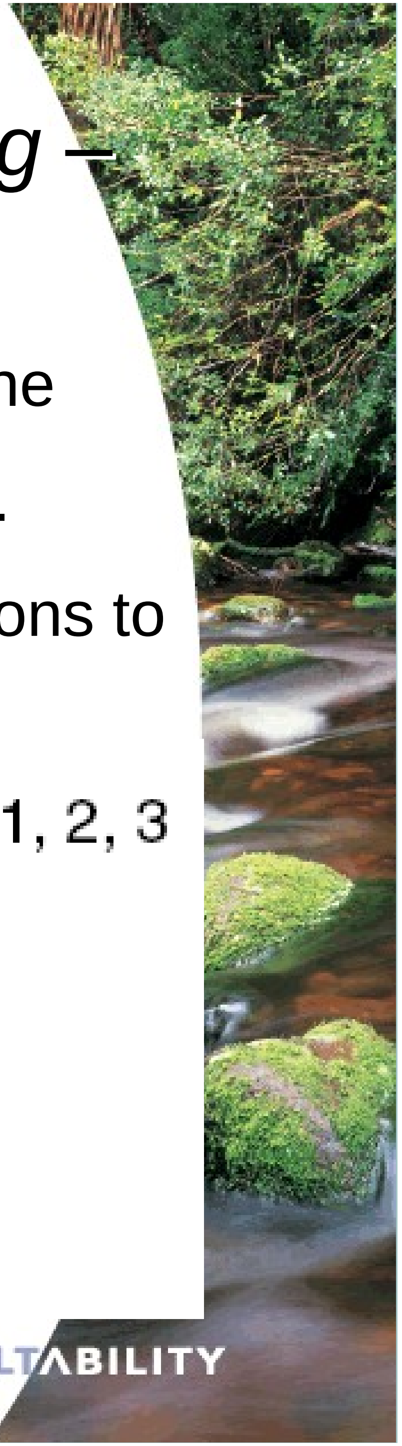
- The use of I_{TOT} instead of I_{rest} can be found in the SEPAM Series 80 range (machine and trfr diff).
- SEPAM uses throughcurrent, I_t, and the equations to derive I_{rest} are as follows:

$$Idx^2 - \frac{Itx^2}{32} > Is^2 \quad \text{where } 0 \leq Itx \leq \sqrt{2}\,In \text{ and } x = 1, 2, 3$$

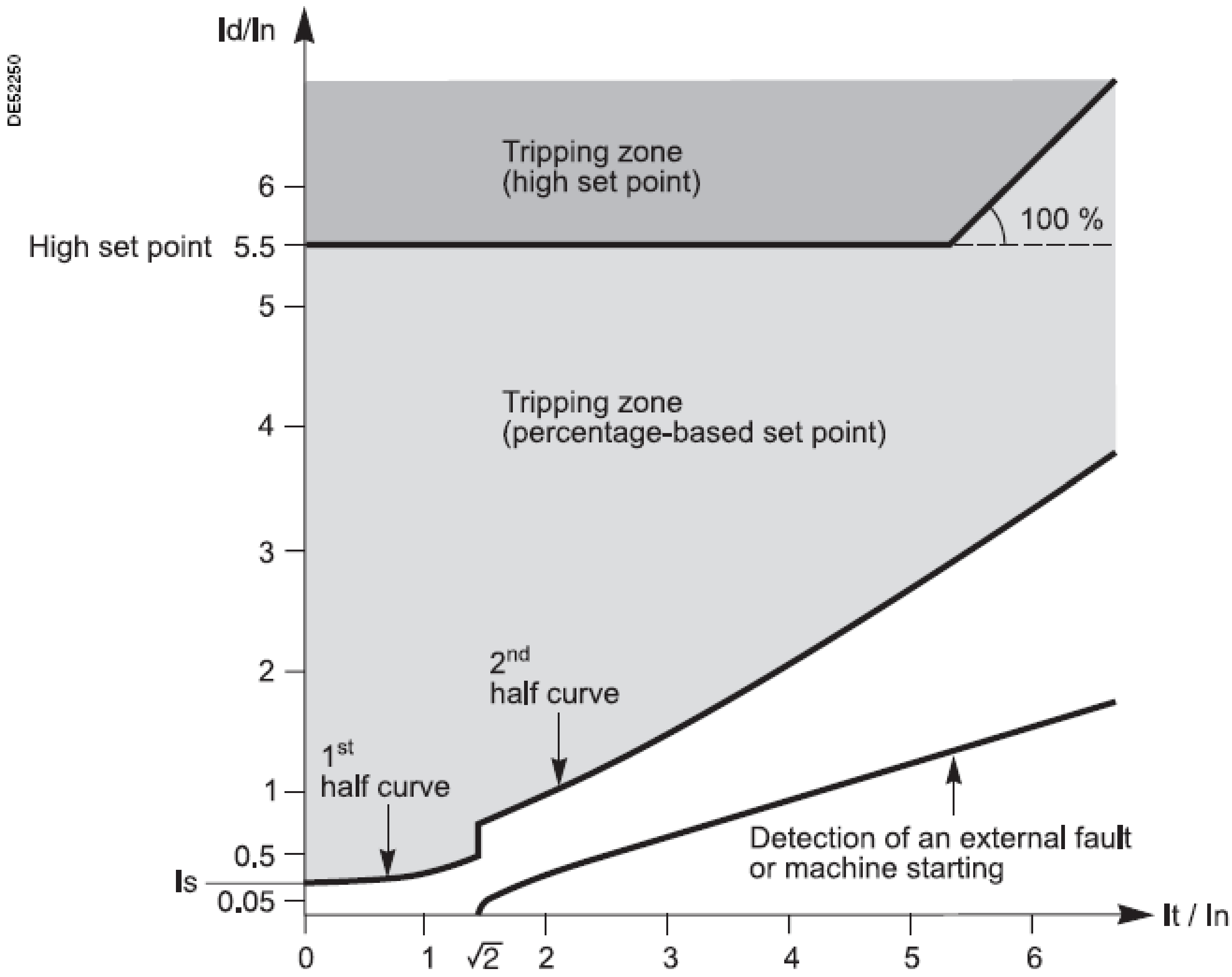
■ 2nd half curve

$$\frac{Idx^2}{8} - \frac{Itx^2}{32} > (0.005\ In)^2 \quad \text{where } \sqrt{2}\,In < Itx$$

and x = 1, 2, 3.



Principles of Differential Relaying – The Restraint Characteristic



Principles of Differential Relaying – The Restraint Characteristic

The SEPAM formulas need a bit of rearranging:

Principles of Differential Relaying – The Restraint Characteristic

Thus the actual process of determining I_{rest} is a

2-stage process:

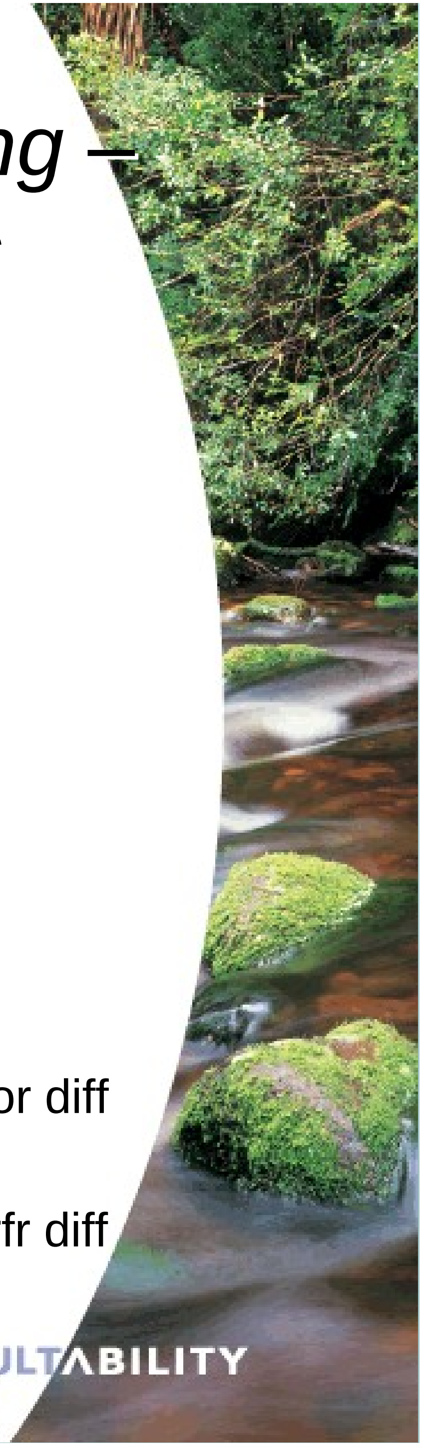
1. Determine I_{TOT}

Type A, $$I_{TOT} = \frac{|I_1| + |I_2|}{2}$$ KBCH, MICOM P54x, SEL

Type B, $$I_{TOT} = |I_1| + |I_2|$$ SIEMENS 7SD

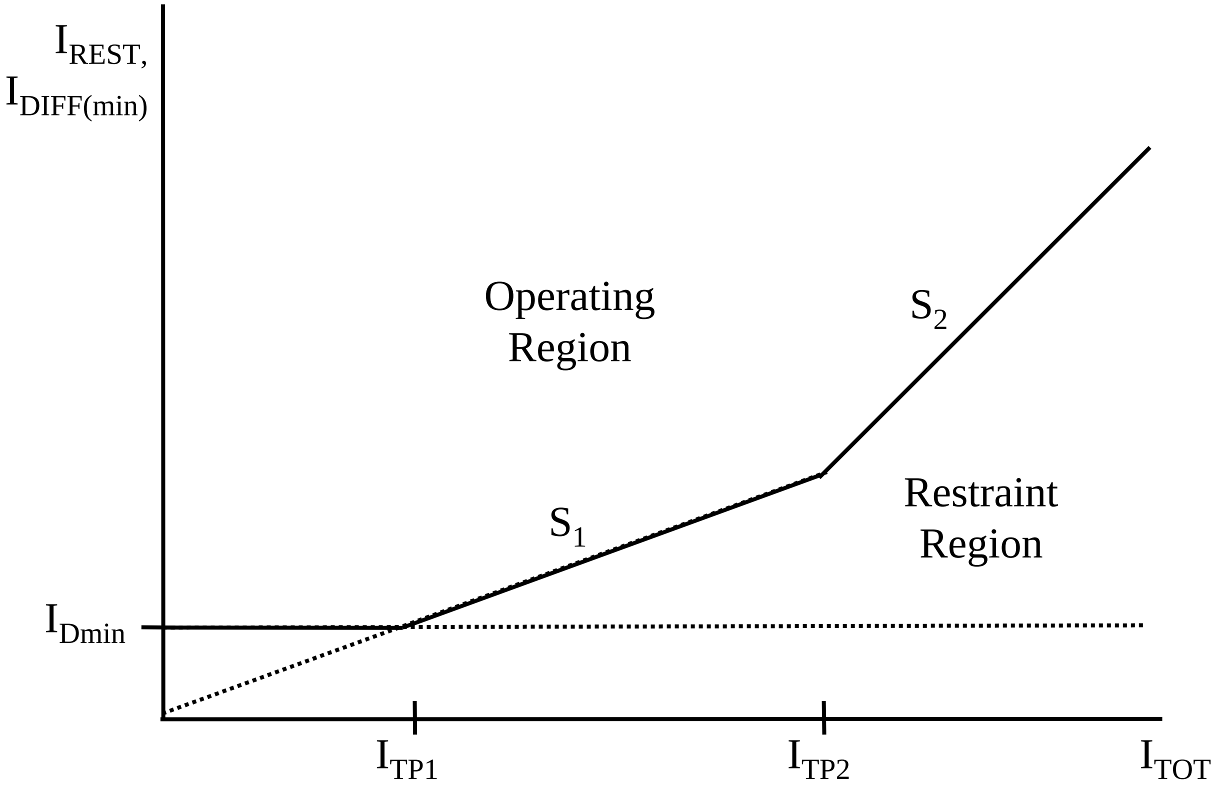
Type C, $$I_{TOT} = \frac{|I_1 - I_2|}{2}$$ SEPAM 80 Series – motor diff

Type D, $$I_{TOT} = \max(|I_1|, |I_2|)$$ SEPAM 80 Series – trfr diff



Principles of Differential Relaying – Setting a low z diff relay

- Typically 3 – 5 settings



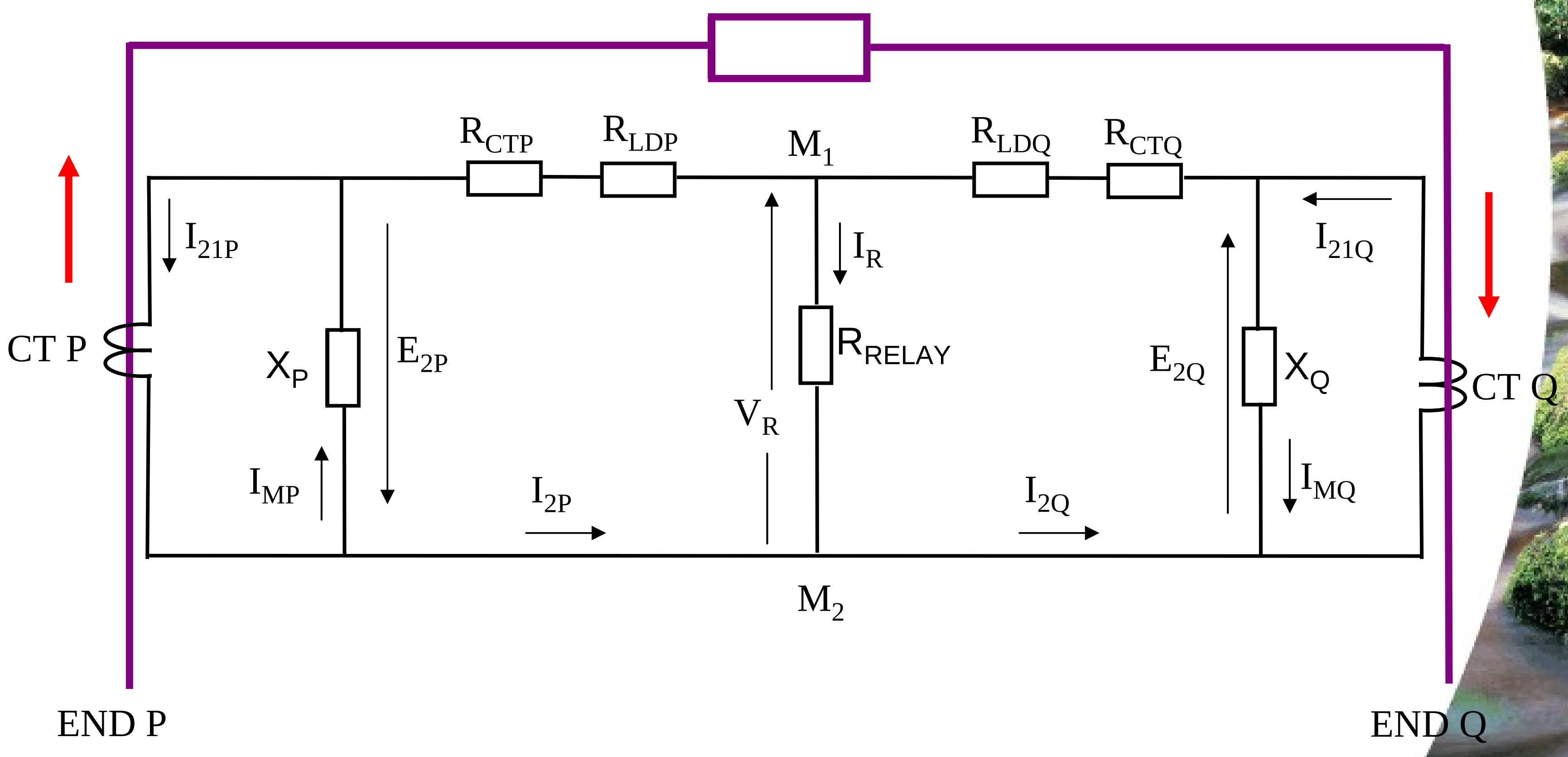
Principles of Differential Relaying – Setting a low z diff relay

- Settings generically defined as follows:
- I_{dmin} = minimum differential current required for operation
- I_{TP2} = turning point 2
- S_1 = slope 1
- S_2 = slope 2
- $I_{diff\text{-}hi}$ = diff hi-set (when $I_{diff} > I_{diff\text{-}hi}$ operation occurs irrespective of I_{rest}.
- (turning point 1 automatically defined by intersection

  of I_{dmin} and Slope 1)

Principles of Differential Relaying – Setting a low z diff relay –

More background theory…



Principles of Differential Relaying – Setting a low z diff relay –

$$E_{2P} = I_{2P}\left(R_{LDP} + R_{CTP}\right) + \left(I_{2P} - I_{2Q}\right)\cdot R_{RELAY} \quad (3.1)$$

$$E_{2Q} = I_{2Q}\left(R_{LDQ} + R_{CTQ}\right) + \left(I_{2Q} - I_{2P}\right)\cdot R_{RELAY} \quad (3.2)$$

Limiting case – R_{RELAY} = 0. Equations now become,

$$E_{2P} = I_{2P}\left(R_{LDP} + R_{CTP}\right) \quad (3.3)$$

$$E_{2Q} = I_{2Q}\left(R_{LDQ} + R_{CTQ}\right) \quad (3.4)$$

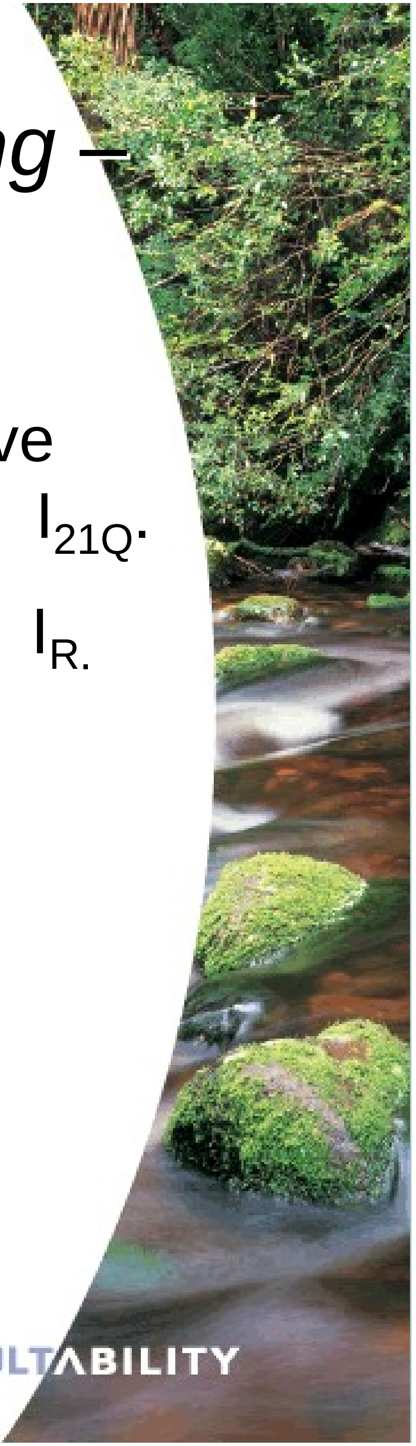
Principles of Differential Relaying – Setting a low z diff relay –

When primary current both ends are the same, have identical turns ratios and no saturation then, $I_{21P} = I_{21Q}$.

Thus $I_{MP} + I_{2P} = I_{MQ} + I_{2Q}$ or $I_{2P} - I_{2Q} = I_{MQ} - I_{MP} = I_{R}$.

Thus the relay current equals the difference of the respective magnetisation currents.

Question – why are there different magnetisation currents?



Principles of Differential Relaying – Setting a low z diff relay –

Non-zero I_{DIFF} can result if the CT mag curves, CT resistance or lead resistances are substantially different. This is the case when the relay is not located at the ***electrical midpoint*** of the secondary system.

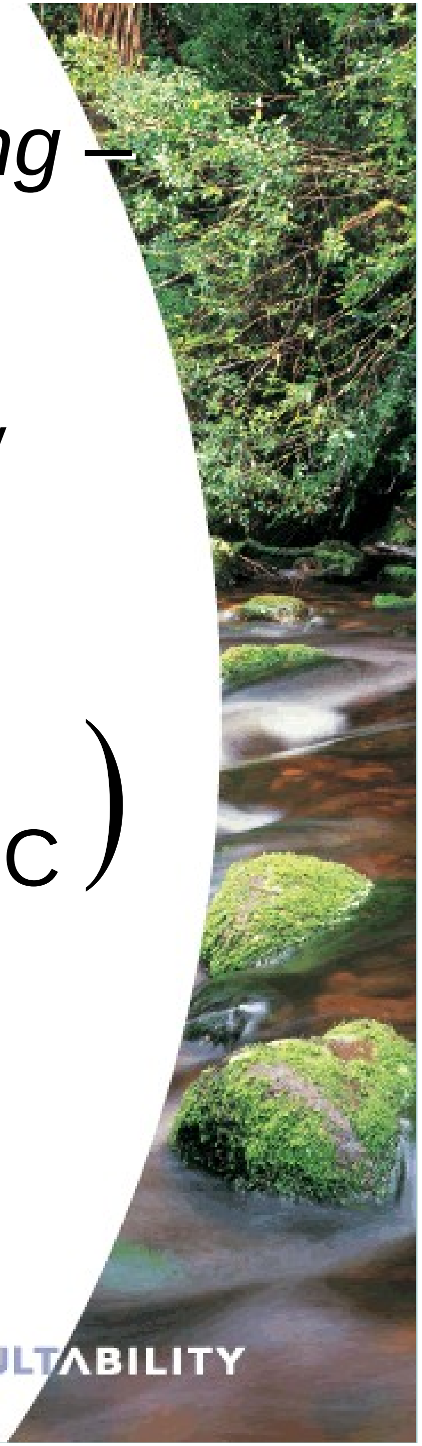
Let the relay operating current be I_{ROC}. Then to ensure stability must have $I_R = I_{MP} - I_{MQ} < I_{ROC}$.

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,*** $I_{ROC} > I_{MP} + I_{MQ}$.

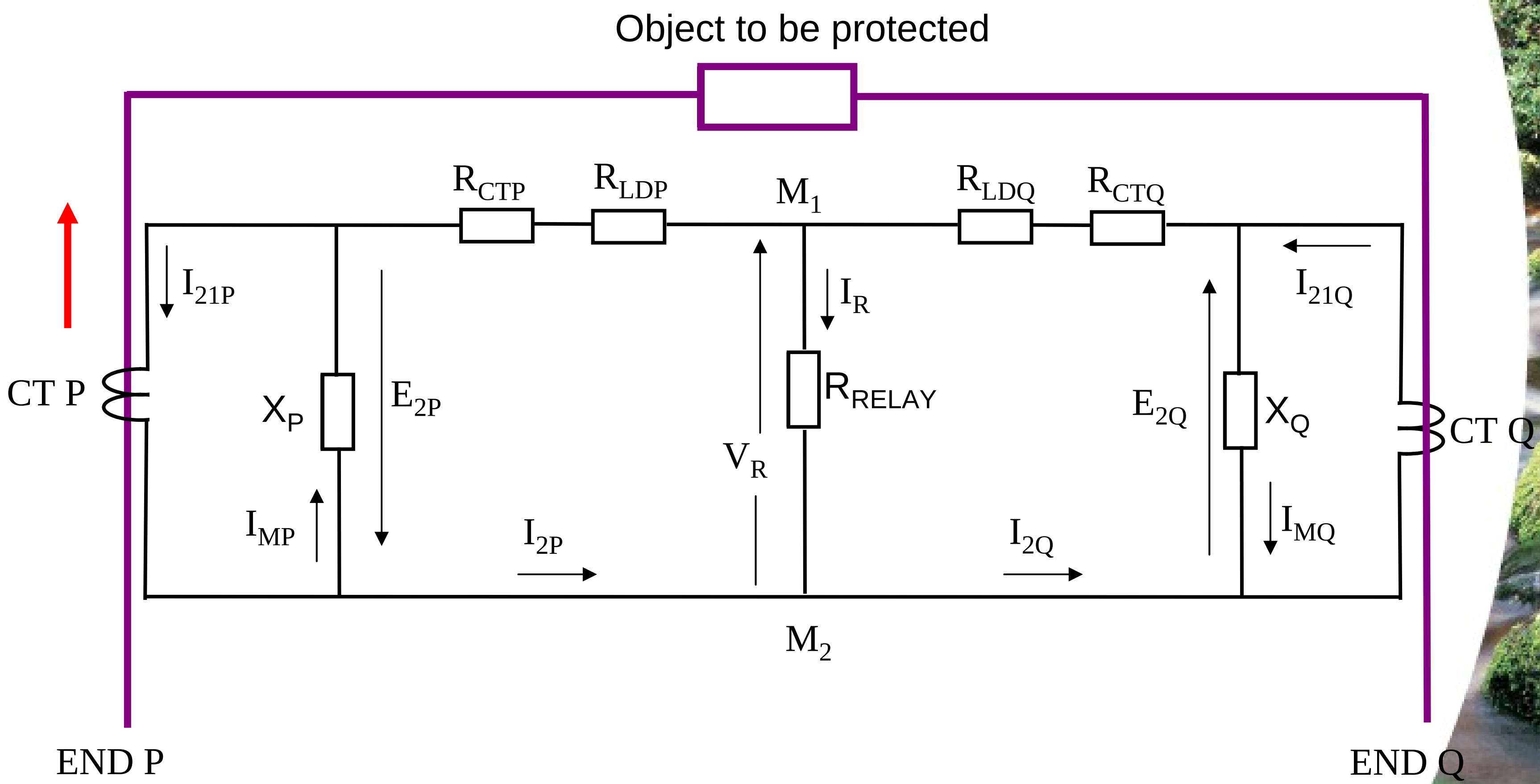
Principles of Differential Relaying – Setting a low z diff relay –

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

$$I_{FOC} = N \cdot \left(I_{MP} + I_{MQ} + I_{ROC} \right)$$



Principles of Differential Relaying – Setting a low z diff relay –



LEADERS IN CONSULTABILITY

Principles of Differential Relaying – Setting a low z diff relay – I_{dmin}

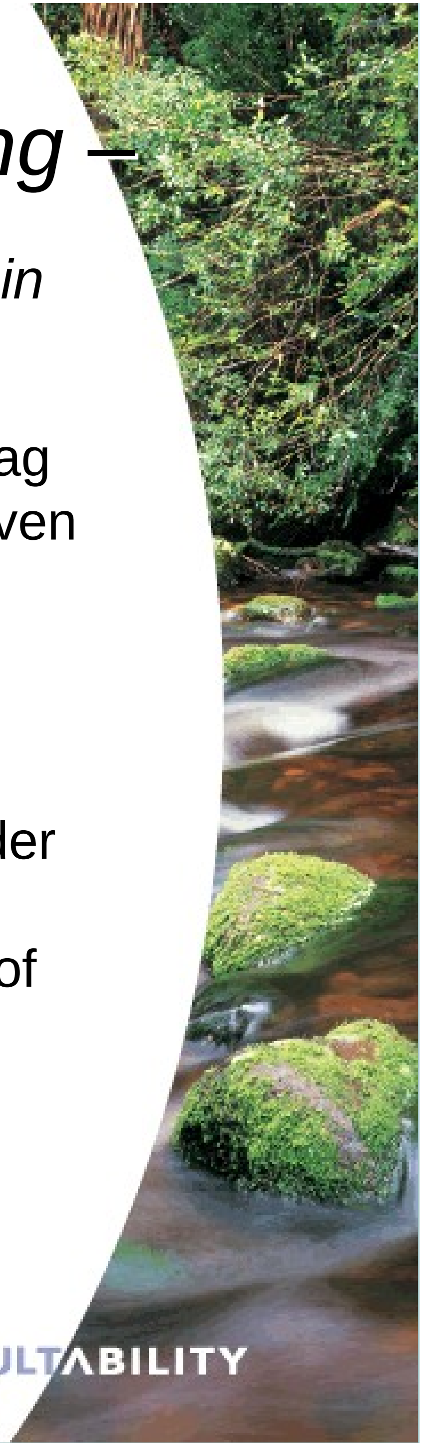
1. The minimum current required to operate the relay, I_{ROC}, should be at least > maximum difference between the mag currents at the two ends. Thus $I_{ROC} > \max(I_{MP}, I_{MQ})$ or even more conservatively,

$$I_{ROC} > |I_{MP}| + |I_{MQ}|$$

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.

$$\mathbf{I_{ROC} > 0.05 * I_{FLA} * K_1}$$

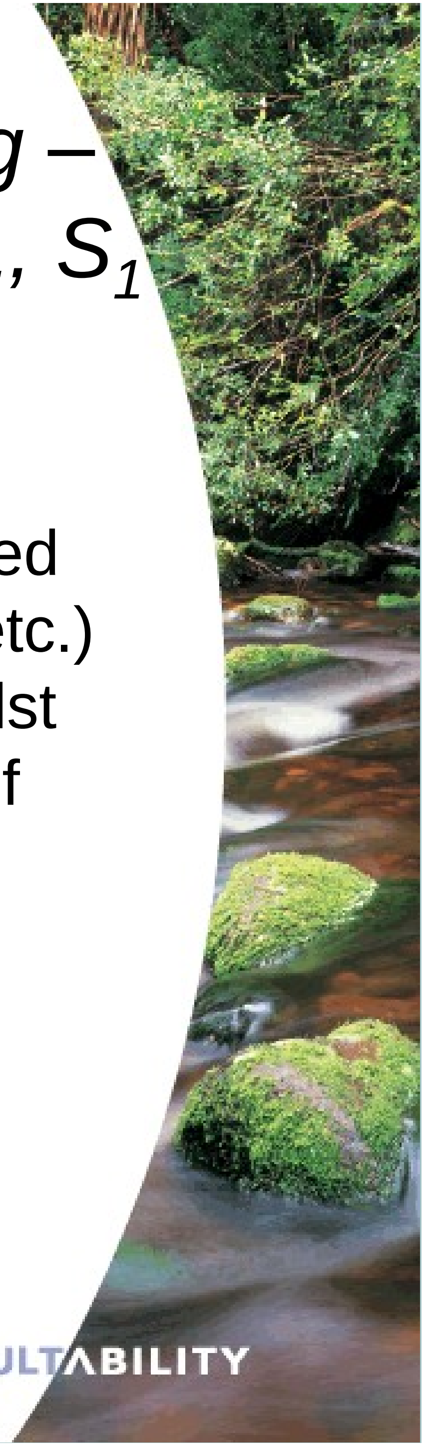
K_1 allows for CTR factor



LEADERS IN CONSULTABILITY

Principles of Differential Relaying – Setting a low z diff relay – 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, 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.

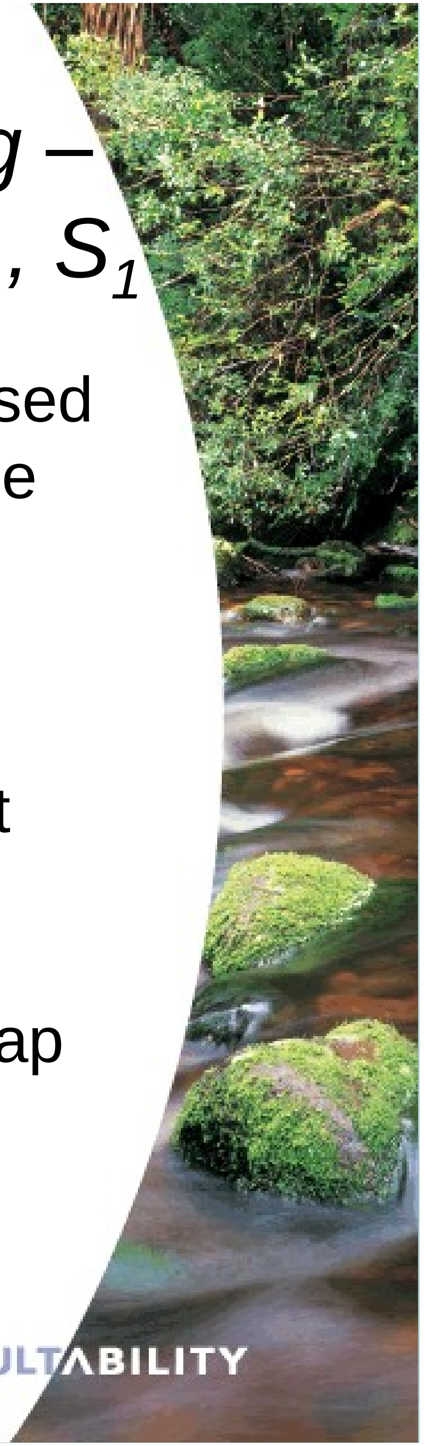


Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

- When applied to power transformers this is based on the worst case I_{DIFF} that could result due to the action of the tapchanger.

Transformers

- Determine the tap which results in the largest unbalance.
  This is usually the maximum boosting tap.
- Denote the turns ratio corresponding to this tap position by TRMIN (maximum boosting corresponds to the minimum turns ratio).



Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

TR_{MIN} is calculated as follows:

$$TR_{MIN} = \frac{V_{HV-MAXTAP}}{V_{HV-NOM}} \cdot TR_{NOM}$$

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

Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

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

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

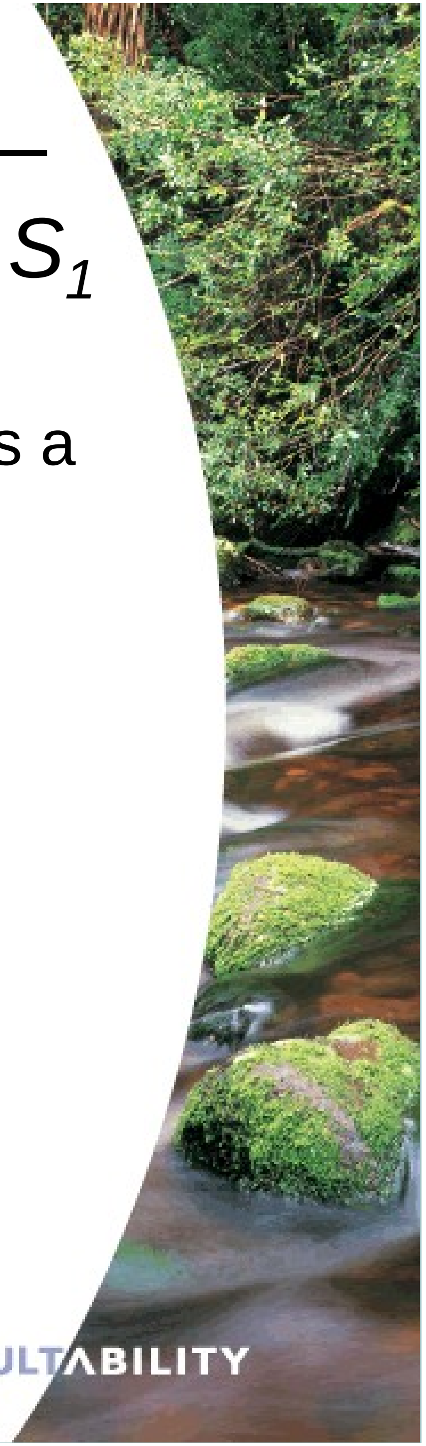
CTR_{CFLV} = LV CTR correction factor
CTR_{CFHV} = HV CTR correction factor

Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

- $I_{DIFF} = \left| I_{HV} + I_{LV} \right|$, I_{REST} depends on whether it is a Type A, B, C or D relay.
- In each case the slope setting is given by,

$$S_1 = \frac{I_{DIFF}}{I_{TOT}} \cdot 100\%$$

Allow 5% for relay and calculation errors.



Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

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.

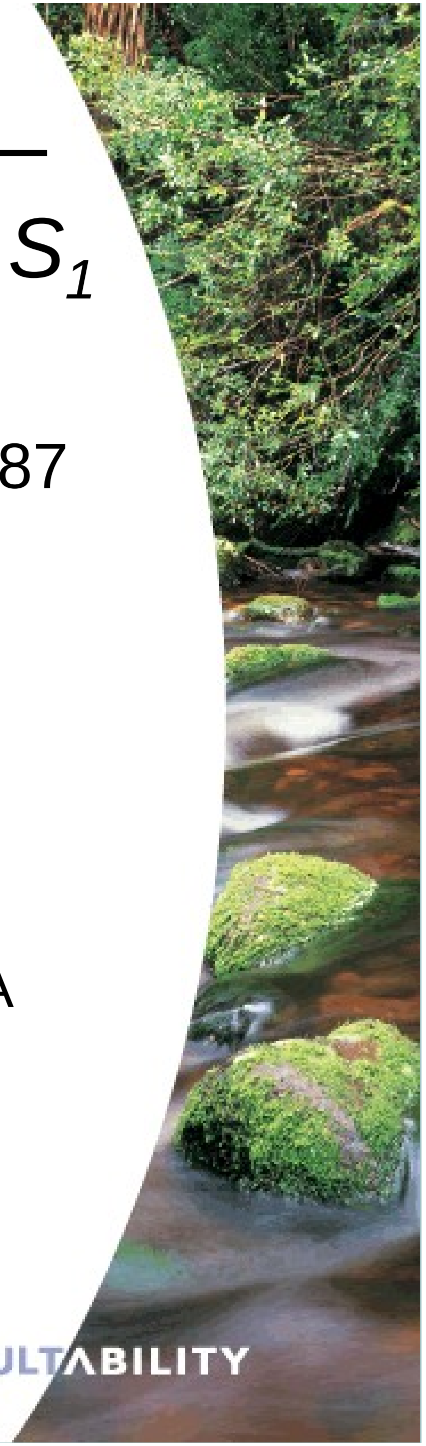
Thus CTR_{CFHV} = 1/0.305 = 3.28

Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

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

$$I_{LV} = 0.555 \cdot 1.8 = 1$$

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



Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

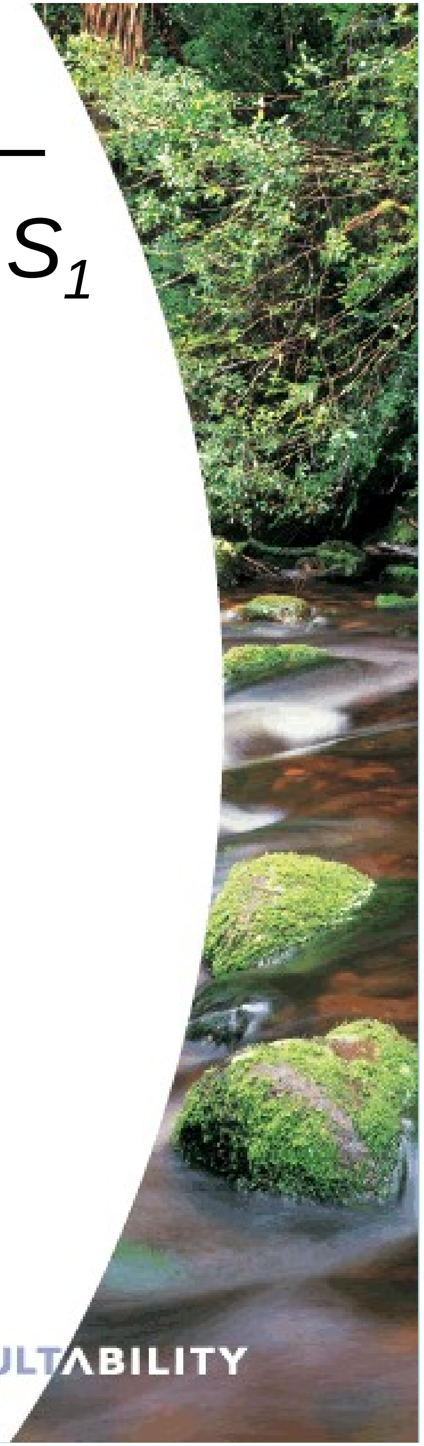
Type A relay,

$$I_{DIFF} = |1.177 - 1| = 0.177A$$

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

$$S_1 = \frac{0.177}{1.0885} \cdot 100\% = 16.26\%$$

Allowing for a 5% error, get a slope setting of 17.1%. Set to 20%.



Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

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%.

Principles of Differential Relaying – Setting a low z diff relay – Slope 1, S_1

Type D relay,

$$I_{DIFF} = |1.177 - 1| = 0.177A$$

$$I_{TOT} = \max(|I_{HV}|, |I_{LV}|) = \max(1.177, 1) = 1.177A$$

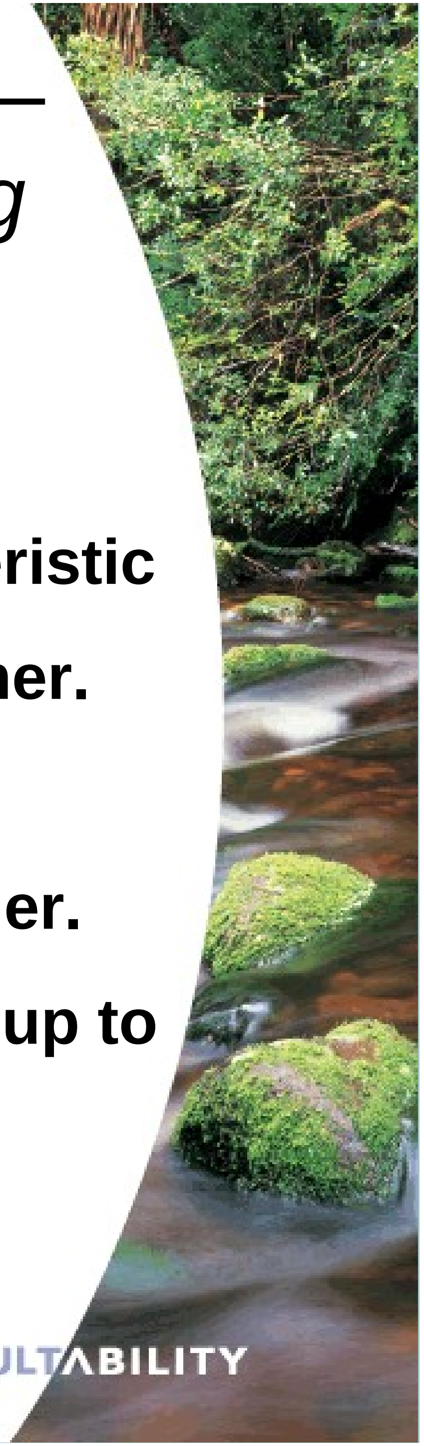
$$S_1 = \frac{0.177}{1.177} \cdot 100\% = 15.04\%$$

Allowing for a 5% error, get a slope setting of 15.6%. Set to 20%.

Principles of Differential Relaying – Setting a low z diff relay – Turning Point 2, I_{TP2}

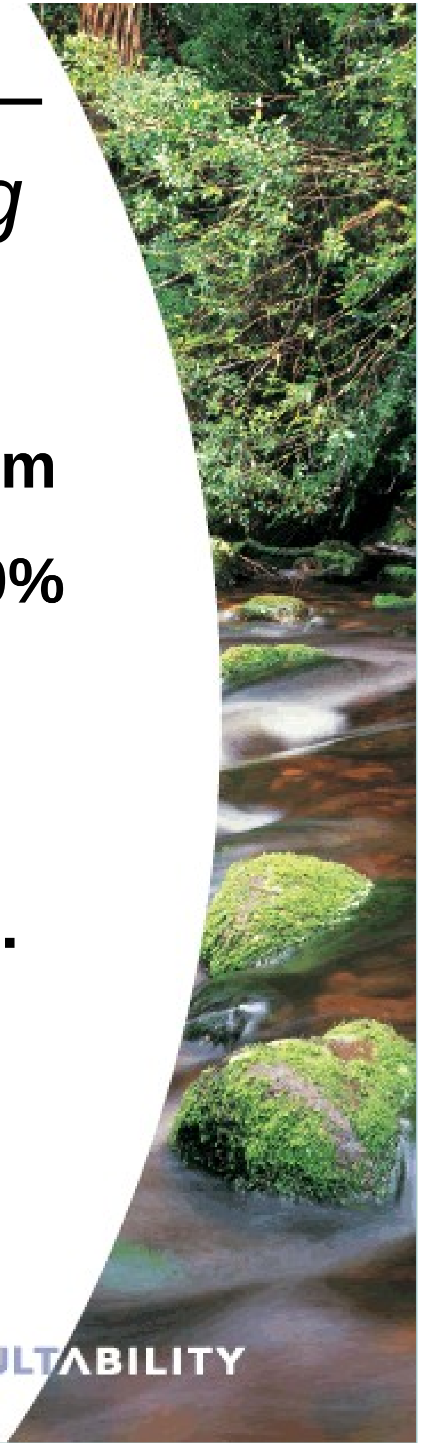
C) Turning Point 2, I_{TP2}

- **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 power transformers this could be up to 200% of rated current.**



Principles of Differential Relaying – Setting a low z diff relay – Turning Point 2, I_{TP2}

- **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.**

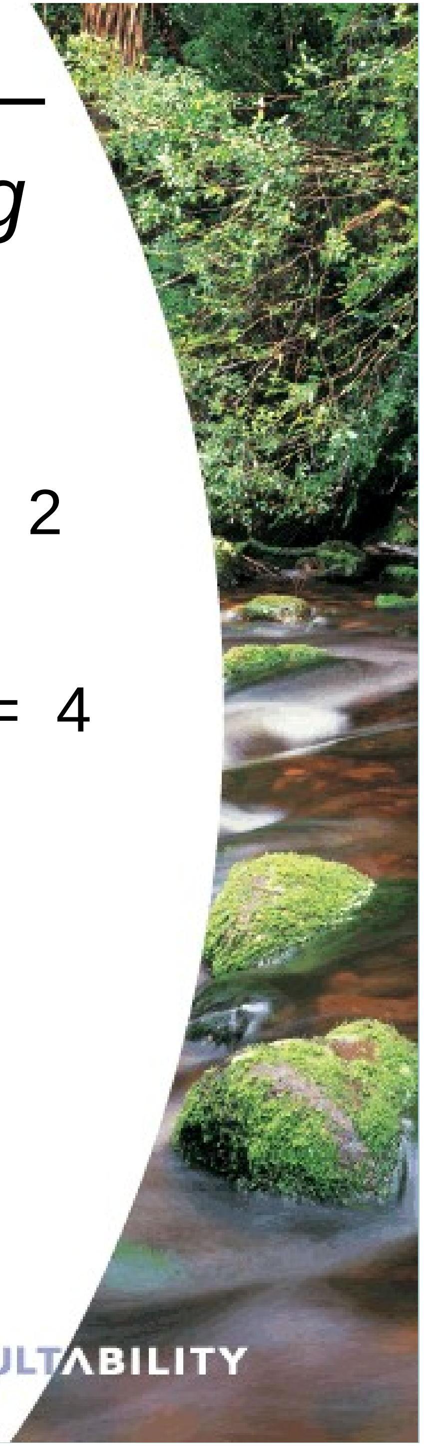


Principles of Differential Relaying – Setting a low z diff relay – Turning Point 2, I_{TP2}

Type A: $I_{TOT} = \dfrac{2 \cdot I_{FLA} + 2 \cdot I_{FLA}}{2} = 2 \cdot I_{FLA}$ thus $I_{TP2} = 2$

Type B: $I_{TOT} = 2 \cdot I_{FLA} + 2 \cdot I_{FLA} = 4 \cdot I_{FLA}$ thus $I_{TP2} = 4$

Type C: $I_{TOT} = \max(2 \cdot I_{FLA})$ thus $I_{TP2} = 2$



Principles of Differential Relaying – Setting a low z diff relay – Turning Point 2, I_{TP2}

- Alternatively some texts advocate that slope 1 is effective over the linear operating range of the current transformer.

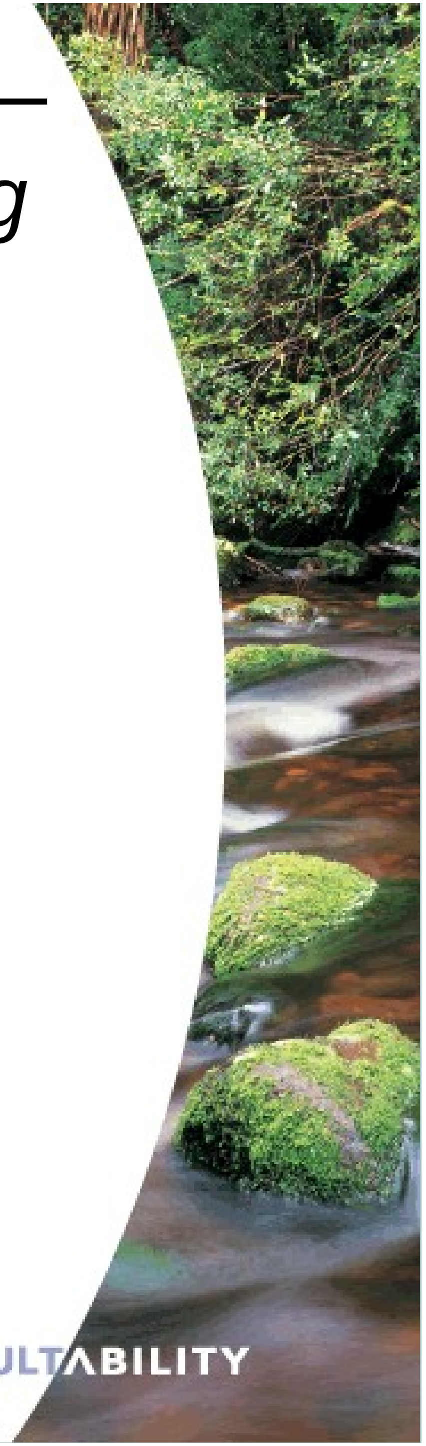
- I_{TP2} should thus be set at this limit.

- This approach leads to I_{TP2} typically being greater than I_{TP2} = 2 as advocated above.

- Implies improved sensitivity over the linear operating range but less stability.

Principles of Differential Relaying – Setting a low z diff relay – Turning Point 2, I_{TP2}

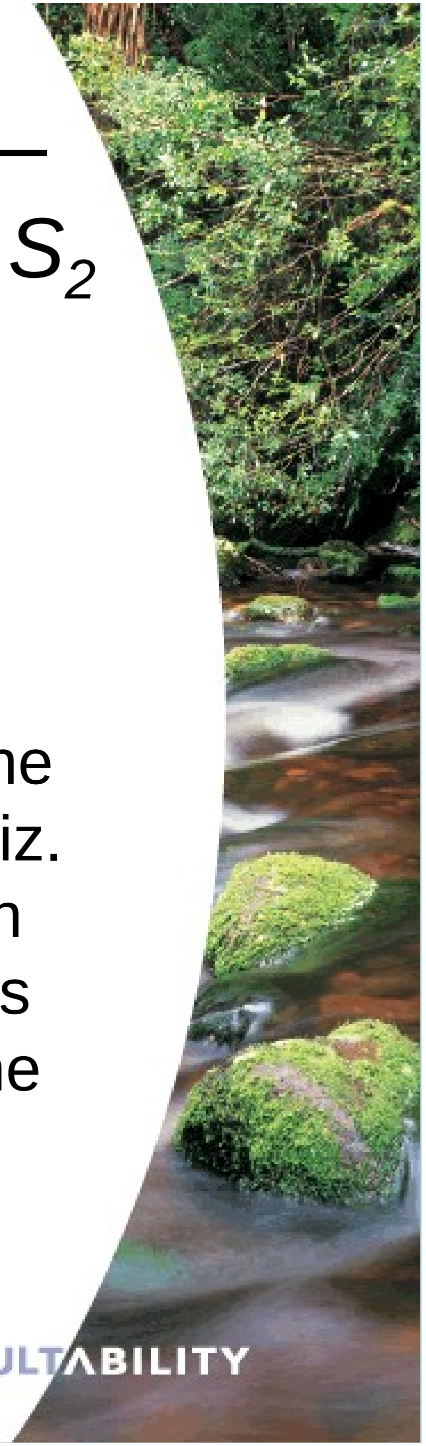
- For this reason the approach of $I_{TP2} = 2$ is adopted in this text.
- When it comes to generators and motors a turning point of 120% times rated current is generally considered sufficient as motors and generators are rarely loaded above this.



Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2

- The second bias slope is intended to ensure additional restraint with severe throughfault currents that could lead to CT saturation.

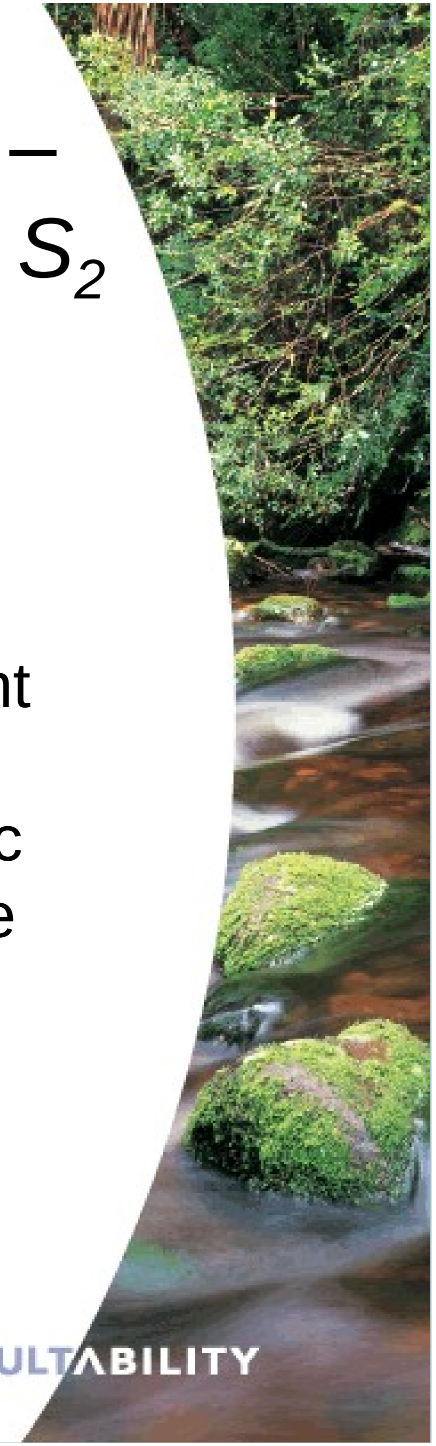
- Thus additional restraint is provided on top of the two other restraints already mentioned so far, viz. I_{Dmin} to cater for differences in CT magnetisation currents and transformer magnetisation currents and the slope 1 which caters for the action of the tapchanger.



Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2

- 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.



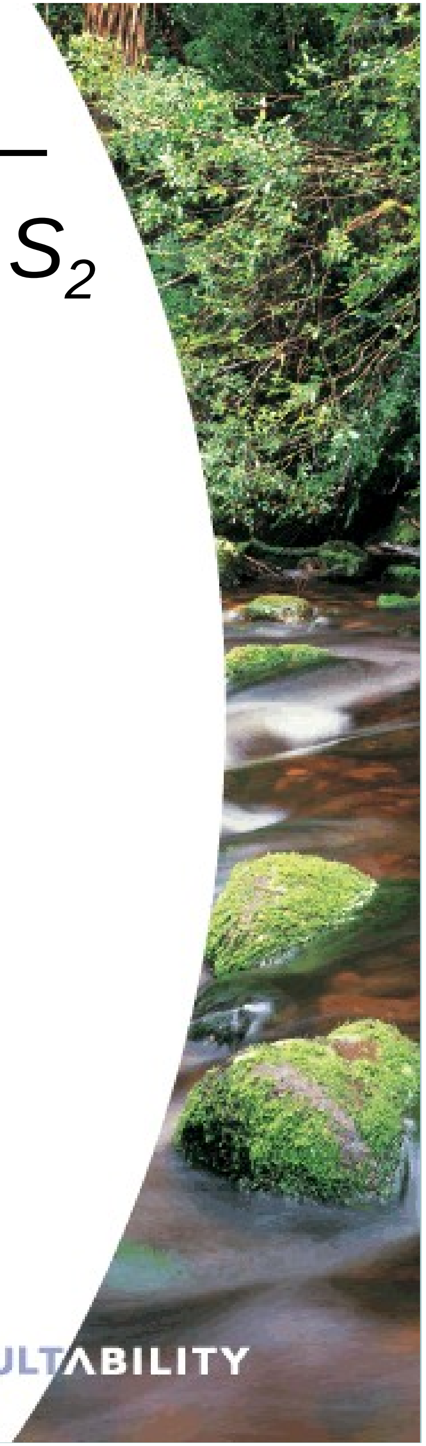
Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2

Singe-ended inzone fault characteristic:

$$I_{DIFF} = \left|I_{HV} + I_{LV}\right| = \left|I_{HV}\right|$$

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

and so slope $$= \frac{\left|I_{HV}\right|}{\left|I_{HV}\right|/2} \cdot 100 = 200\%$$



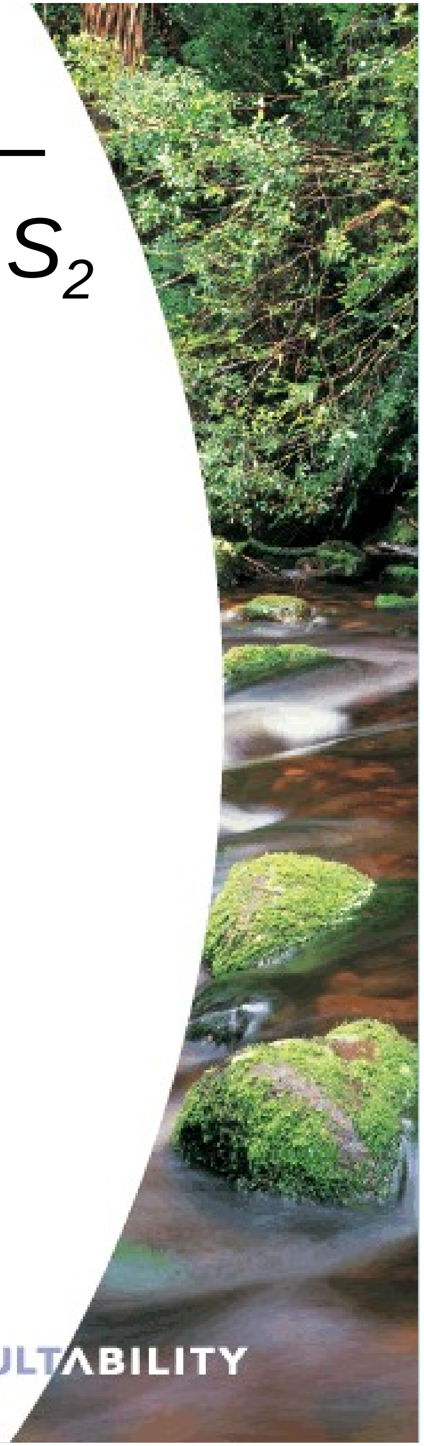
Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2

Singe-ended inzone fault characteristic:

$$I_{DIFF} = \left| I_{HV} + I_{LV} \right| = \left| I_{HV} \right|$$

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

and so slope $$= \frac{\left| I_{HV} \right|}{\left| I_{HV} \right|} \cdot 100 = 100\%$$



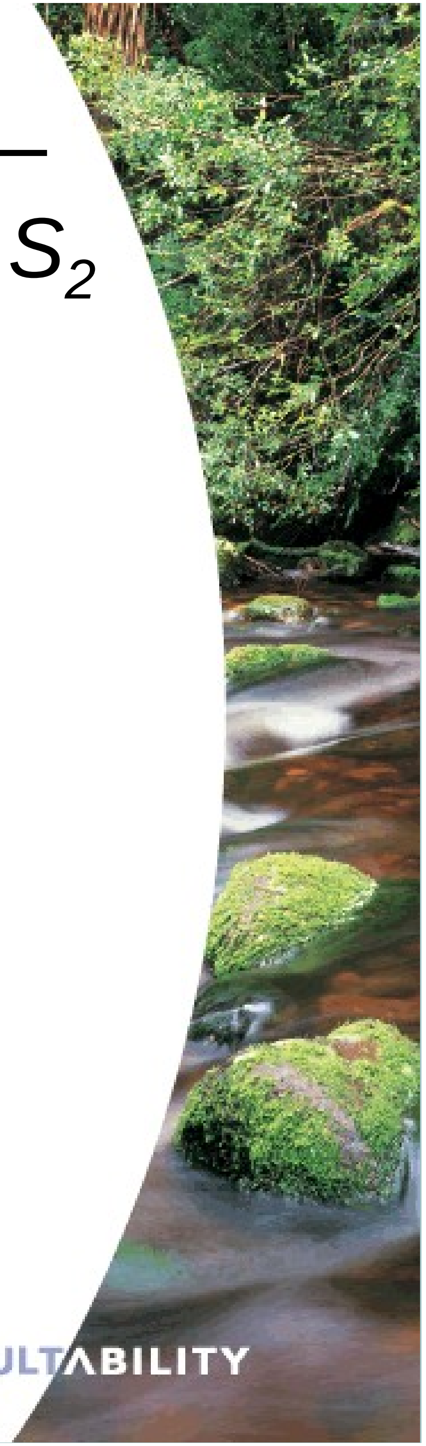
Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2

Singe-ended inzone fault characteristic:

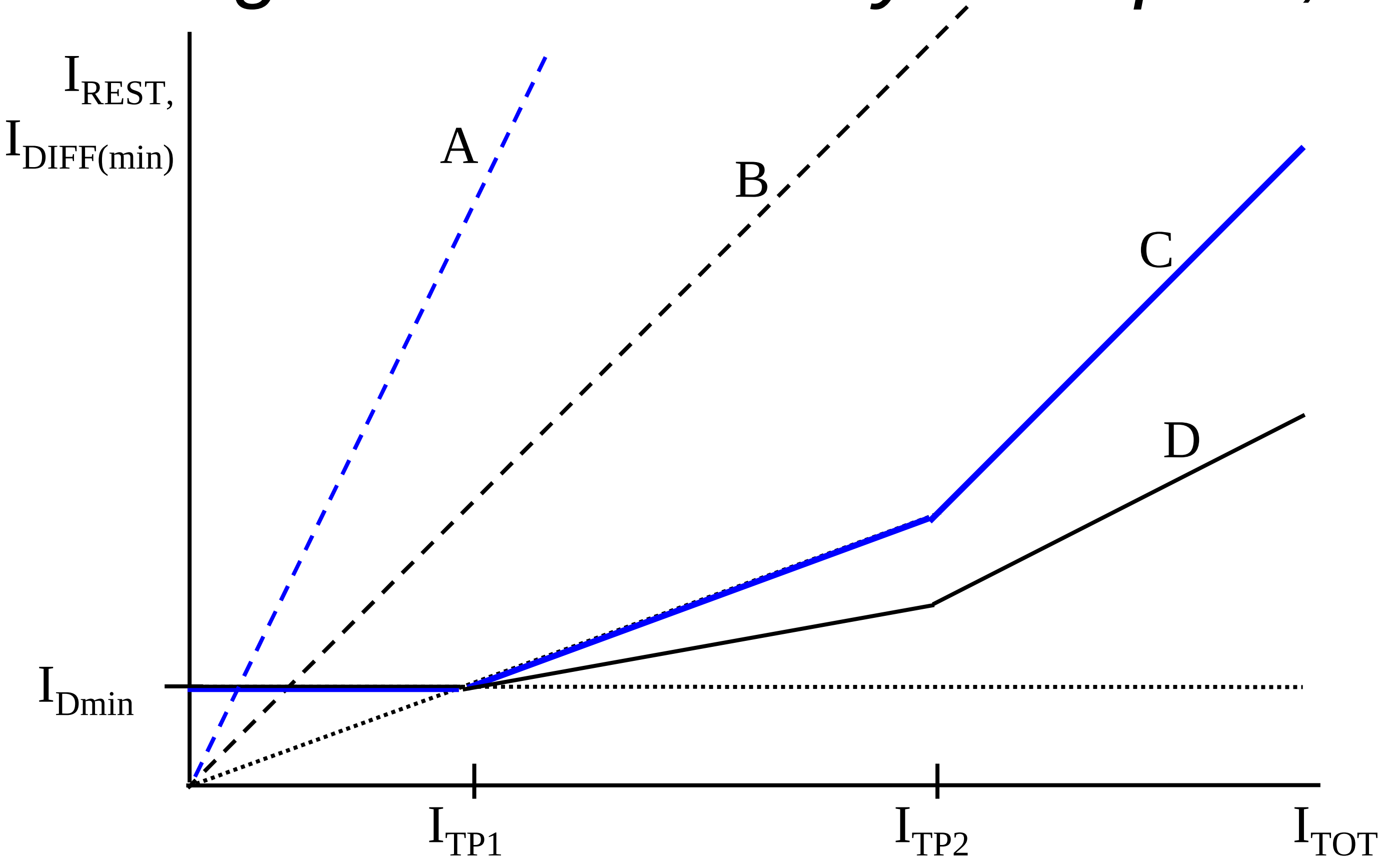
$$I_{DIFF} = \left|I_{HV} + I_{LV}\right| = \left|I_{HV}\right|$$

Type C: $I_{TOT} = \max\left(I_{HV}, I_{LV}\right) = \left|I_{HV}\right|$

and so slope $= \dfrac{\left|I_{HV}\right|}{\left|I_{HV}\right|} \cdot 100 = 100\%$



Principles of Differential Relaying – Setting a low z diff relay – Slope 2, S_2



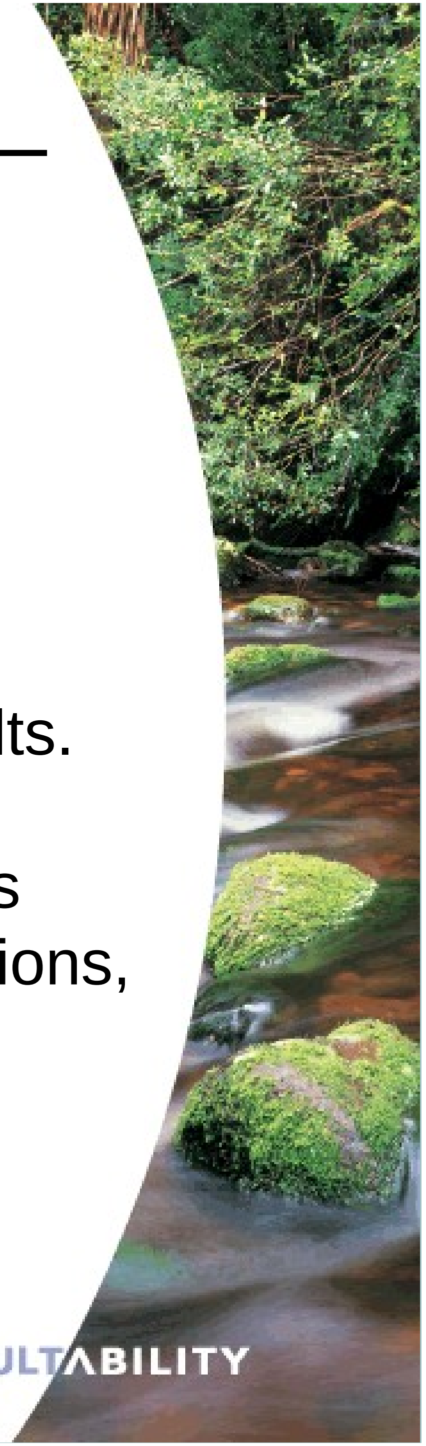
A = single-ended inzone fault characteristics for a Type 1 relay
B = single-ended inzone fault characteristics for Type 2 and 3 relays
C = typical restraint characteristic for a Type 1 relay
D = typical restraint characteristic for Types 2 and 3 relays

Principles of Differential Relaying – Setting a low z diff relay – $I_{diff\text{-}hi}$

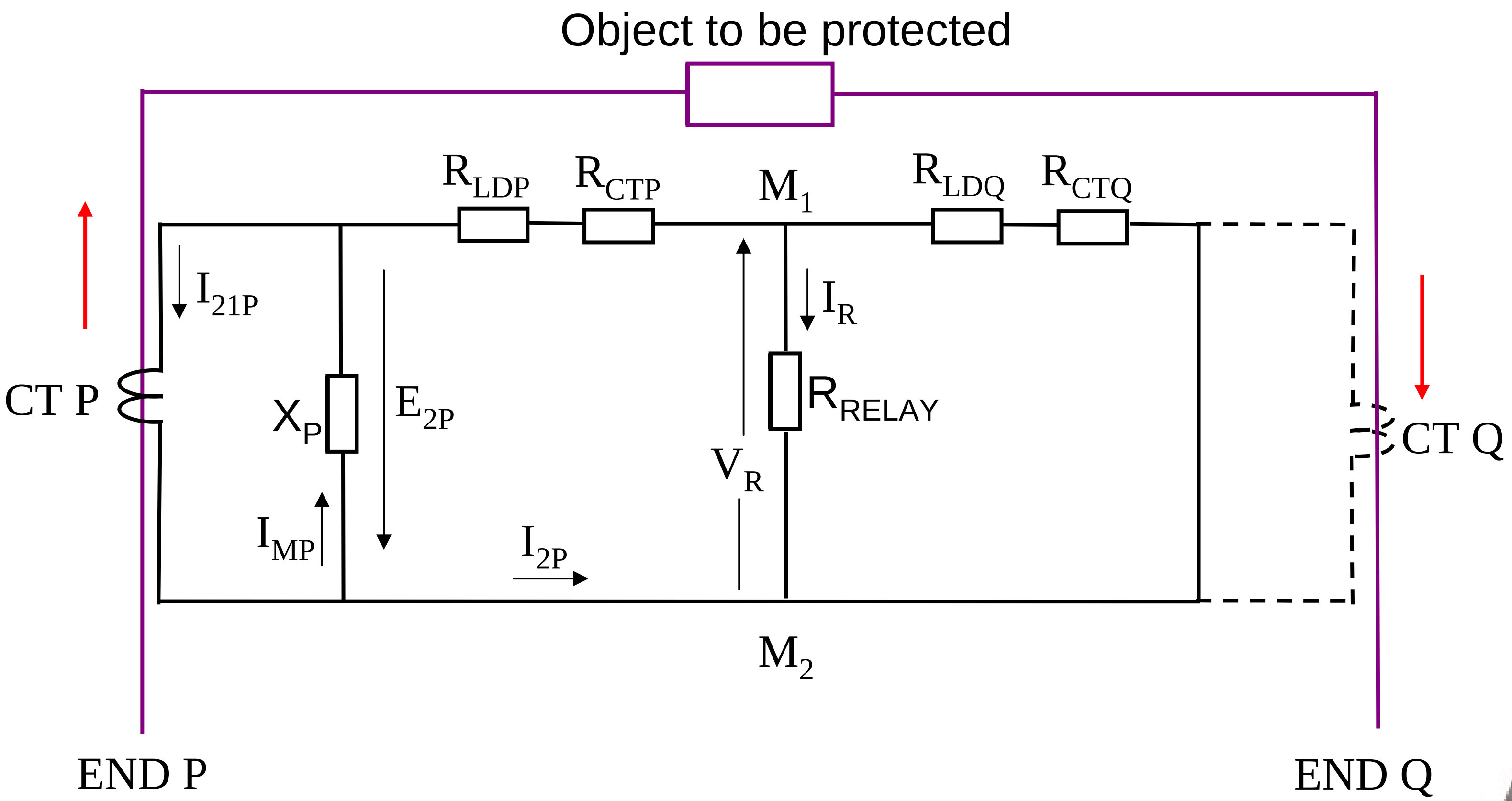
- Whenever $I_{DIFF} > I_{DIFF\text{-}HI}$ operation results irrespective of the value of I_{REST}.

- 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.



Principles of Differential Relaying – Setting a low z diff relay – $I_{diff\text{-}hi}$



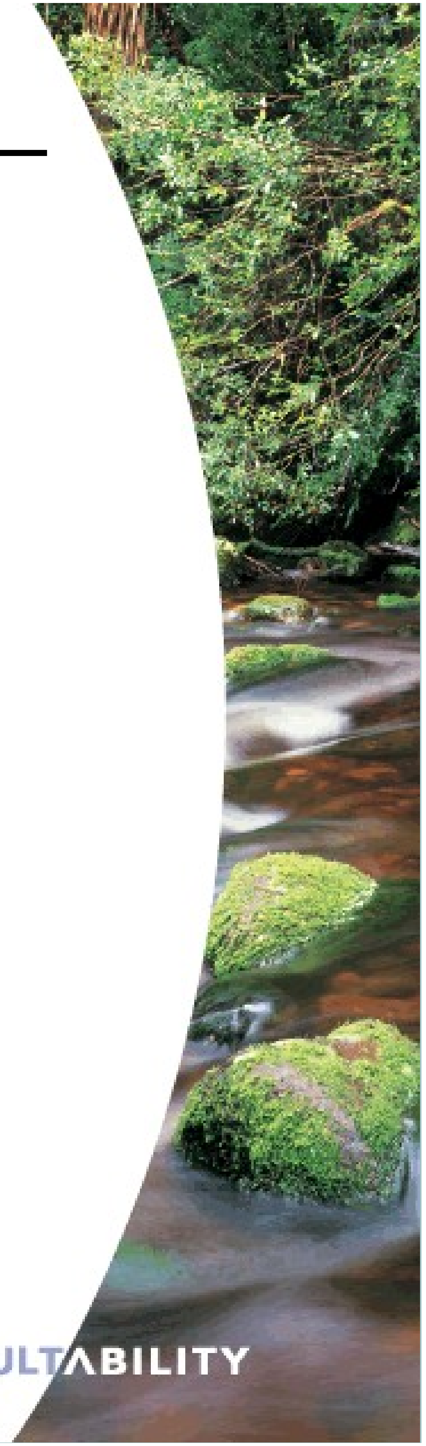
Principles of Differential Relaying – Setting a low z diff relay – $I_{diff\text{-}hi}$

In the previous figure have that the throughfault current leads to CT Q being fully saturated.

The differential current is thus $I_{DIFF} = I_{2P} = I_F/CTR$. Thus,

$$I_{DIFF-HI} = \frac{I_F}{CTR} \cdot K_1 \cdot K_2$$

I_F	=	maximum symmetrical throughfault current
CTR	=	current transformer ratio
K_1	=	allows for the CTR correction factor
K_2	=	safety factor



Principles of Differential Relaying – Setting a low z diff relay – $I_{diff\text{-}hi}$

<u>Note:</u> there is parallel path for I_{2P}, via R_{LDQ} and R_{CTQ} as well. However, it is conservatively assumed that $R_{RELAY} << R_{LDQ}$ and R_{CTQ}

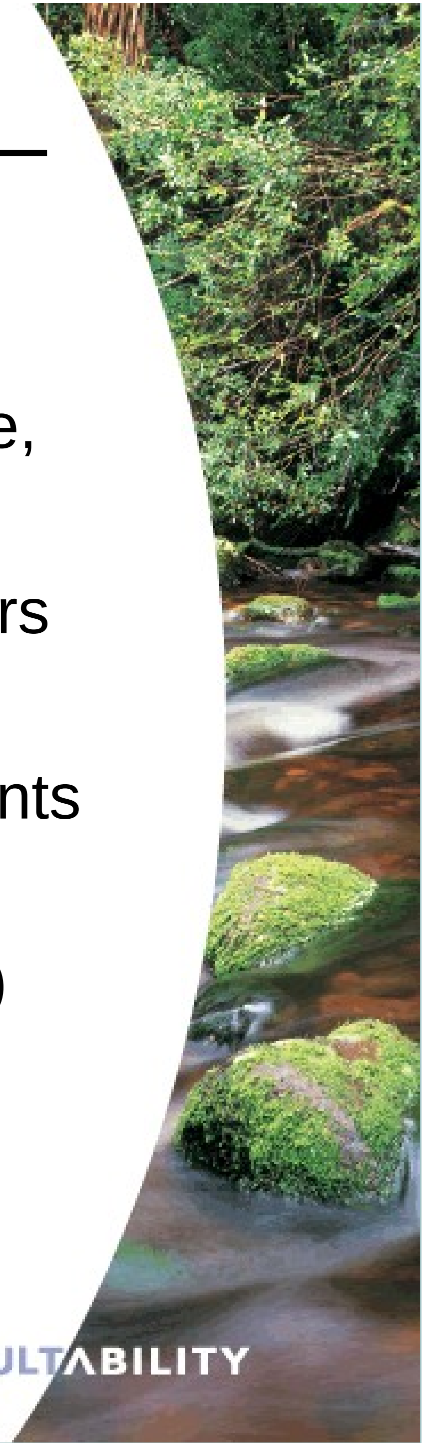
- The choice of safety factor, K_2, depends on several factors.

- 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.

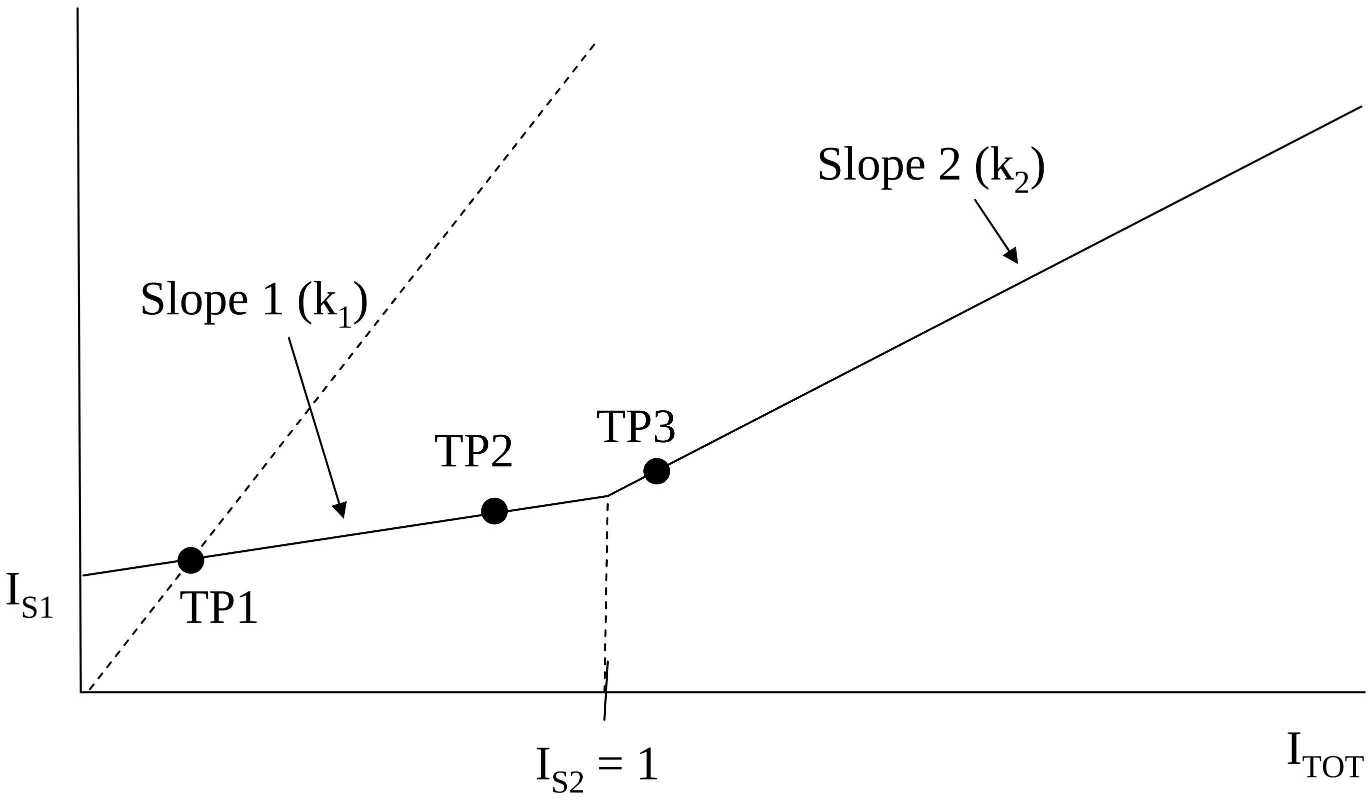
- Clearance times are then in the order of 100ms and with high X/R ratios full saturation may take up to 1s.

Principles of Differential Relaying – Setting a low z diff relay – $I_{diff-hi}$

- A safety factor of 5% or at most 10% will suffice, i.e. $K_2 = 1.05$ to 1.1.
- 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) 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 ($K_2 = 1.3$).



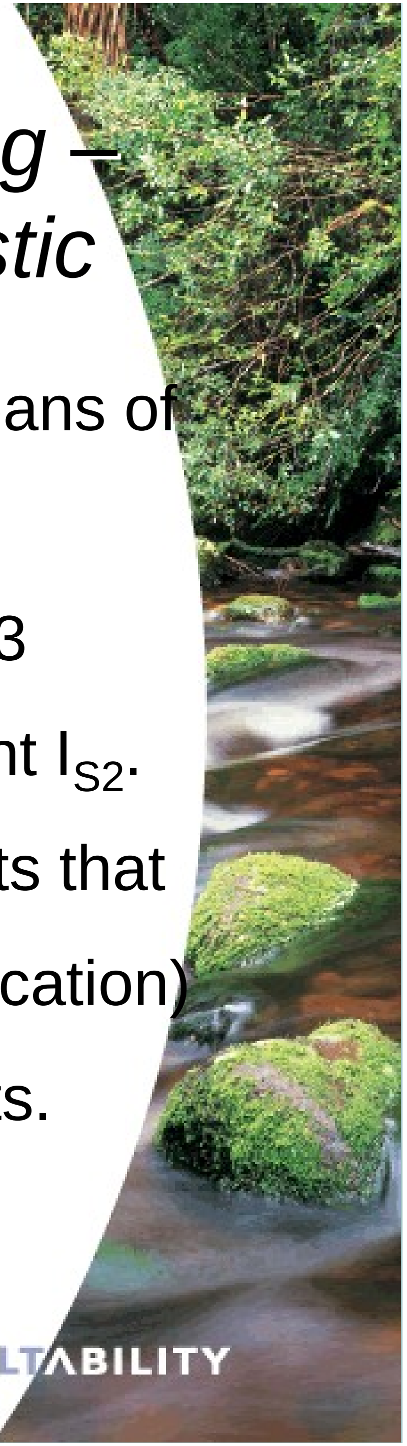
Principles of Differential Relaying – Testing the restraint characteristic



Restraint characteristic of the P541

Principles of Differential Relaying – Testing the restraint characteristic

- The restraint characteristic may be verified by means of test points TP1, TP2 and TP3.
- TP1 verifies the pickup setting while TP2 and TP3 checks slopes 1 and 2, as well as the turning point I_{S2}.
- The objective here is thus to calculate the currents that need to be injected at each end (2-terminal application) corresponding to the above-mentioned test points.



Principles of Differential Relaying – Testing the restraint characteristic

Methodology :

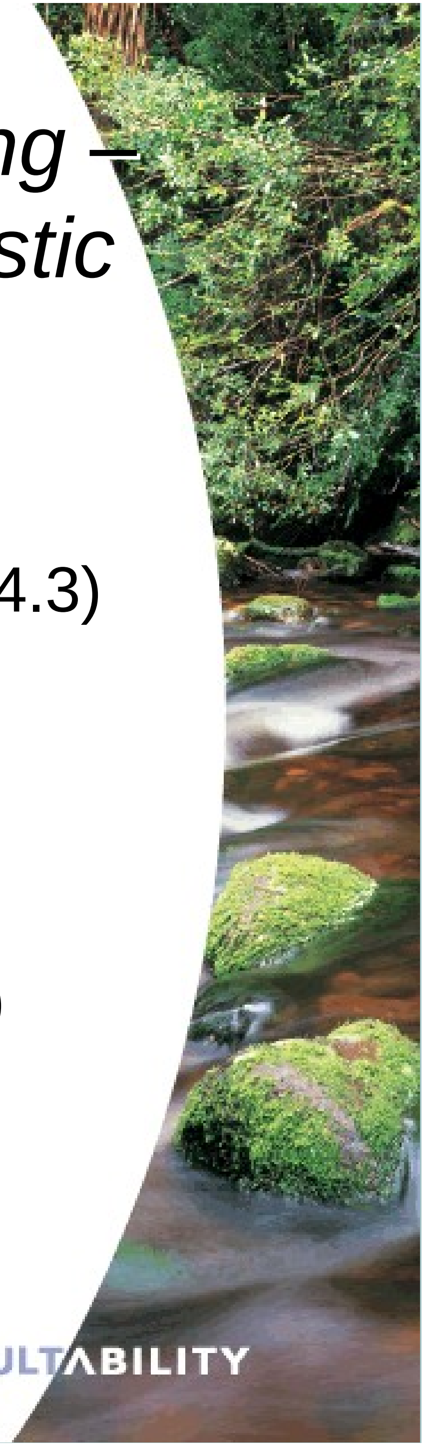
Find the expressions for I_d, I_{rest} and I_{TOT}. Set $I_d = I_{rest}$ (one equation) and using the expression for I_{TOT} (2nd equation), we now have two equations and two unknowns – solve for I_1 and I_2.

Test Point 1 (TP1)

$$I_d = \left|I_1 + I_2\right| = \left|I_1\right| = I_1 \qquad (4.1)$$

$$I_{TOT} = \frac{\left|I_1\right| + \left|I_2\right|}{2} = \frac{I_1}{2} \qquad \text{Type 1} \qquad (4.2)$$

Principles of Differential Relaying – Testing the restraint characteristic



For $I_{TOT} < I_{S2}$ have,

$$I_{rest} = I_{S1} + k_1 \cdot I_{TOT} = I_{S1} + k_1 \cdot \frac{I_1}{2} \qquad (4.3)$$

Set $I_d = I_{rest}$ and solve for I_1. Thus

$$I_1 = I_{S1} + k_1 \cdot \frac{I_1}{2} \quad \text{or} \quad I_1 = \frac{I_{S1}}{\left(1 - \frac{k_1}{2}\right)} \qquad (4.4)$$

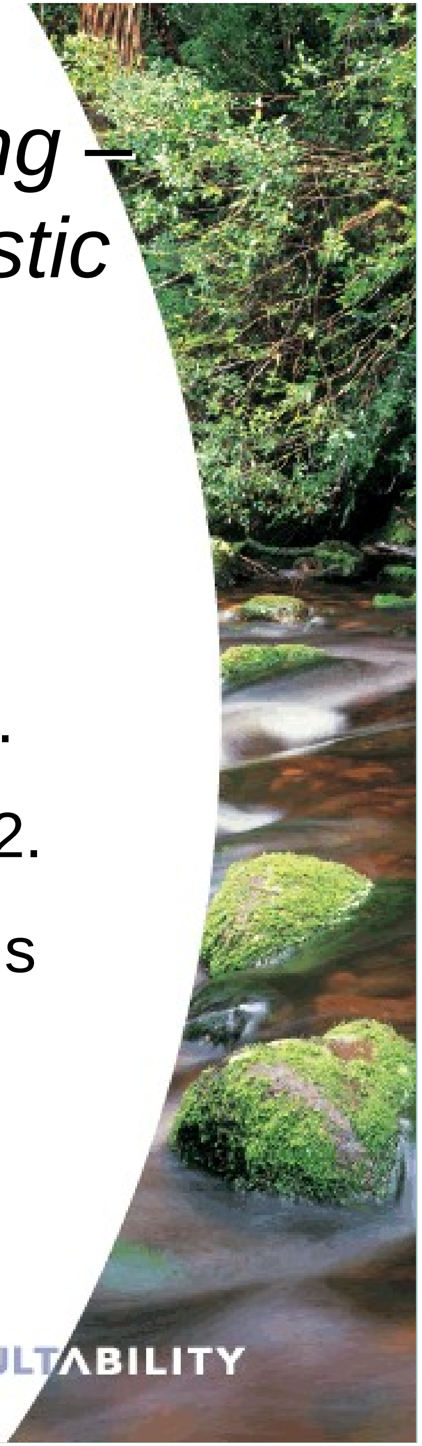
Principles of Differential Relaying – Testing the restraint characteristic

Test Point 2 (TP2)

$$I_d = \left| I_1 + I_2 \right| \qquad I_{rest} = I_{S1} + k_1 \cdot I_{TOT}$$

- Need TP2 to be to the left of the turning point.
- Define its exact location by means of factor f2.
- Value of f2 determining exactly how far TP2 is to the left of I_{S2}. Thus,

$$I_{TOT} = \frac{\left|I_1\right| + \left|I_2\right|}{2} = f_2 \cdot I_{S2} \qquad (4.5)$$



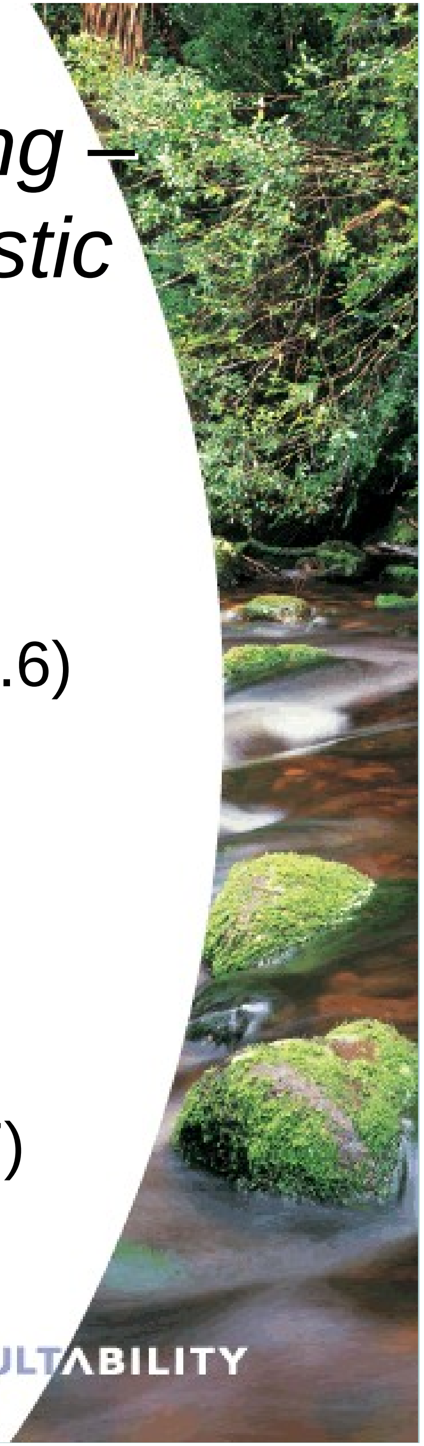
Principles of Differential Relaying – Testing the restraint characteristic

$$I_{rest} = I_{S1} + k_1 \cdot f_2 \cdot I_{S2}$$

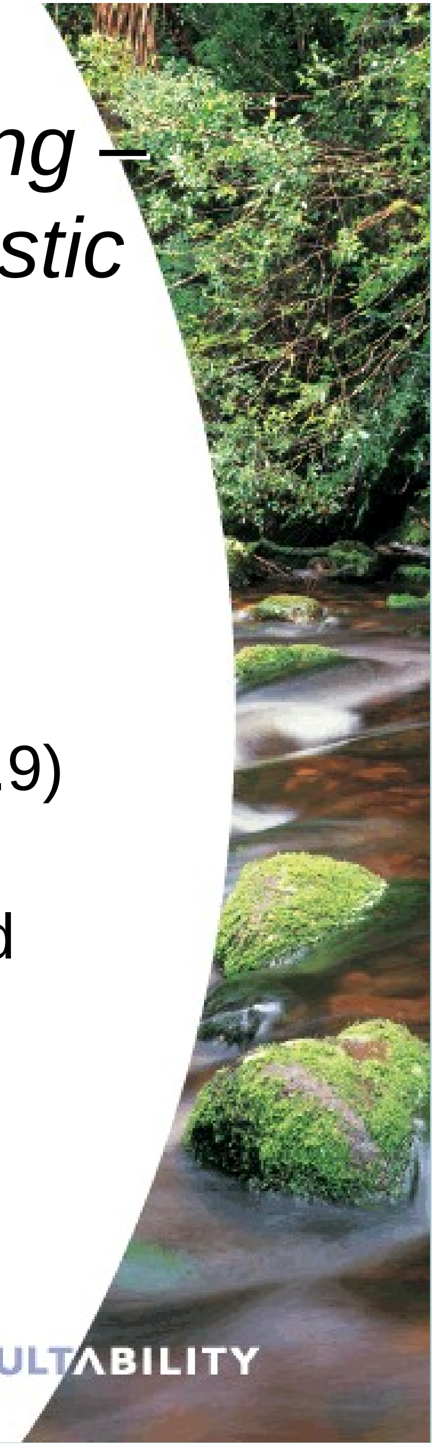
and so $\left|I_1 + I_2\right| = I_{S1} + k_1 \cdot f_2 \cdot I_{S2}$ (4.6)

To get rid of the absolute value signs, let $I_1 > 0$ and $I_2 < 0$ with $\left|I_2\right| > \left|I_1\right|$. Then

$$I_d = \left|I_1 + I_2\right| = -\left(I_1 + I_2\right) \quad (4.7)$$



Principles of Differential Relaying – Testing the restraint characteristic



Similarly $$\left|I_1\right| + \left|I_2\right| = I_1 - I_2 \qquad (4.8)$$

Substituting get, $$I_1 - I_2 = 2 \cdot f_2 \cdot I_{S2}$$

$$-\left(I_1 + I_2\right) = I_{S1} + k_1 \cdot f_2 \cdot I_{S2} \qquad (4.9)$$

Two equations, two unknowns. Solve for I_1 and I_2 to get,

Principles of Differential Relaying – Testing the restraint characteristic

$$I_1 = f_2 \cdot I_{S2} - \frac{1}{2} \cdot I_{S1} - \frac{1}{2} \cdot k_1 \cdot f_2 \cdot I_{S2} \qquad (4.10)$$

$$I_2 = I_1 - 2 \cdot f_2 \cdot I_{S2} \qquad (4.11)$$

Principles of Differential Relaying – Testing the restraint characteristic

Test Point 3 (TP3)

$$I_d = \left| I_1 + I_2 \right| \qquad\qquad I_{TOT} = f_3 \cdot I_{S2} \qquad (4.12)$$

- Here f_3 determines how far to the right of I_{S2} does TP3 lie.
- Need an expression for the restraint function when $I_{TOT} > I_{S2}$.
- Equation is of the form $y = mx + c$.
- As the slope necessarily equals k_2, have $y = k_2 \cdot x + c$.
- Need to find a point on the restraint characteristic in order to determine c.
- Choose $x = I_{S2} = I_{TOT}$. Use $I_{rest} = I_{S1} + k_1 \cdot I_{S2}$ and so point is $(I_{S2}, I_{S1} + k_1 \cdot I_{S2})$.

Principles of Differential Relaying – Testing the restraint characteristic

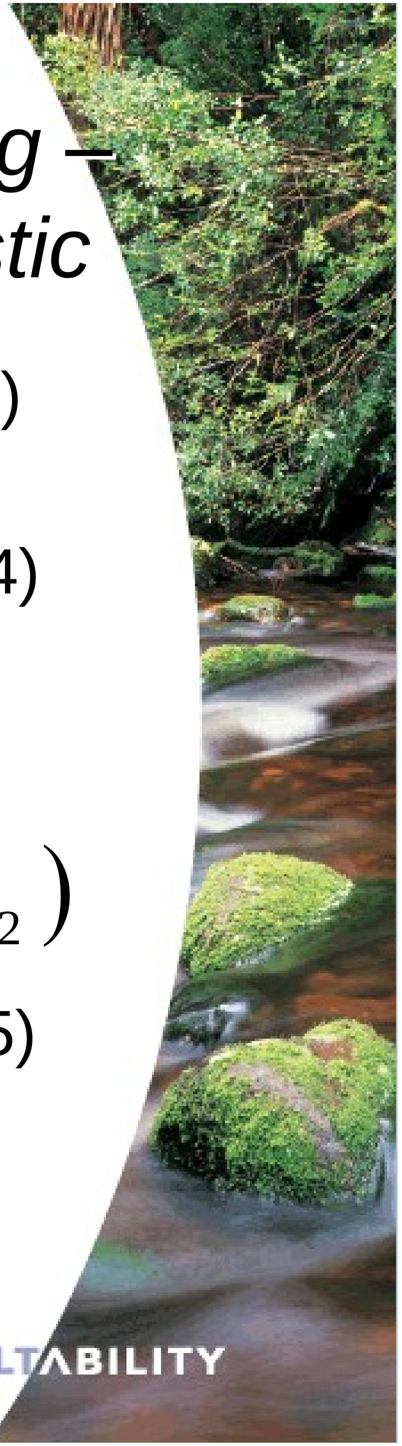
- And so, $I_{S1} + k_1 \cdot I_{S2} = k_2 \cdot I_{S2} + c$ (4.13)

from which we get, $c = I_{S1} + I_{S2} \cdot (k_1 - k_2)$ (4.14)

The desired restraint equation is thus,

$$I_{rest} = k_2 \cdot f_3 \cdot I_{S2} + I_{S1} + I_{S2} \cdot (k_1 - k_2)$$

(4.15)



Principles of Differential Relaying – Testing the restraint characteristic

Again let $I_1 > 0$ and $I_2 < 0$ with $\left|I_2\right| > \left|I_1\right|$. Then

$$I_d = \left|I_1 + I_2\right| = -\left(I_1 + I_2\right)$$

and $$\left|I_1\right| + \left|I_2\right| = I_1 - I_2$$

Two equations:

$$I_1 - I_2 = 2 \cdot f_3 \cdot I_{S2} \quad \text{or} \quad I_1 = 2 \cdot f_3 \cdot I_{S2} + I_2 \qquad (4.16)$$

$$-\left(I_1 + I_2\right) = k_2 \cdot f_3 \cdot I_{S2} + I_{S1} + I_{S2} \cdot \left(k_1 - k_2\right) \qquad (4.17)$$

Principles of Differential Relaying – Testing the restraint characteristic

Solve for I_1 and I_2 to get

$$I_2 = \frac{-k_2 \cdot f_3 \cdot I_{S2} - I_{S1} - I_{S2} \cdot (k_1 - k_2) - 2 \cdot f_3 \cdot I_{S2}}{2} \quad (4.18)$$

and $$I_1 = 2 \cdot f_3 \cdot I_{S2} + I_2 \quad (4.19)$$

Principles of Differential Relaying – Testing the restraint characteristic

The above methodology may be applied to any biased differential relay in order to verify the restraint characteristic. For example in order to test the M87 motor diff, let's first revisit:

$$Idx^2 - \frac{Itx^2}{32} > Is^2 \quad \text{where } 0 \leq Itx \leq \sqrt{2}\,In \text{ and } x = 1, 2, 3$$

- 2nd half curve

$$\frac{Idx^2}{8} - \frac{Itx^2}{32} > (0.005\ In)^2 \quad \text{where } \sqrt{2}\,In < Itx$$

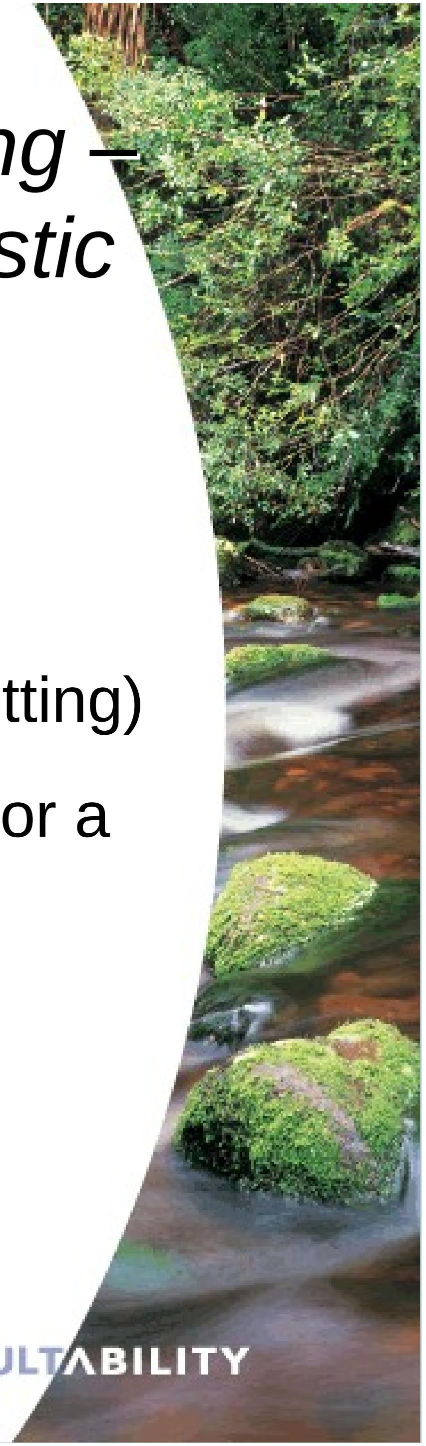
and $x = 1, 2, 3$.

Principles of Differential Relaying – Testing the restraint characteristic

These are actually highly secret equations for the restraint quantity when $I_{TOT} \leq \sqrt{2}$ and for $I_{TOT} > \sqrt{2}$

Is = minimum I_d required for relay operation (setting)

Idx = minimum I_{diff} required for relay operation for a given Itx (I_{TOT}) = I_{rest}



Principles of Differential Relaying – Testing the restraint characteristic

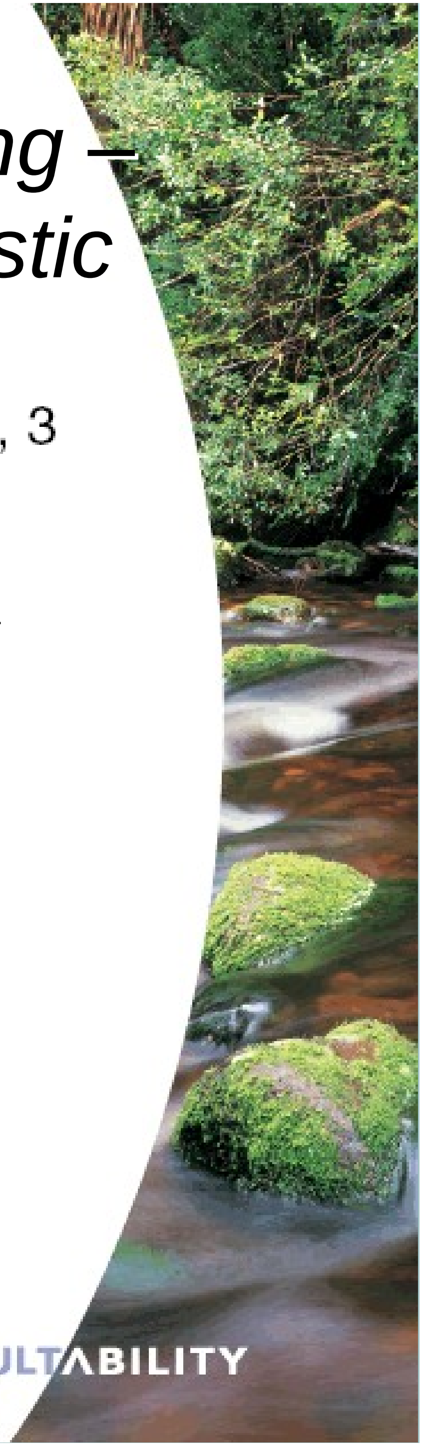
$$Idx^2 - \frac{Itx^2}{32} > Is^2$$ where $0 \leqslant Itx \leqslant \sqrt{2}\,In$ and x = 1, 2, 3

May thus be rewritten as: $$I_{rest}^2 = Is^2 + \frac{I_{TOT}^2}{32}$$

$$\frac{Idx^2}{8} - \frac{Itx^2}{32} > (0.005\ In)^2$$ where $\sqrt{2}\,In < Itx$

May be rewritten as:

$$I_{rest}^2 = 8 \cdot 0.005^2 + 8 \cdot \frac{I_{TOT}^2}{32} = 0.0002 + \frac{I_{TOT}^2}{4}$$



Principles of Differential Relaying – Testing the restraint characteristic

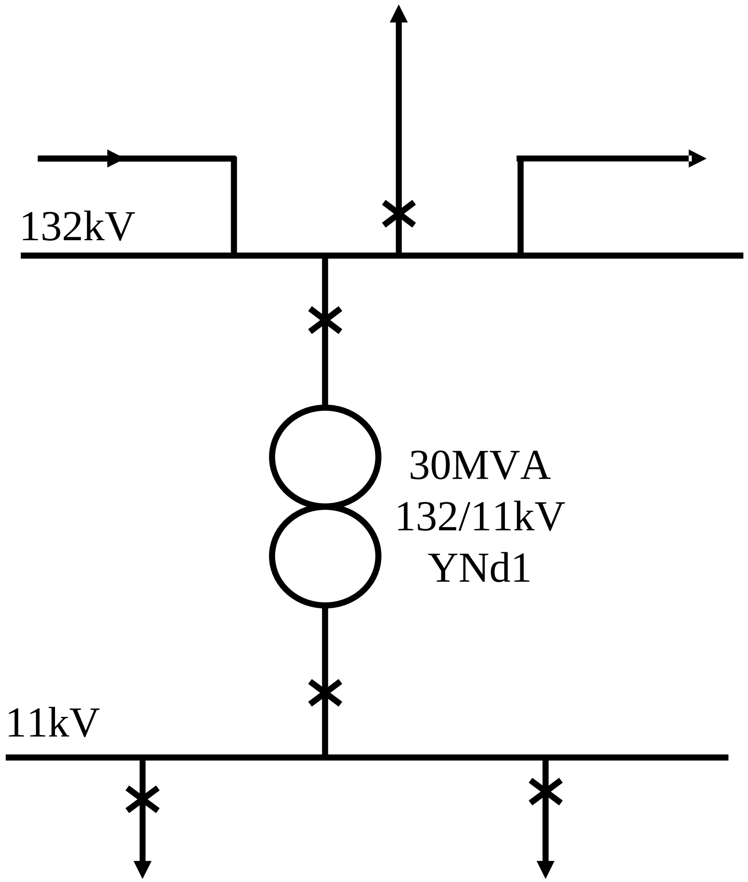
If we neglect the 0.0002 in $I_{rest}^2 = 0.0002 + \frac{I_{TOT}^2}{4}$

get $I_{rest} = \frac{I_{TOT}}{2}$, i.e. 2nd part of restraint characteristic has a 50% slope

Thus have $I_d = \left| I_1 + I_2 \right|$ $\quad I_{TOT} = \frac{\left| I_1 - I_2 \right|}{2}$

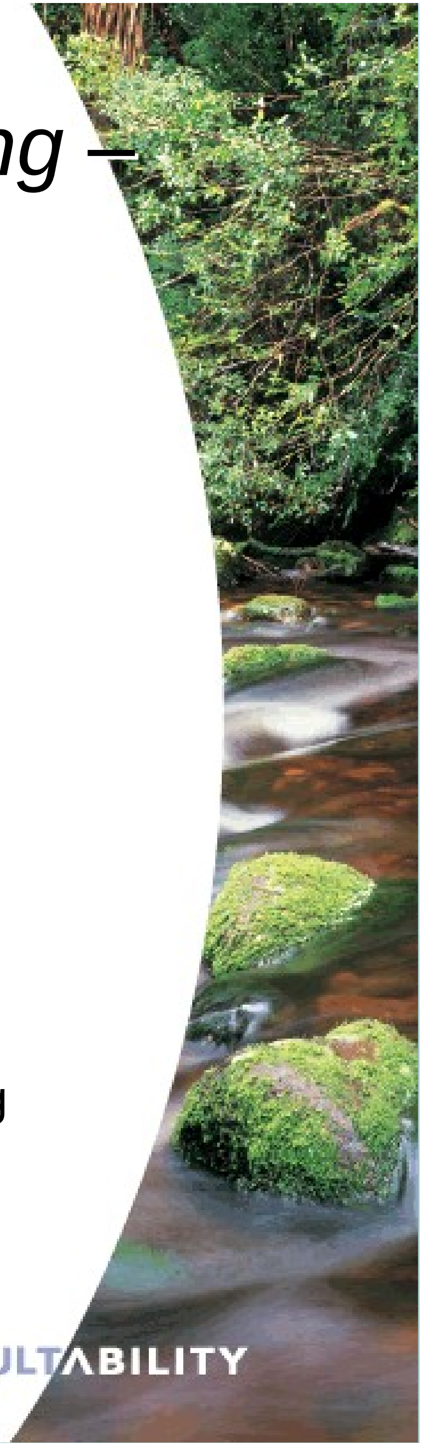
And the two restraint equations so we are now in a position to calculate the test points…

Principles of Differential Relaying – Case Study

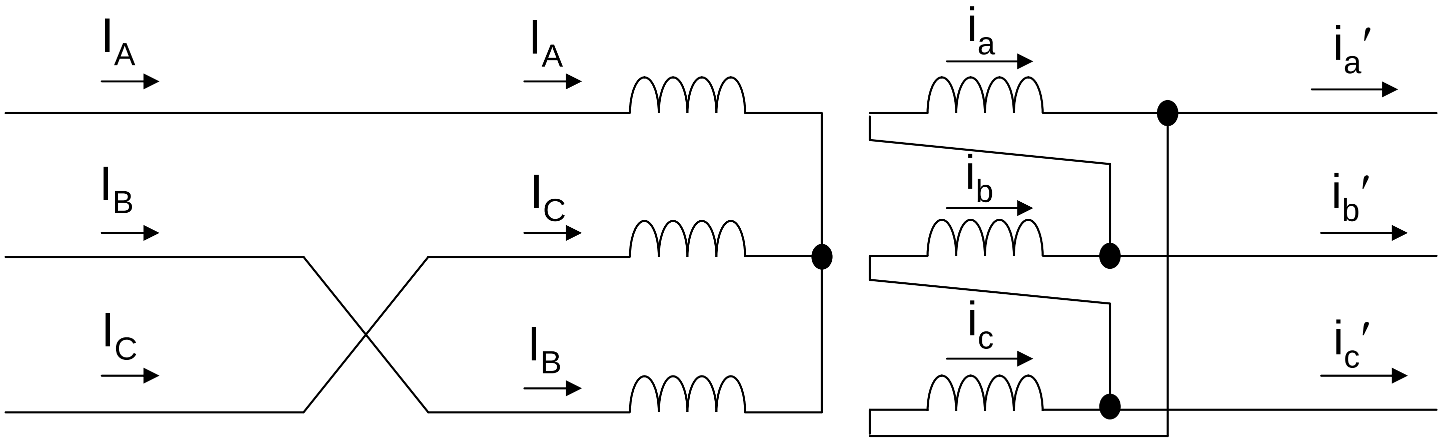


Principles of Differential Relaying – Case Study

- Numerical transformer differential relay
- Internal compensation for CTR correction and vector group
- Vector group numeral for winding 2 = 1
- Shortly after commissioning transformer tripped on differential protection
- Occurred a further two times and then I really sat up!
- Investigation revealed that two phases had been swopped on the incoming supply to the substation.
- Field services had swopped two phases on the two outgoing feeders somewhere outside the substation to ensure customers had correct rotation.



Principles of Differential Relaying – Case Study

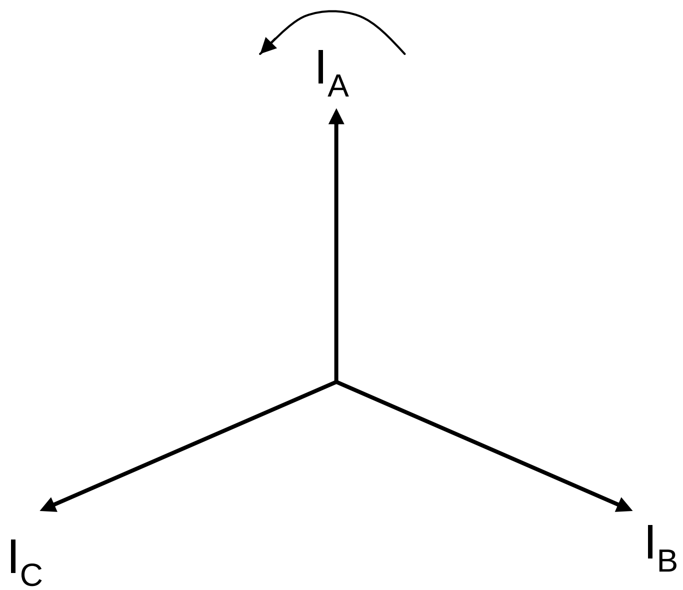


$$i_a' = i_a - i_c$$

$$i_b' = i_b - i_a$$

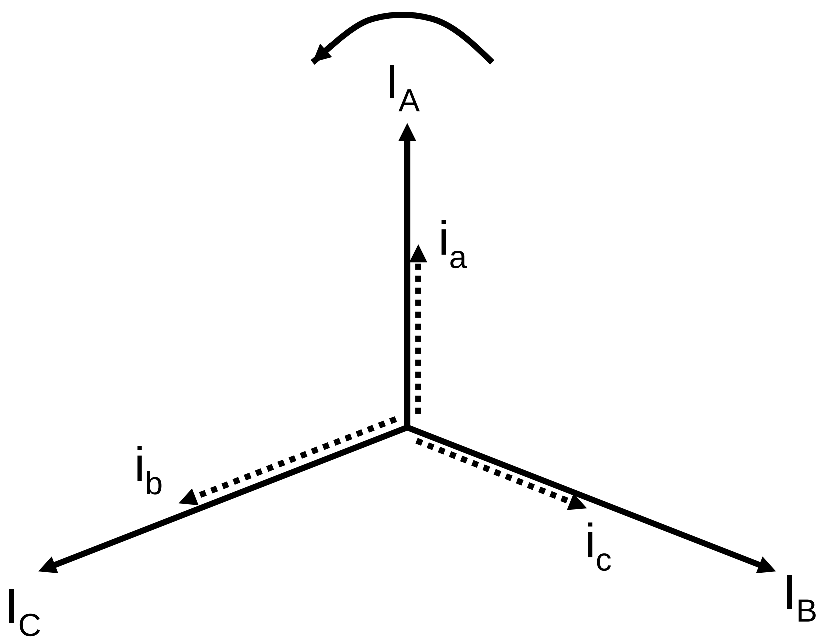
$$i_c' = i_c - i_b$$

Principles of Differential Relaying – Case Study



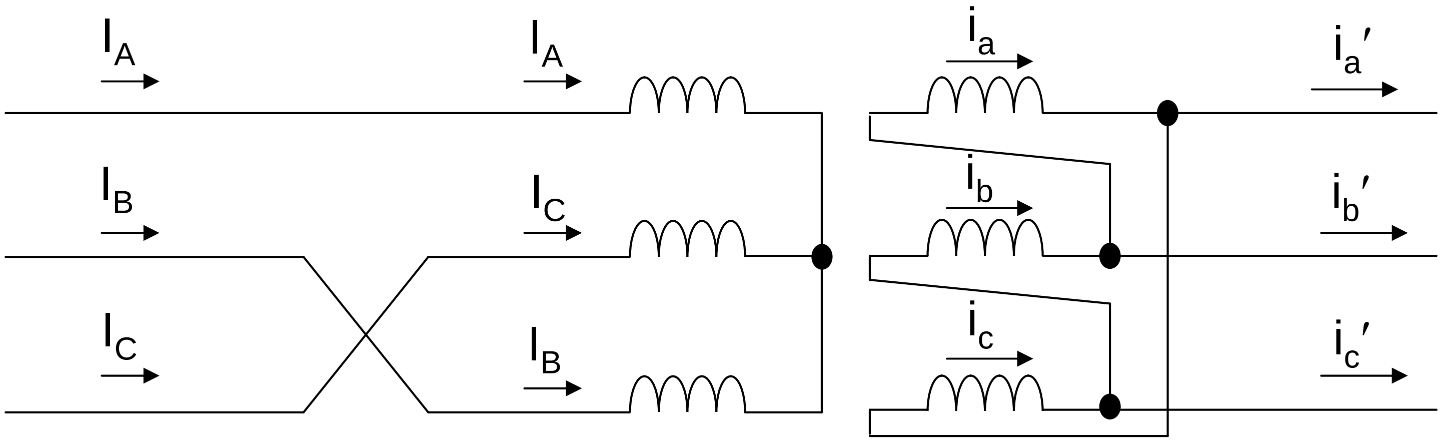
Incoming primary currents – direction of rotation

Principles of Differential Relaying – Case Study



Adding secondary currents – direction of rotation

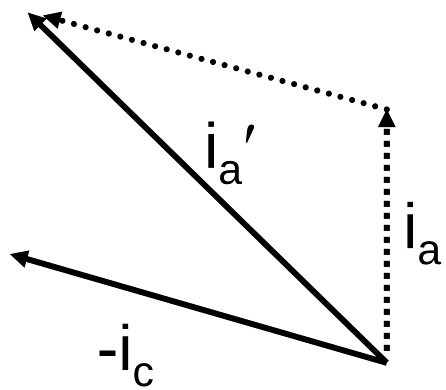
Principles of Differential Relaying – Case Study



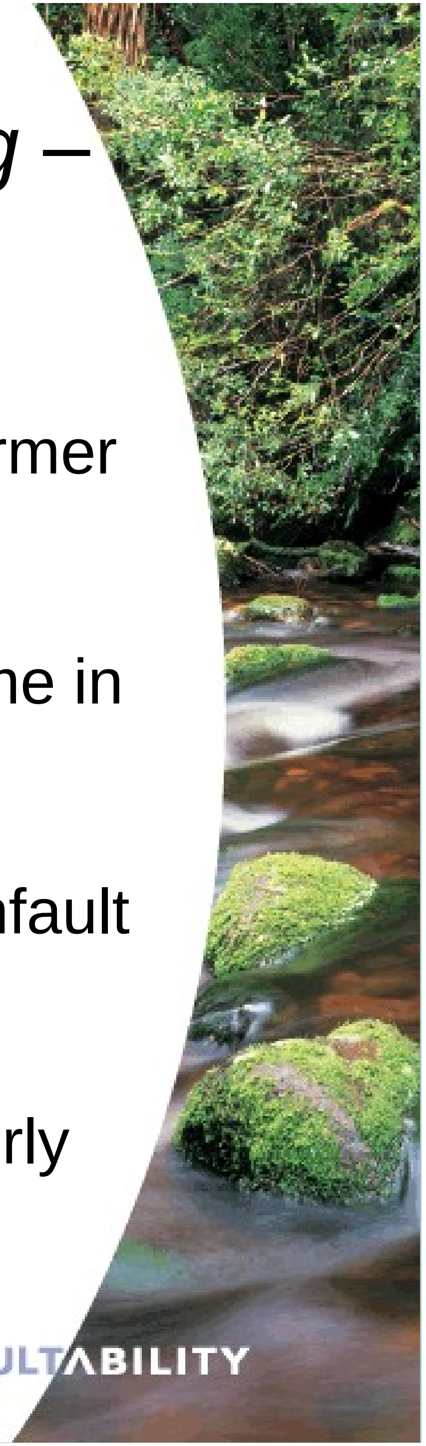
$i_a' = i_a - i_c$

$i_b' = i_b - i_a$

$i_c' = i_c - i_b$



Principles of Differential Relaying – Case Study

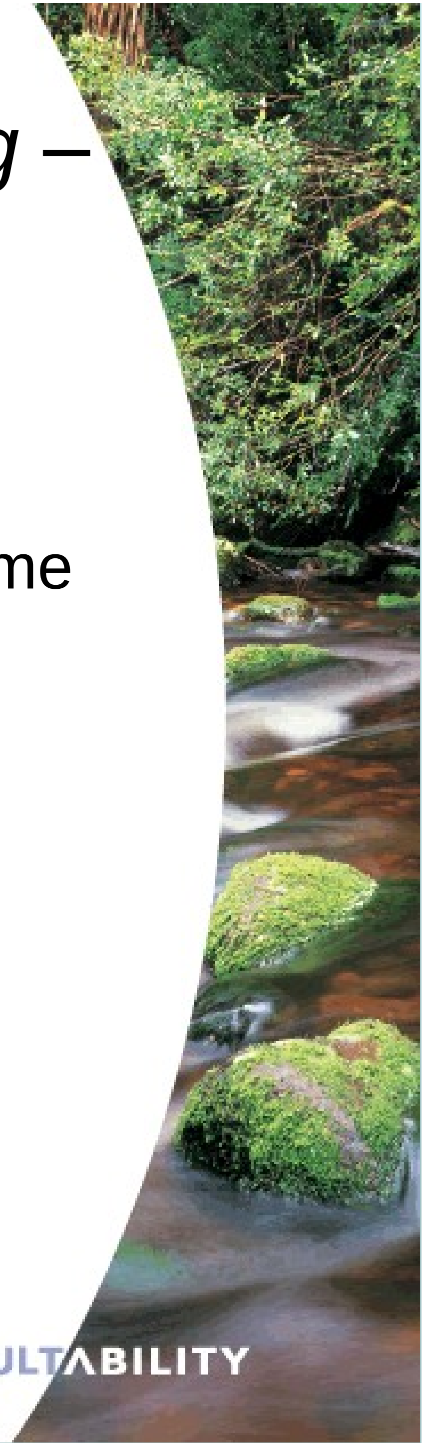


- Since I_a’ now leads I_A by 30˚ I gathered transformer vector group is now YNd11.
- New setting was implemented and all went home in high spirits !!!
- The peace was shortlived. Shortly after throughfault lead to another diff trip.
- Operations shutdown the sub until issue properly resolved.

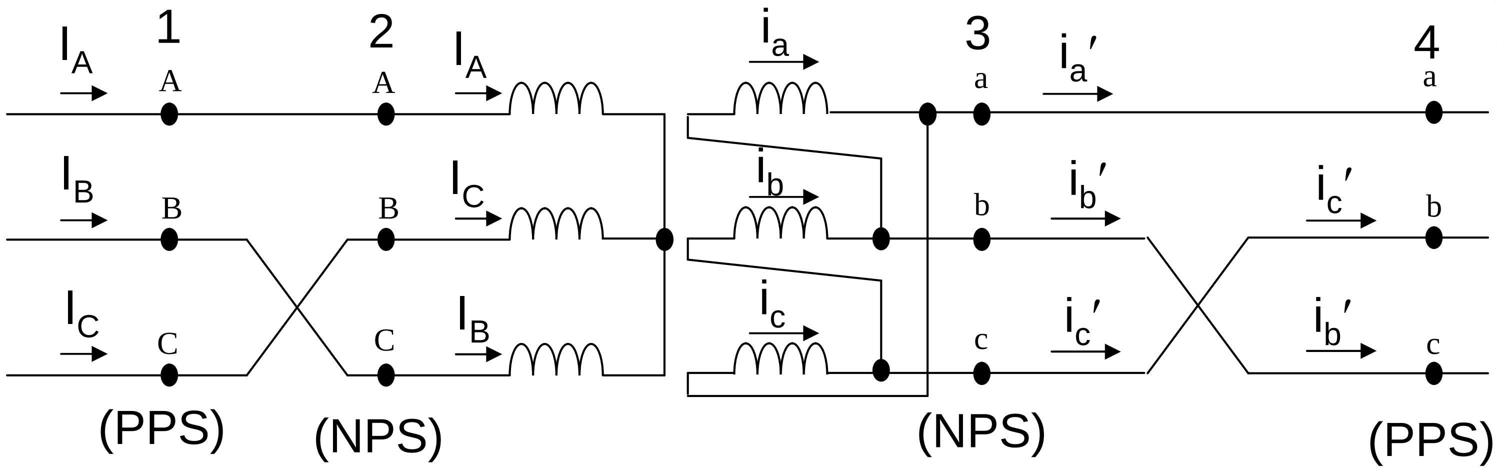
Principles of Differential Relaying – Case Study

- Solicited the help of two experts.
- Said a prayer and two days later it dawned on me what was happening!!!

Eureka!!!



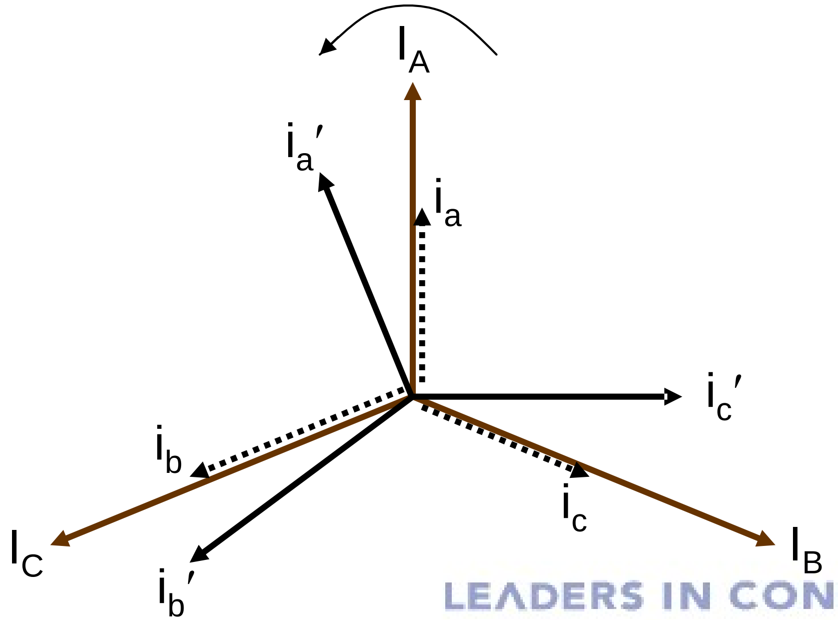
Principles of Differential Relaying – Case Study



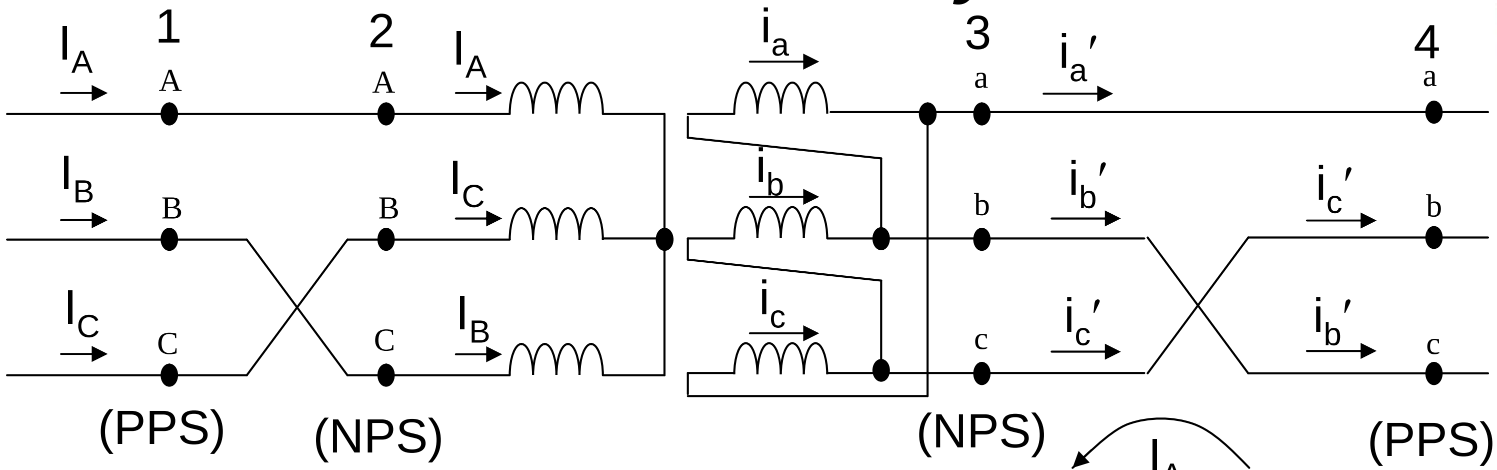
$$i_a' = i_a - i_c$$

$$i_b' = i_b - i_a$$

$$i_c' = i_c - i_b$$



Principles of Differential Relaying – Case Study

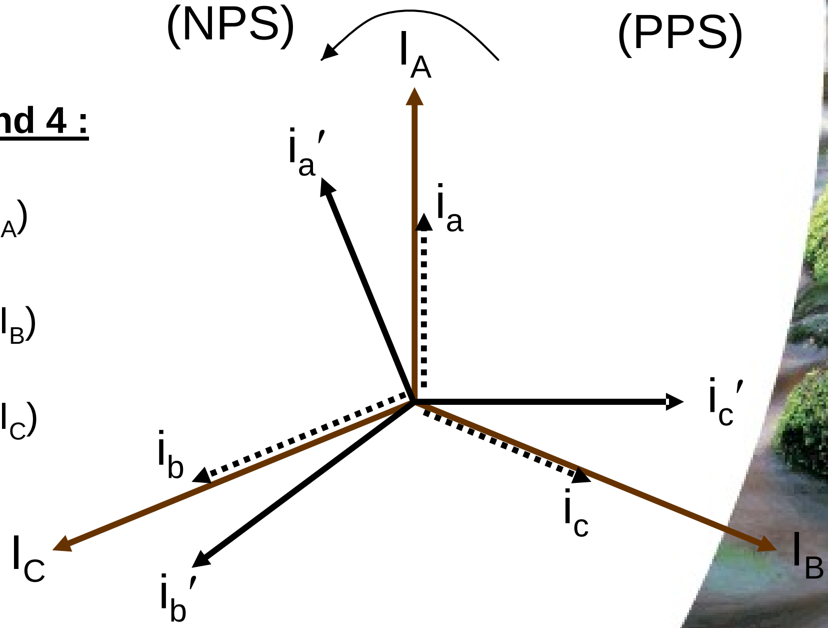


<u>Suppose the ct's were located at positions 1 and 4 :</u>

i_a' leads I_A by 30° ⟶ Yd11 (comparing i_a with I_A)

i_c' leads I_B by 30° ⟶ Yd11 (comparing i_c' with I_B)

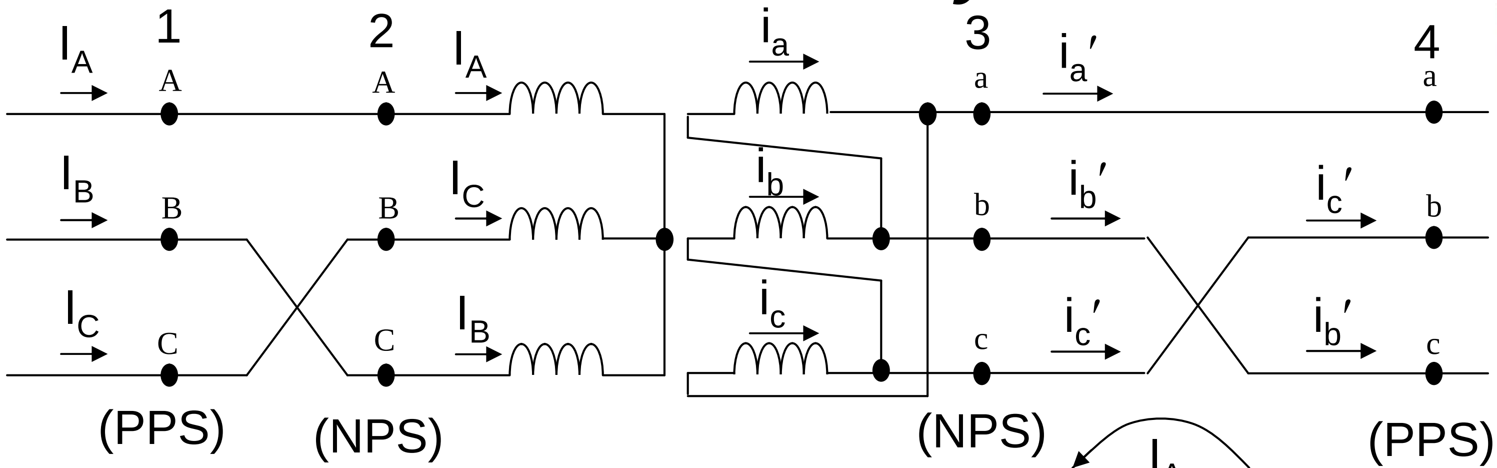
i_b' leads I_C by 30° ⟶ Yd11 (comparing i_b' with I_C)



There is pps rotation at both sides and the transformer appears to be a Yd11. Should the diff ct's be located at 1 and 4 the relay vector group numeral should be set to 11.

LEADERS IN CONSULTABILITY

Principles of Differential Relaying – Case Study



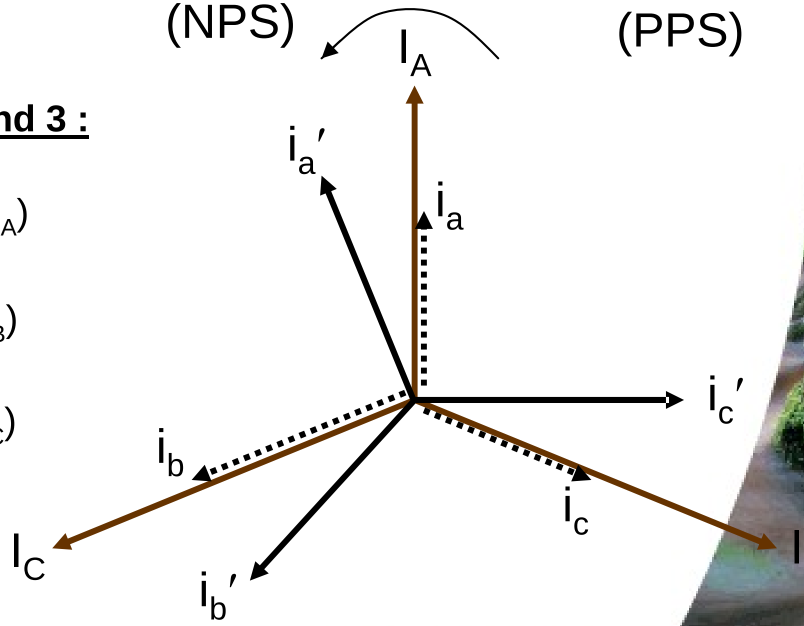
<u>**Suppose the ct's were located at positions 1 and 3 :**</u>

i_a' leads I_A by 30° ⟶ Yd11 (comparing i_a with I_A)

i_b' lags I_B by 90° ⟶ Yd3 (comparing i_b' with I_B)

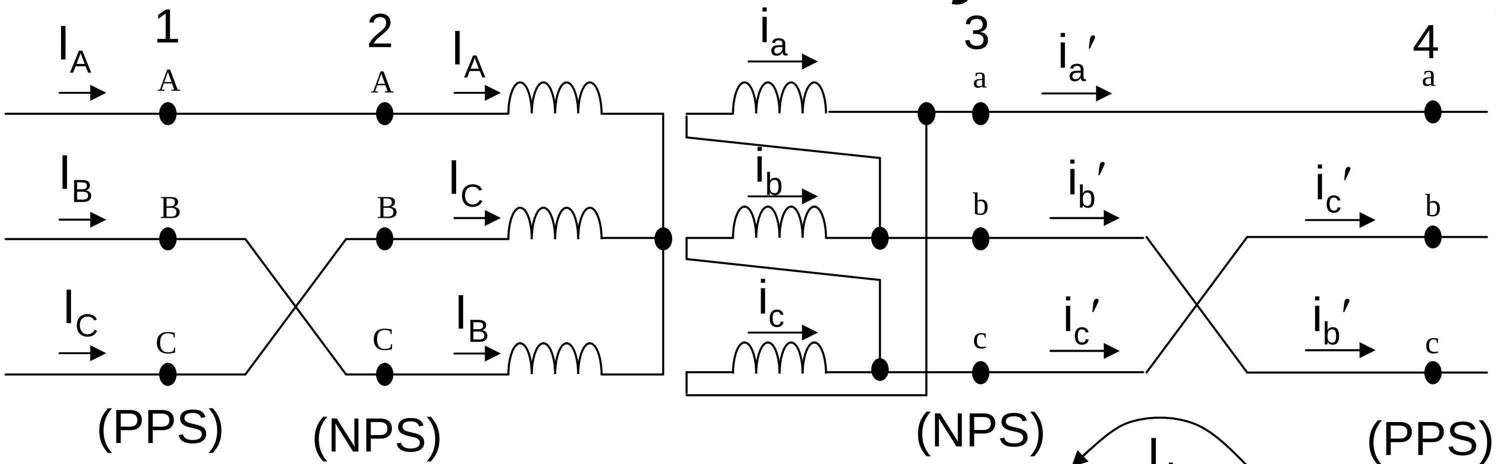
i_c' leads I_C by 150° ⟶ Yd7 (comparing i_c' with I_C)

There is pps rotation on the HV side but nps on the LV side. What must the relay vector group numeral be set to?



LEADERS IN CONSULTABILITY

Principles of Differential Relaying – Case Study



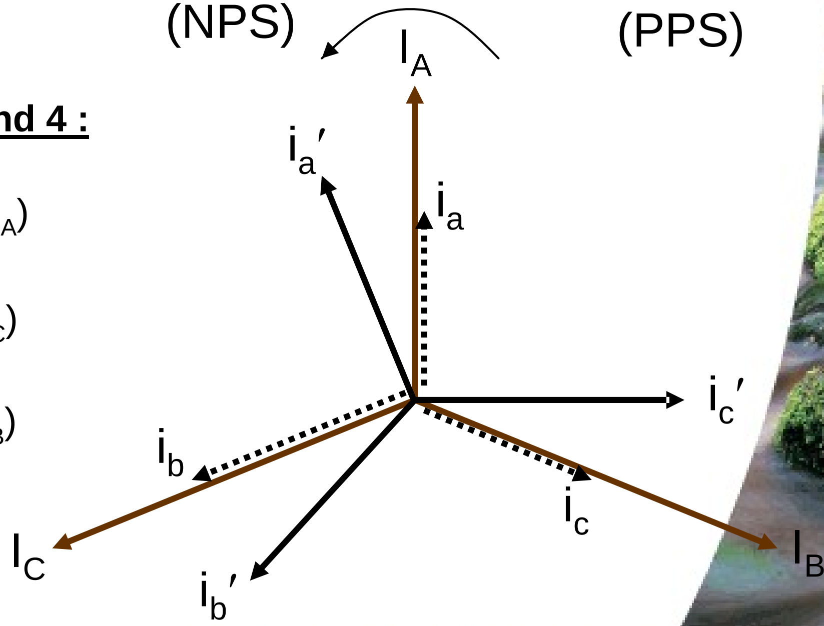
<u>Suppose the ct's were located at positions 2 and 4 :</u>

i_a' leads I_A by 30° ⟶ Yd11 (comparing i_a with I_A)

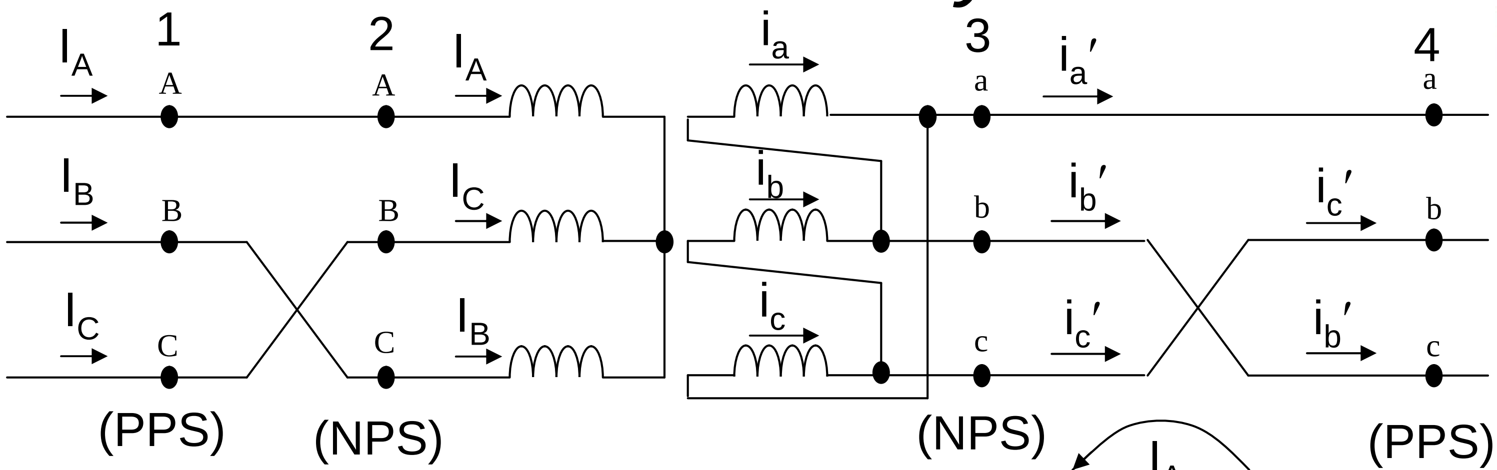
i_c' leads I_C by 150° ⟶ Yd7 (comparing i_c' with I_C)

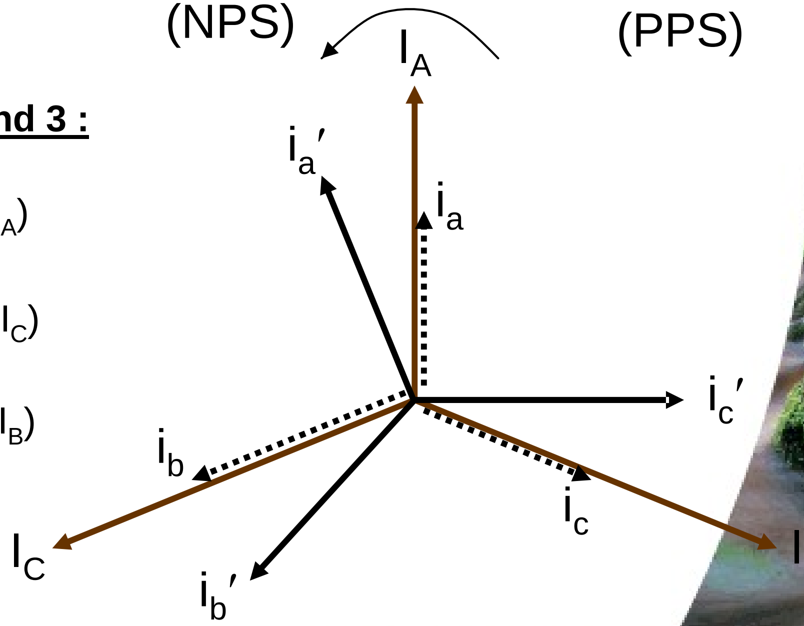
i_b' lags I_B by 90° ⟶ Yd3 (comparing i_b' with I_B)

There is pps rotation on the HV side but nps on the LV side. What must the relay vector group numeral be set to?



Principles of Differential Relaying – Case Study





Suppose the ct's were located at positions 2 and 3 :

i_a' leads I_A by 30° ⟶ Yd11 (comparing i_a with I_A)

i_b' leads I_C by 30° ⟶ Yd11 (comparing i_b' with I_C)

i_c' leads I_B by 30° ⟶ Yd11 (comparing i_c' with I_B)

There is nps rotation on the HV side but nps on the LV side. What must the relay vector group numeral be set to?

Principles of Differential Relaying – Case Study

<u>Suppose the ct's were located at positions 2 and 3 :</u>

i_a' leads I_A by 30° ⟶ Yd11 (comparing i_a with I_A)

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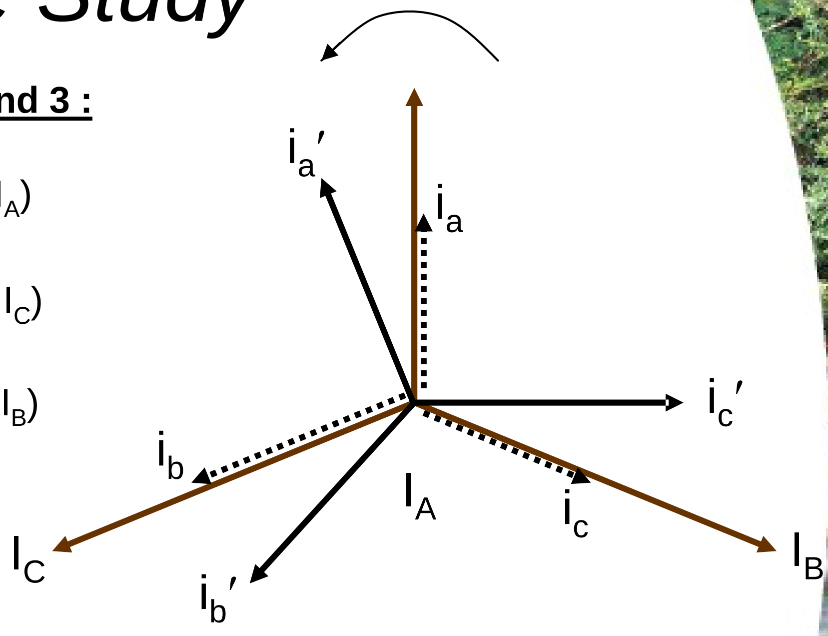
i_c' leads I_B by 30° ⟶ Yd11 (comparing i_c' with I_B)



There is nps rotation on the HV side but nps on the LV side. What must the relay vector group numeral be set to?

- In reality both HV and LV sets of currents phasors are rotating in the clockwise direction (NPS) – relay "sees" a Yd1 phase relationship in all 3 phases.

- Relay vector numeral was set to 1 again, a few tests were conducted and the diff relay was stable!!!

PHEW!!!

Thank you!

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