Transformer Protection – Restricted Earth Fault (REF, 87R)

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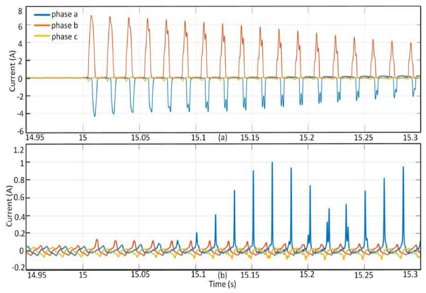
(after LMT Tx H1 Through Fault Tripped Incident)

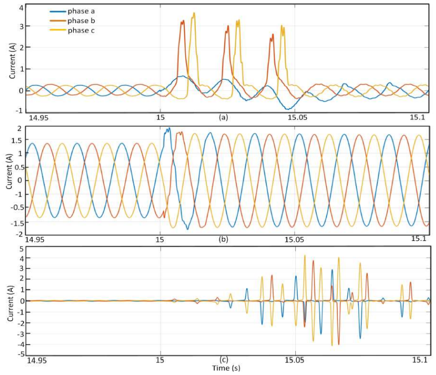
Challenges in Transformer Protection

- Required detection of disturbance and fault, such as
  - Internal Fault (SLG, LLG, LL, LLL) Note – External LLG can fail directional check
  - External Fault with CT Saturation (phase shifting effect) $a\angle -\varphi$
  - Magnetizing Inrush (and Sympathetic Inrush) during Transformer Energization
  - Other events such as Capacitor Switching and Ferroresonance.



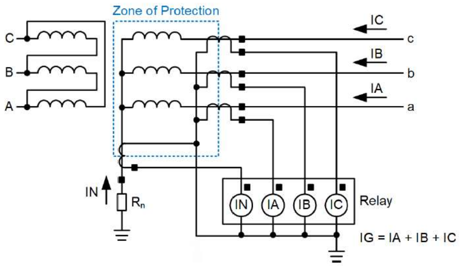
(a) Magnetizing Inrush
(b) Sympathetic Inrush

(a) External Fault with CT Sat
(b) Capacitor Switching
(c) Ferroresonance

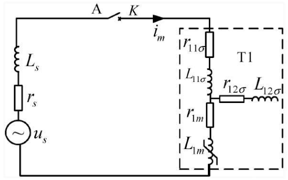


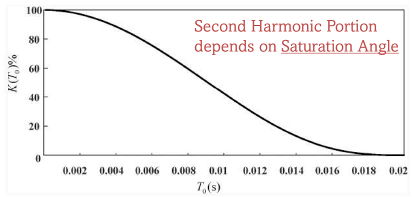
Why Transformer Inrush causes a Problem?

- Transformer Inrush is a disturbance originally with current balanced in the restricted zone, i.e. $|i_A(t)+i_B(t)+i_C(t)|-|i_N(t)| = |3i_0(t)|-|i_N(t)| = 0$, regardless of second harmonics components or total component. → It should remain stable.
- However, transformer inrush often leads to CT saturation due to its large DC offset. (Note – high impedance scheme vs low impedance scheme). → It does not cause any problem if the CTs saturate together.
- Yet, CT at phase could saturate first due to remanence flux (+ inception angle); and CT at neutral could saturate first due to CT mismatch (lower CT ratio with higher sensitivity). → It does not saturate simultaneously and causes a differential.
- Magnitude of Inrush depends on
  - Remanence Flux Φ_{RES}
  - Inception Angle α
  - System X/R ratio [Note – Inrush damps slower than fault]
- Mal-operation of Sympathetic Inrush due to
  - Superconducting Winding $R\downarrow$
  - Softer Core $V_K\downarrow$
  - CT Local Transient Saturation

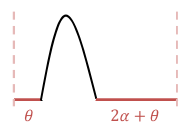


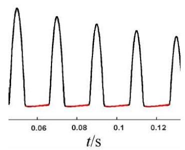
Equivalent Circuits to Transformer Energization (No Load Closing)





Dead Angle $\beta = 2\alpha + 2\theta$





When the transformer is unsaturated, the value of L_{1m} will be very large and the inrush current is almost zero. After the core is saturated, L_{1m} will be greatly reduced and the inrush current will be greatly increased. It is assumed that at the time of ωt = θ, the core of the transformer is saturated, it is easy to deduce, that at the time of ωt = 2π − 2α − θ, it will exit saturation

constant, to be decayed with R in closing circuit

$$\phi = \boxed{\phi_{RES} + \phi_m \cos\alpha} - \phi_m \cos(\omega t + \alpha)$$

$$i_m = \frac{1}{L}\int_{\theta/\omega}^{t} U_m \sin(\omega t + \alpha)\, dt$$

where L is the total inductance of closing circuit $L = L_s + L_{11\sigma} + L_{1m}$ and θ is the corresponding electrical angle for core saturation moment, i.e. saturation angle.

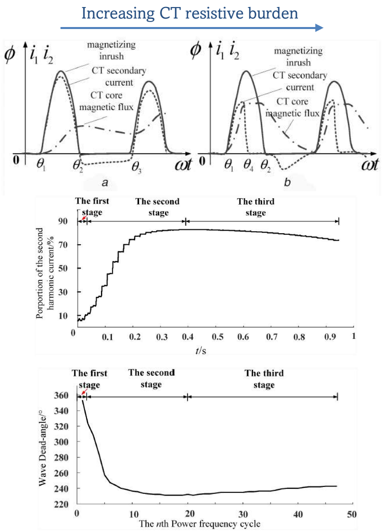
$$i_m = \frac{U_m}{\omega L}(\cos\theta - \cos\omega t), \qquad \theta < \omega t < 2\pi - 2\alpha - \theta$$

Through Fourier Decomposition,

$$I_m[n] = \frac{U_m T_0}{2\omega_0 L T}\left[S_a\frac{(n-1)\omega_0 T_0}{2} - 2\cos\frac{\omega_0 T_0}{2} S_a\frac{n\omega_0 T_0}{2} + S_a\frac{(n+1)\omega_0 T_0}{2}\right]$$

where $T = 2\pi/\omega_0$ is the power frequency period, $T_0 = 2\theta/\omega_0$ is the time from CB closing to core saturation, and $S_a(x) = \sin x / x$ is the sampling function.

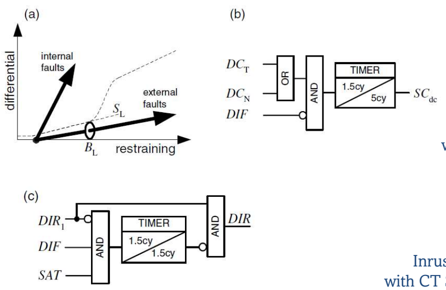
CT Saturation with Inrush

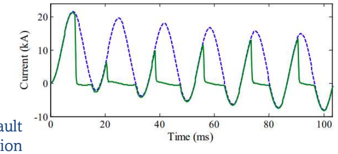


1. The second harmonic proportion of the inrush current and the dead angle of the waveform depend on the saturation angle of the transformer core. The larger the saturation angle is, the smaller the second harmonic proportion is, and the larger the dead angle of the waveform is.
2. The second harmonic proportion of the inrush current will increase after the CT transformation, more conducive to the inrush current braking with the second harmonic proportion as the braking criterion.
   $$\frac{dK(n)}{dn} = \frac{\omega_0 L_{ma} {R_L'}^2}{\{[n\omega_0(L_{ma}+L_L')]^2 + {R_L'}^2\}^{\frac{3}{2}}} \to \frac{dK(n)}{dn} > 0 \to K(2) > K(1)$$
3. The larger the equivalent secondary load resistance of CT, the easier the CT type is to saturate, and the larger the dead angle of the inrush current waveform after CT transfer is. It is more conducive to the dead angle criterion braking.
4. After CT transfer, the dead angle of sympathetic inrush will decrease. When compared with the inrush current, the braking criterion of the dead angle of the waveform is more likely to fail.
5. Dead angle of the inrush current after the PR type of CT transfer is smaller than that of the P-type CT. Therefore, it can be inferred that the more difficult the PR type CT is to be saturated.

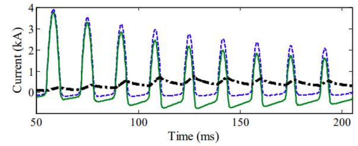
CT Saturation Detector

- Harmonic inhibit is an obvious method of mitigating the problem. It has two major disadvantages though: degraded dependability during faults combined with inrush and slower operation.
- CT saturation detector and phase comparison switched on and off dynamically in order to cope with CT saturation occurring at <u>low currents</u>: inrush, load change, or a distant external fault.
- AC saturation detector is anticipated if large restraining current is measured under small differential. Such pattern implies an external fault and possible CT saturation to follow.
- DC saturation detector triggers if significant DC component is detected in either neutral (DC_N) and terminal (DC_T) CTs in a given phase while the differential function is still dropped out.





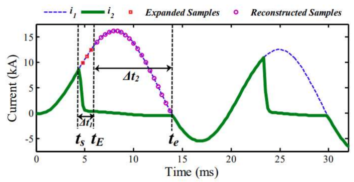
External Fault with CT Saturation

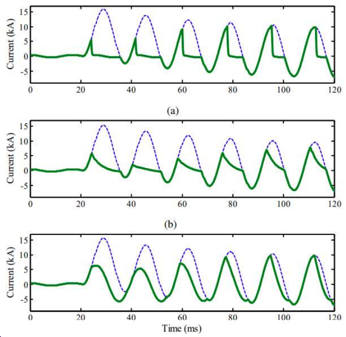


Inrush Current with CT Saturation

CT Saturation Signal Reconstruction

Fault Current - i_1 = primary, i_2 = secondary





Resistive Burden

Nominal Burden (PF = 0.8)

Gapped CT

Inrush Current – $i_{in}(t) = \begin{cases} \frac{1}{m}(\lambda_r - \cos(\omega t)) & t_1 < t < t_2 \\ 0 & \text{otherwise} \end{cases}$

Fault Current – $i_{fu}(t) = I_{DC}\exp\left(-\frac{t}{\tau}\right) + I_m\cos(\omega t + \tau)$

Reconstruct AC saturation with CT magnetizing current

$$i_m^e(t_n) = \frac{1}{L_{inf}}\lambda(t_n) + \left(i_m^{sat} - \frac{\lambda^{sat}}{L_{inf}}\right) = \frac{1}{L_{inf}}(\lambda(t_n) - t_0)$$

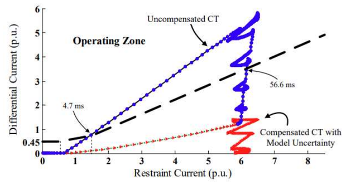
$$\frac{d}{dt}\lambda(t) = (R_{CT} + R_B)i_2(t) + L_B\frac{d}{dt}i_2(t)$$

where L_{inf} is the saturation inductance.

Reconstruct DC saturation with Bias Averaging

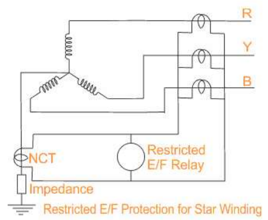
$$I_{shift}[n] = \begin{cases} 0 & |I_{mag}[n]| > \varepsilon_1 \\ I_{DC}[n] & |I_{mag}[n]| \le \varepsilon_1 \end{cases}$$

$$I_{bias}[n] = -\frac{\sum_{i=0}^{N-1}|I_{shift}[n-i]|}{\sum_{i=0}^{N-1}\mathrm{sgn}(I_{shift}[n-i])}$$



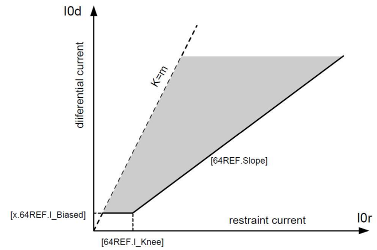
High Impedance vs Low Impedance

<u>High Impedance Element</u>



- Require all CTs forming the boundary with the same characteristics (i.e. matched in ratio, DC resistance, excitation)
- Assume CTs are either not saturated, or saturated together
- All frequency components summed up to go through the shunt branch and triggered OC element with instantaneous value $i_\Sigma(t)$

<u>Low Impedance Element</u>



- Boundary CTs could be mismatched. (could match with pre-processing, i.e. CT ratio input)
- Prefiltering (to fundamental) or Post-filtering (AR(1) filter) can be used to maintain its stability
- Different I_{DIFF} (differential quantities) and I_{REST} (restraint quantities) could be used for decisioning. Yet, setting is hard to define and reason.
- Need other elements (e.g. external fault detectors, inrush detectors, CT saturation) to maintain its stability.

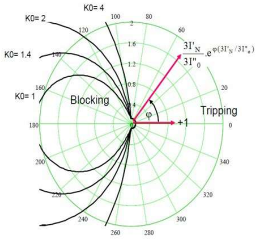
Protection Designs in Different Manufacturer

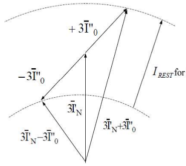
Siemens

$I_{DIFF} = I_N$

$I_{REST} = K(|I_N - 3I_0| - |I_N + 3I_0|)$

Separate filter included for inrush and over-excitation.





ABB

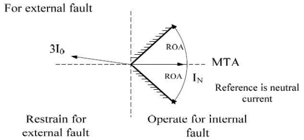
$I_{DIFF} = |I_N + 3I_0|$

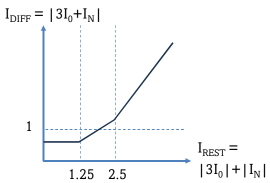
$I_{REST} = 0.5\,|I_N| + |3I_0|$

Filter to Fundamental Frequency

Included Directional Check and Second Harmonics Blocking

$$\frac{|I_{2f}|}{|I_f|} > 60\% \;\rightarrow\; \text{Block}$$





GE

$I_{DIFF} = |I_N + 3I_0|$

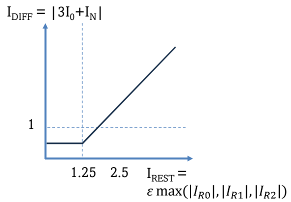
$I_{REST} = \varepsilon \max(|I_{R0}|, |I_{R1}|, |I_{R2}|)$

$\varepsilon(.) = \max(|I_R[k]|, A|I_R[k-1]|)$

Exponential Decaying Restraint to remain its stability in external fault

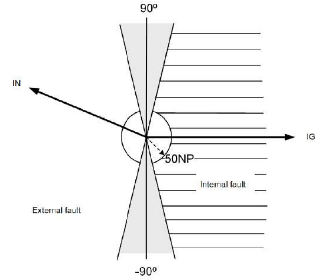
Note – digital filter over-estimates I_2 during energization

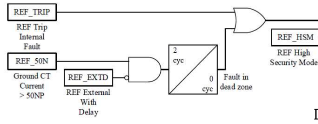
Secure as it uses sequence current to product restraint current



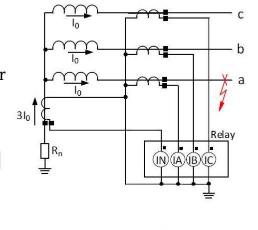
Directional Check for External Fault Vs Internal Fault

- Angle check between I_N and $3I_0$ with CTs wired with differential polarities (180° out of phase for external fault) can be used for differentiating internal fault and external fault.
- A dead zone is included at the 90° boundary where no decision should be made.
- Challenges –
  - CT saturation:
    Unstabilizing effect with $a\angle -\varphi$
    (Field test – angle error < 75°)
  - External LLG Fault with NER:
    Phase CT may saturate and neutral CT waits for permission for tripping.
  - Charging Current:
    $3I_0$ and I_N may have current angle differing to 90°. Hence the relay may be inoperative under internal fault.

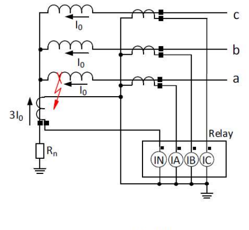




Solution to Dead Zone Blocking



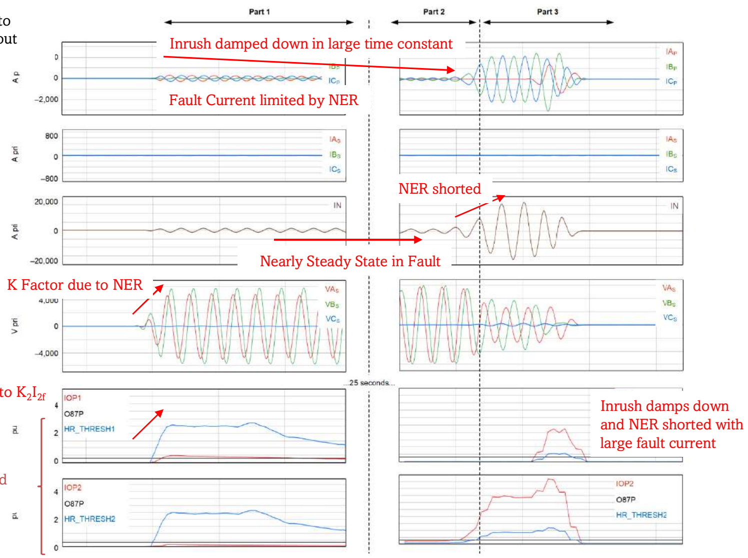
External fault



Internal fault

Transformer Energization with HV Internal Fault (Earthed with NER)

87R (Duo Bias) to Protection without HVREF

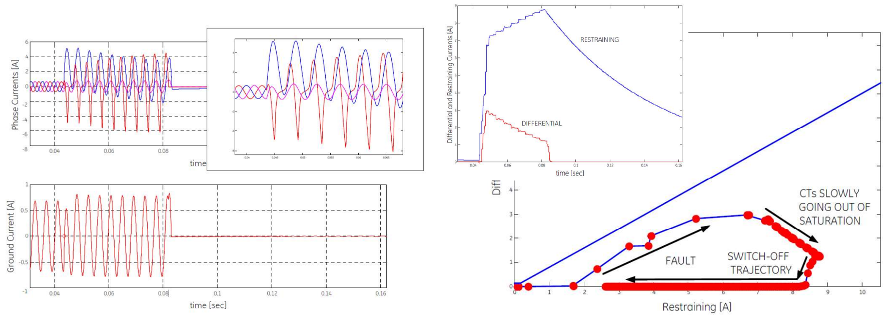


Large I_{REST} due to $K_2 I_{2f}$ during inrush

Phase Segregated Design

External Fault with CT Saturation [GE Relay]

- Recall the differential current and restraint current in GE's relay are –
  $I_{DIFF} = |I_N + 3I_0|$, $I_{REST} = \varepsilon \max(|I_{R0}|, |I_{R1}|, |I_{R2}|)$ $\varepsilon(.) = \max(|I_R[k]|, A|I_R[k-1]|)$
- A = 0.5 such that it decays 50% in about 15 cycles.
- It produces significant restraint before CT fully saturates (assumption – stay stable at 1/8 cycles, 2.5ms). Large restraint produced after fault inception decays slowly due to memory effect of exponential filter.
- An external fault may saturate one or more CTs and bring the $I_D - I_R$ operating point close to the boundary. When the external fault is subsequently cleared, both differential and restraining starts decreasing. The switch-off trajectory may temporarily enter the characteristics and cause maloperation. A crude way for prevention is to add delay timer.

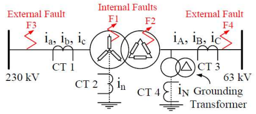


Detection of Internal Fault From External Fault

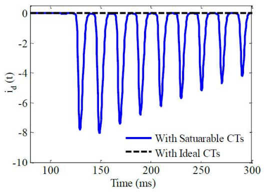
Requirement – Given $I_D = (I_A + I_B + I_C) - I_N = 3I_0 - I_N$

- $I_N > I_{N\,SET}$ and $I_D > I_{D\,SET}$
- $I_D > 3I_0$
- $I_D > I_N$

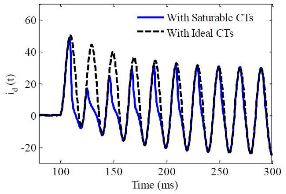
To differentiate internal earth fault with external fault



Severe External Fault -



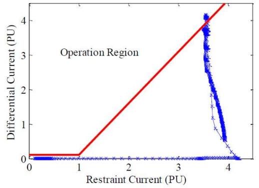
Severe Internal Fault -

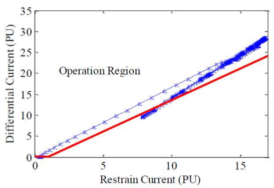


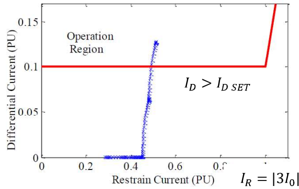
Method	# of misoperation for 1053 cases of internal fault	# of maloperation for 880 cases of external fault	Total Accuracy (%)
Conventional Method [20]	0	203	88.10
Intelligent Method [17]	0	13	99.32
Proposed Method	0	9	**99.53**

Light Internal Fault -

$I_D = |3I_0 + I_N|$





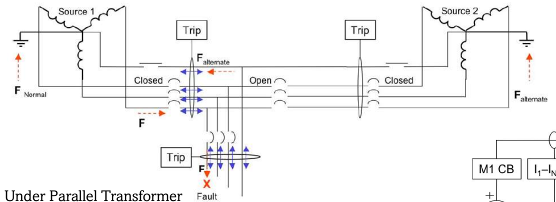


$I_D > I_{D\,SET}$

$I_R = |3I_0| + |I_N|$

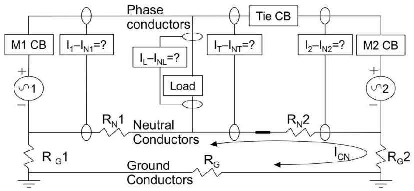
Other Concerns for REF Elements

- Alternative Path for Ground Returning Current

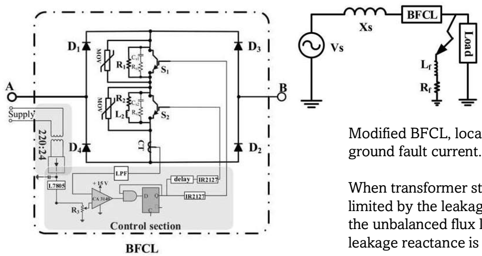


Under Parallel Transformer

Circulating Current at Neutral due to two point earth



- Limiting current with NER (or variable NER device)



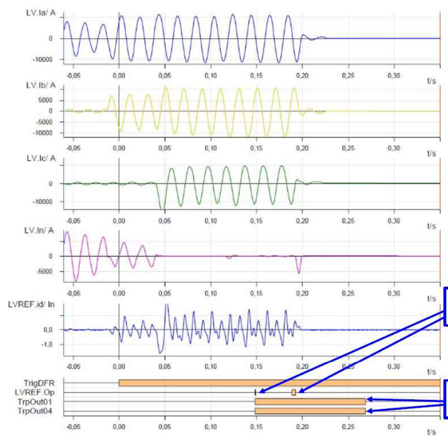
BFCL

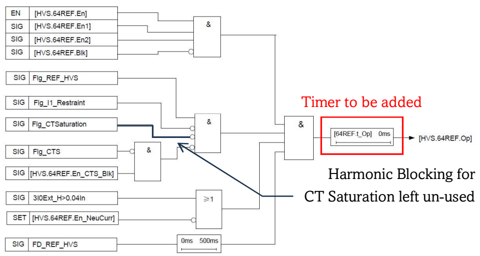
Modified BFCL, located at neutral point of industrial transformers to limit phase-to-ground fault current. (Z_S, X_L, R_{NER}, winding connection)

When transformer star winding is solidly grounded, the fault current is primarily limited by the leakage reactance of the winding, which varies non-linearly due to the unbalanced flux linkage. For the faults that are near the neutral point, the leakage reactance is very low, which causes high amplitude fault currents.

LMT H1 Tripped by LVREF with Through Fault Incident

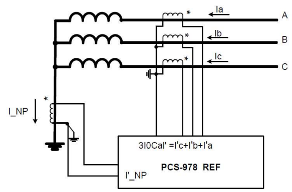
- Overhead line fault left uncleared for 280ms. Tx LVREF operated with trip and intertrip signal initiated before OCEF for OHL operates.
- As an interim measure, it is recommended to add a time delay of **25ms** to HVREF and LVREF element to PCS978 to ride through the possible intermittent operation upon inrush or through fault current.





Timer to be added

Harmonic Blocking for CT Saturation left un-used



Setting Calculation for LVREF Elements

Full Load Stability

For a given 50MVA transformer with LV CT = 1/1600, full load current

$$I_{FL} = \frac{50\text{MVA}}{\sqrt{3} \times 11\text{kV}} = 2624\text{A}_{\text{pri}} = 1.64\text{A}_{\text{sec}}$$

Through Fault Current with Transformer Impedance 27% –

$$I_{TF} = \frac{50\text{MVA}}{\sqrt{3} \times 11\text{kV} \times 27\%} = 9720\text{A}_{\text{pri}} = 6.075\text{A}_{\text{sec}}$$

Select Sensitivity = 20% of Transformer Rated Current, i.e.

For unbalance current, charging current, harmonics, the current should be < 20%.

$$2\text{ik} = 20\% \times 1.64\text{A} = 0.330$$

Through Fault Stability

Slope Setting (2p2) should be smaller than that of the Fault Line, i.e. 100%

Hence, 2p2 is selected to be 50%.

To determine when the horizontal line starts to bend, we should allow at least full load current between the fault line and the LVREF setting.

Hence, 2kp > 1.64A and is selected to be 1.65.

Through Fault Stability without CT Saturation?

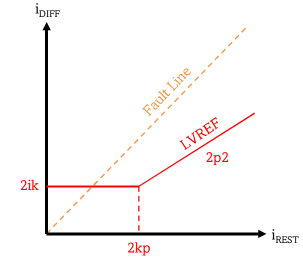
Checking

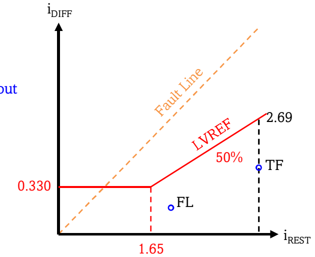
At full load condition, where only phase CT has current, consider both CT errors to be 5%, the maximum differential under full load current would be

$$I_{D\,FL} = 10\%\, I_{FL} = 0.164, \qquad I_{R\,FL} = (1 + 5\%) I_{FL} = 1.722$$

At maximum through fault condition,

$$I_{D\,TF} = 10\%\, I_{TF} = 0.608, \qquad I_{R\,TF} = (1 + 5\%) I_{TF} = 6.379$$

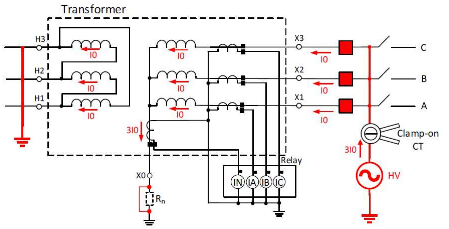




Commissioning Test for REF Elements

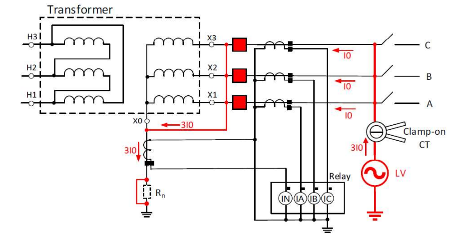
Wiring errors that can affect a REF element are:

1. Wye-side zone boundary CT secondary mistakenly connected in delta instead of wye.
2. Incorrect CT ratio or tap on wye-side zone boundary CTs and neutral CT.
3. Wye-side zone boundary CTs and the ground CT not connected with differential polarities, possibly swopped in primary or secondary.
   [Note – Check relay requirement]

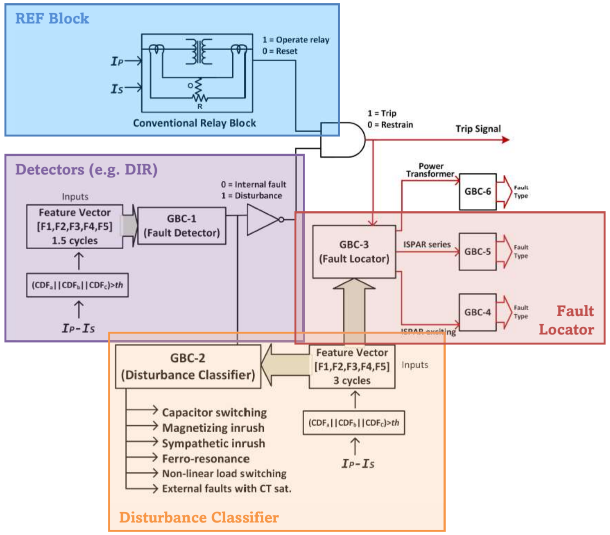


Primary Injection is to prove REF through fault stability before commissioning and on load test.

- Depending on the CT location (inside or outside transformer), the transformer can be bypassed by short wire and inject with a test set in lower voltage / rating (without injecting through transformer impedance).
- Depending on the utility requirement, some utilities may prefer connecting the HV to 380V source in wall socket, and shorting the LV to ground to provide 3 phase current.



Protection Designs



Elements can be used –

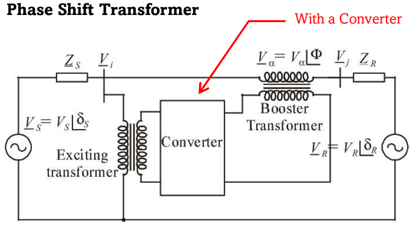
- Neutral OC (50N) with Directional Guard [Siemens]
- Percentage Bias Plane

Parameter can be used –

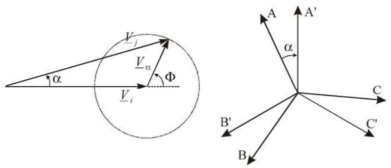
- Differential and Delayed Restraint [GE]
  Note – if vector sum is used, filtering to fundamental is necessary.
  – restraint could include $K_2 I_{2f} + K_4 I_{4f}$
- Average Change Quantities
- Fourier Transform Spectrum
- Power Density Spectrum
- Cross Correlation between CTs
- Auto-Correlations

Questions – How to provide protection for PST?

Phase Shift Transformer



a.



b. c.