Protection of Phase Angle Regulating Transformers Using Digital Relays

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1. Abstract

Phase Angle Regulating transformers are dynamic changers, used to control the real power flow through interconnected power systems. This paper describes the specifics of an installed Phase Angle Regulating (PAR) transformer, and protection techniques using modern digital relays. More specifically, the paper is focused on issues applying current differential protection to a 120 MVA Phase Regulating Transformer on 138kV power system at CLECO's Beaver Creek 138/34.5 kV substation in Pineville, Louisiana.

2. Introduction

The PAR's are used to control active and/or reactive power flow based on varying the phase angle between the source and load voltages. The PAR controls the power by inserting regulated quadrature voltage in series with the line to neutral voltage of the series unit. The inserted quadrature voltage is derived from phase to phase voltage of the other two phases. There are different PAR types, depending on their application and construction: with, or without Load Tap Changer (LTC), Delta/Wye, or Wye/Wye exciting unit configuration, with or without voltage regulating winding. They also differ by power and voltage ratings to provide different phase angle regulation, and hence power flow. The one described in this paper is of conventional type with Series Unit secondary winding connected in Delta, and Wye/Wye connected windings of the Exciting Unit with grounded neutral. The Load Tap Changer is located on the secondary Wye connected winding of the Exciting unit, and is used to control the magnitude of the quadrature voltage, used to shift the Load phase to ground voltage, from the one of the Source side.

The power flow between the Source and Load sides of the PAR can be approximated by the following equation:

$$P = \frac{V_S * V_L * \sin\Theta}{X}$$, where

where P is real power flow per unit, V_S is phase to ground voltage of the Source side, V_L is per unit voltage of the Load side, Θ is phase angle between V_S and V_L voltages, and X is per unit reactance between the Source and Load sides.

3. PAR at Beaver Creek Substation

Power flow studies indicated, that under certain conditions, the loss of the Rodmacher – Montgomery 230kV line (Figure 1), causes the 138/115kV autotransformer and the 115kV line to exceed their ratings of 93MVA, and 122MVA respectively. The Beaver Creek autotransformer is an interconnection point between CLECO and Entergy. CLECO owns the autotransformer and the 115kV bus.

Four alternatives were investigated:

1. Install series inductive reactors - not preferred, since it does not give the flexibility to increase reactance as the system conditions change, and physical substation property not large enough to accommodate, since additional property can't be purchased.

2. Install a 138kV Phase Angle Regulator transformer in CLECO's substation and leave existing Beaver Creek autotransformer.

3. Replace existing autotransformer with Phase Angle Regulating transformer.

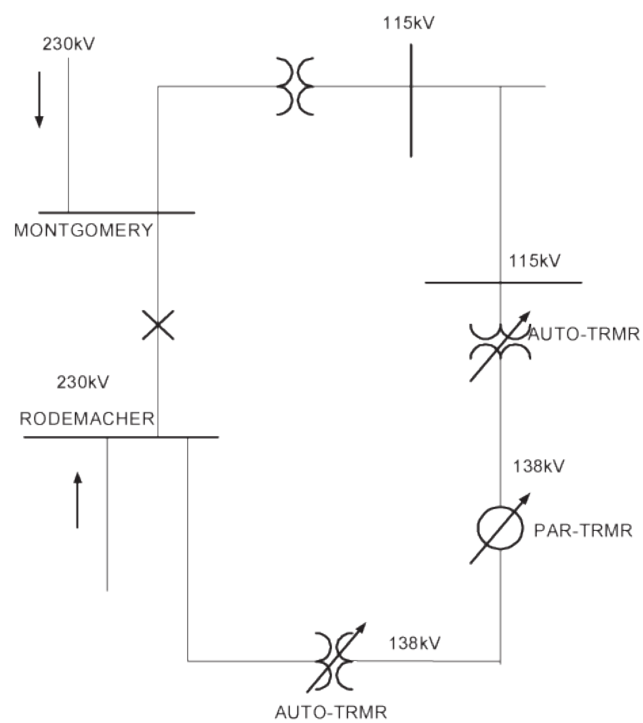


Figure 1.
Rodmacher - Montgomery 230kV line

4. Replace existing Beaver Creek 138/115kV autotransformer and re-conductor the 115kV line - viable alternative, but not preferred due to cost in excess of 10 times the cost of alternative 2 or 3.

Therefore, the installation of a Phase Angle Regulator transformer at Beaver Creek appeared to be most economical solution. (Option 2)

The current electrical configuration consists of a 230kV line in parallel with a 138/115 kV autotransformer and 115kV line. In situations in which the 230 kV line is carrying power from southern part of the service territory to the northern part of the service territory, loss of the 230 kV line may cause the flow on the 138/115 kV autotransformer to exceed the current carrying capacity of the 115 kV line. Therefore, the purpose of this PAR is to limit the power flow through CLECO's Beaver Creek 138/115KV autotransformer and the 115kv line for loss of the 230 kV segment in order to avoid limiting transfer capability as well as possible damage to the autotransformer and conductor.

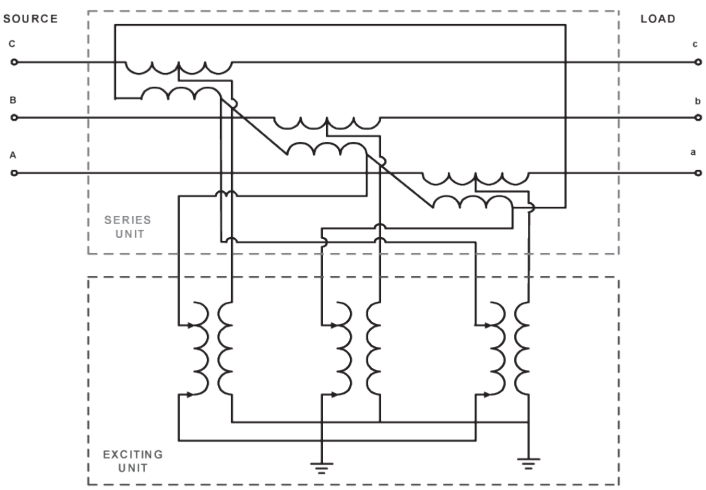


Figure 2.
PAR configuration

4. Phase Angle Regulator - Protection

4.1 Electromechanical-type Differential Protection

In the past, the differential protection for the PAR (Figure 2) would require six single phase electromechanical-type transformer differential relays – three for the primary differential system – 87P, and another three for the secondary differential system – 87S. A single phase differential electromechanical relay is set to respond on per-phase differential current, that may result from summation of the electrically connected source, load and exciting unit primary currents, as part of the primary differential protection. A single phase differential electromechanical relay is also set on per phase basis, and respond on differential current, that may appear during internal for the series and exciting unit secondary winding faults, as includes the source, load and exciting unit secondary winding currents. To set electromechanical relays for protection of the primary differential system, no special treatment is required, as it is similar to providing differential protection on the autotransformer. However, applying electromechanical relays for protection of the secondary differential system, Figure 3 would require the load and source side CTs to be connected in delta, interposing auxiliary CTs for magnitude compensation, etc.

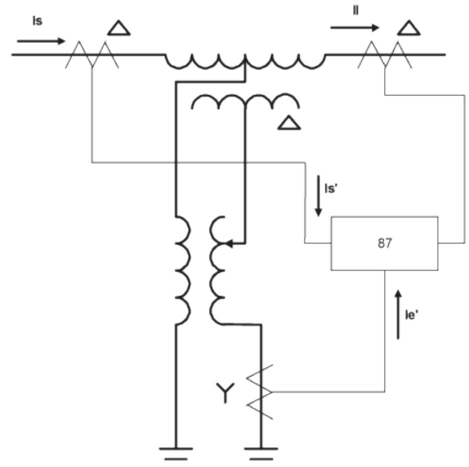


Figure 3.
87S Differential Protection

4.2 Digital Differential Relay Protection

Used for protecting this PAR are two three-phase current differential protection relays – one for primary differential system 87P, and another for secondary 87S.

4.3 Primary Differential Protection - 87P.

Biased differential protection is set to protect the common primary series unit winding and the primary exciting unit winding. The summation of the currents forming the operating differential current (Figure 4) can be expressed by the formula: $\bar{I}_S + \bar{I}_L + \bar{I}_{Exciting} = 0$, where $\bar{I}_S$ is per-phase primary source side current, $\bar{I}_L$ is per-phase primary load side current, and $\bar{I}_{Exciting}$ is per-phase current from the primary winding of the exciting unit.

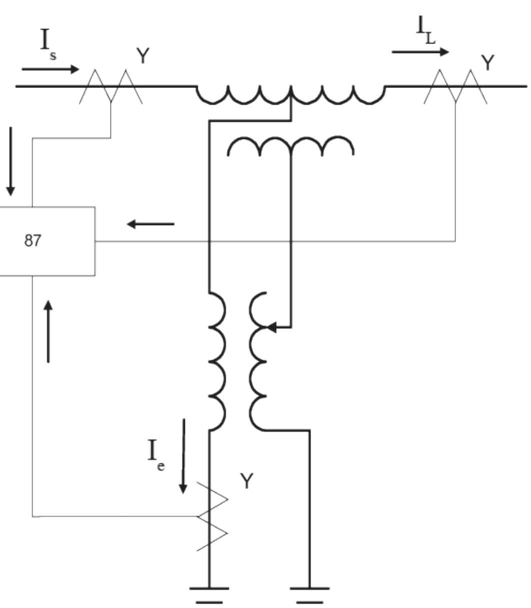


Figure 4.
87P Differential Protection

One digital three-phase current differential relay provides 87P protection, and no special treatments are needed. The CTs on the source, load and excitation unit primary sides can be connected in wye, and they can have different ratios. These modern relays perform automatic magnitude and phase compensations, zero sequence removal, harmonic and DC filtering, and provide more robust protection capability. Advanced relay differential algorithms cope with different techniques in computing and utilizing the restraining current, as to accomplish better selectivity, security and sensitivity.

4.4 Secondary Differential Protection - 87S

The secondary differential relaying system includes per-phase source and load currents, as well as the exciting unit secondary winding current. This protection differs from the one applied on conventional power transformer, as the current on the secondary winding of the exciting unit, appears as a vector sum of the per-phase source and load currents. The relationship among these three currents is kept through any angle variation of the PAR. To understand how the current on the secondary winding of the exciting unit is actually produced, see Figure 5. The secondary winding from the series unit is connected in Delta, where for example the exciting current for phase A - $\vec{I}'ea$, is derived from the source and load phase B and C currents. The primary currents, flowing through the wye connected CTs of phase A, are designated as:

$\vec{I}sa$ - phase A current source side

$\vec{I}la$ - phase A current load side

$\vec{I}'ea = \frac{k}{2}[(\vec{I}sc + \vec{I}lc) - (\vec{I}sb + \vec{I}lb)]$ - phase A exciting current, where $\vec{I}sb, \vec{I}lb, \vec{I}sc, \vec{I}lc$ are source and load currents of B and C, and k is series unit turns ratio.

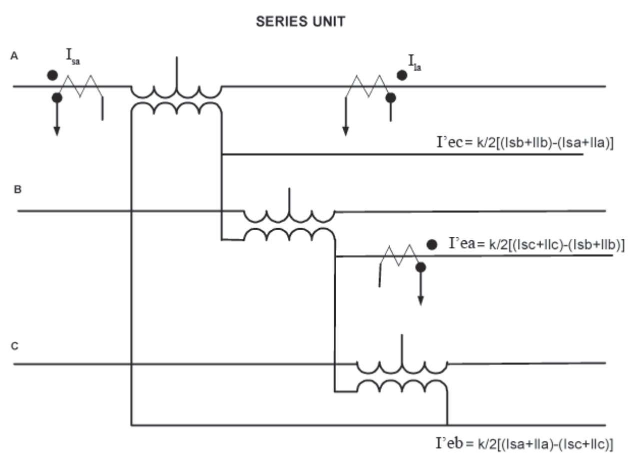


Figure 5.
Secondary Currents for 87S Protection

In Figure 5, the exciting current I 'ea is derived from the source and load currents of the other two phases - B and C. Therefore, to set the digital current differential relay correctly, we shall define their phase and magnitude relationships.

The currents used by the relay to provide 87S protection of phase A, therefore are: $\vec{I}sa_{relay} = \vec{I}sa / n1$ from source side CT, $\vec{I}la_{relay} = \vec{I}la / n2$ from load side, and $\vec{I}'ea_{relay} = \vec{I}ea / n = K[(\vec{I}sc + \vec{I}lc) - (\vec{I}sb - \vec{I}lb] / 2n$ - from the exciting unit secondary winding current. All CTs are rated at 1200:5, and therefore have the same $n = n1 = n2 = 240$ ratio.

Simplifying the formulas of expressing the differential and restraint currents used by the relay, having the same CT ratios, allows us to omit n1, n2 and n:

$\vec{I}da = \vec{I}sa + \vec{I}la + k[(\vec{I}sc + \vec{I}lc) - (\vec{I}sb + \vec{I}lb)]/2$ - differential current of phase A.

$\vec{I}db = \vec{I}sb + \vec{I}lb + k[(\vec{I}sa + \vec{I}la) - (\vec{I}sc + \vec{I}lc)]/2$ - differential current of phase B, and

$\vec{I}dc = \vec{I}sc + \vec{I}lc + k[(\vec{I}sb + \vec{I}lb) - (\vec{I}sa + \vec{I}la)]/2$ - differential current of phase C.

The differential algorithm set in the relay uses per-phase "maximum of" current on per phases basis for restraining signal, and in this case it is defined as:

$$\vec{I}ra = \max\left\{|\vec{I}sa|, |\vec{I}la|, |\vec{I}'ea|\right\}$$
$$\vec{I}rb = \max\left\{|\vec{I}sb|, |\vec{I}lb|, |\vec{I}'eb|\right\}$$
$$\vec{I}rc = \max\left\{|\vec{I}sc|, |\vec{I}lc|, |\vec{I}'ec|\right\}$$

Further on, per phase differential and restraint currents are plotted on a pre-configured dual-slope, dual breakpoint characteristic (Figure 6), for tripping /no tripping decision.

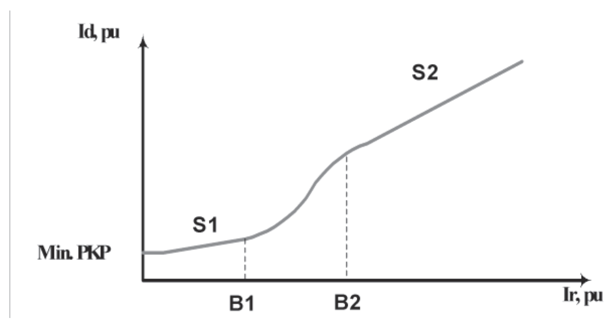


Figure 6.
Dual Slope, Dual Breaker Characteristic

The characteristic is defined by differential pickup setting, S1 and S2 as slope 1 and slope 2, and B1, and B2 as breakpoint 1 and breakpoint 2 settings.

When no phase angle is introduced between the source and load phase to ground voltages and respectively currents, the PARs tap changer is in neutral position, and no quadrature voltage is impressed to the line voltage. In this mode, the exciting current has the largest value (Figure 7).

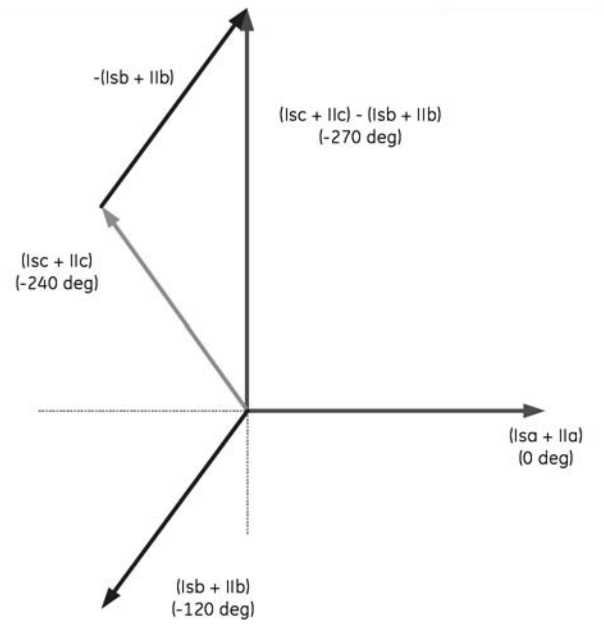


Figure 7.
Source and Load Currents in Phase, and Exciting Current 90° Out of Phase.

The exciting current has the smallest value, when the source and load currents are displaced by the maximum angle, the PAR can control. The one installed at Beaver Creek substation is rated for maximum of ± 50° degrees phase shift. Figures 8, 9, show the steps of summing per phase source and load currents, when 50° degrees apart, and the direction of the resultant current during this conditions.

Figure 9 a) shows the phase relationship of all three summated currents, when source and load currents are displaced on 50°, and b) shows the resultant excitation current with respect to phase A sum. It can be noted, that the excitation current again makes a 90° degrees angle with the resultant vector of source and load phase A currents.

PAR Series unit:

Rating: 120 MVA, 138kV/138kV

Angle Variation: +/- 50 degrees

Series unit rating: 67.579-53.387 kV Delta Winding

Exciting unit:

Exciting unit rating: 124.974Y-53.387Y kV

% Impedance:

Z1 = Z2 = 7.41% @ 0° phase shift @ 120 MVA

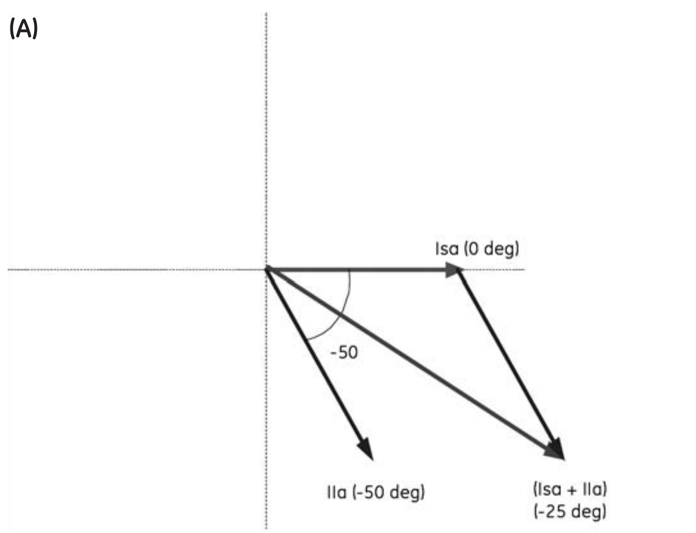
= 16.63% @ full phase shift @ 120 MVA

Z0 = 7.41% @ 120 MVA

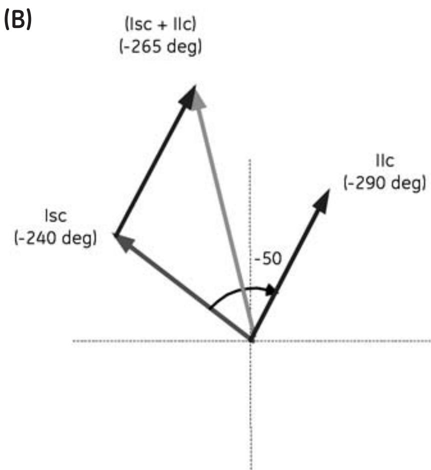
Current Transformers:

(1200 :5) , wye connection.

(A)



(B)



(C)

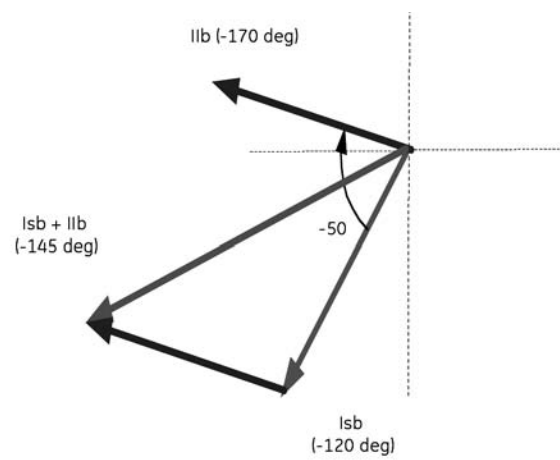


Figure 8.
Summation on per phase Source and Load Currents

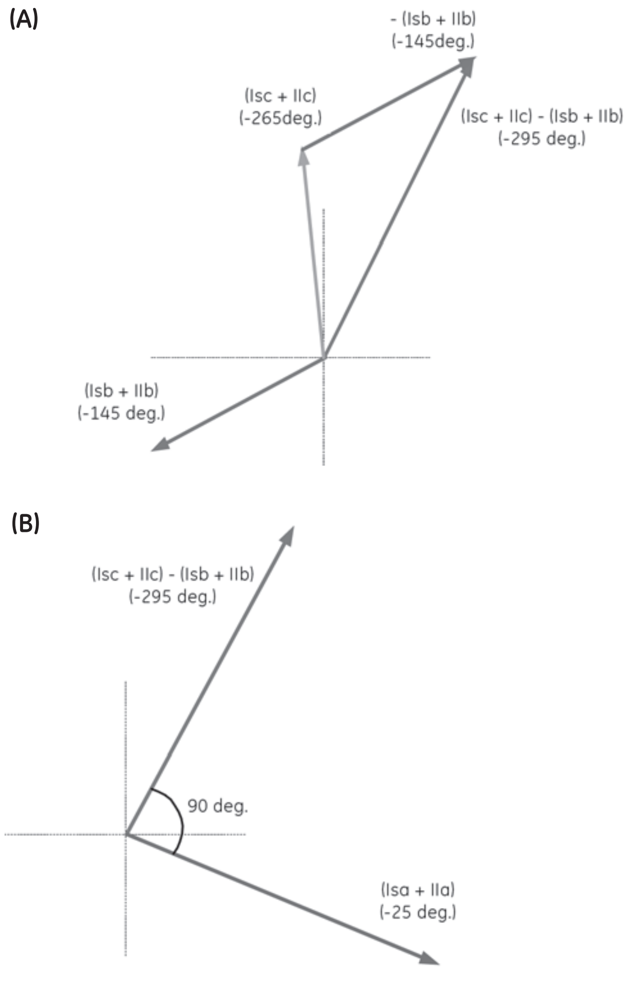


Figure 9.
Summation on per phase Source and Load Currents

Based on PAR data, the nominal currents of source and load sides of the series winding are equal to 502∠0° primary Amps or 2.09 Amps secondary. The excitation current at 0o phase shift is therefore equal to 1100 ∠- 270° Amps primary, or 4.556∠-270° Amps secondary. To obtain zero differential current, we need to adjust the magnitude of the excitation current to (2.09+2.09) = 4.18 Amps and in 180° direction, or the magnitude of the source and load summated current to 4.556 Amps. Providing that the settings of the CT in the relay match exactly the field CT, to obtain correct magnitude compensation factor by which to multiply the currents from source and load sides, the setting of the phase to phase voltage for the exciting unit winding had to be changed. The relay automatically determines the reference winding and CT, by selecting them per winding and CT setup, based on smallest ratio between CT primary and rated winding load. In this case, the compensation of 1.09 = 4.556/4.18 was applied to the source and load currents, and the entered phases to phase voltage for the exciting winding, was decreased to 138kV*(4.18/4.58) = 125.8kV, providing magnitude compensation factor of 1 as automatically selected by the relay as a reference. Performing the calculation for magnitudes of the secondary currents for phase A relay terminals, results in 2.09*1.09=2.278 Amps source and load secondary currents, or their sum equal to 4.556 Amps. The CT polarities and connections should be taken carefully into consideration, when selecting the correct exciting winding shifts. As per Figure 7, the angles for source and load windings, were set to 0° degree and the exciting winding to -270° degrees. Here, the balance was achieved, when the LTC was on neutral position. From Figure 9 b) it can be concluded that the angle phase relationship remains unchanged, during any phase shift, meaning the –270° degrees was the correct angle set in the relay for excitation winding currents. The insertion of quadrature voltage Q V into the line voltage, will be at its maximum, for 50° degrees phase shift, and it is equal to:

$$V_Q = (138kV/\sqrt{3}) * (2 * \sin\tfrac{50°}{2}) = 67.33kV$$

The series unit ratio is calculated as K = 67.579kV / 53.387kV = 1.265, meaning that a voltage of 67.33kV / 1.265 = 53.22 kV must be applied to the secondary of the series unit transformer, to produce 50° phase shift. The Beaver Creek's PAR is equipped with 33 tap LTC, which provides angle change of 3.125° degrees per tap or quadrature voltage of 53.22/16 =3326 V per tap.

4.5 Over-excitation

As seen from PAR data, the rated series winding voltage is lower than the line voltage, and as such is subject to over-voltage or over-excitation conditions during external faults, which may produce saturation, and cause false 87S operation. The care in such situations is taken by computation of 5th harmonic on per-phase differential current, which inhibits the differential protection. Additional logic can be built, to allow a V/Hz protection to take a lead under such conditions. The saturation of the series winding has no impact on the 87P differential protection, as all three input currents, are measured from electrically connected circuits.

4.6 Sensitive ground fault protections

The series and exciting unit primary windings can be effectively protected during ground faults that may not be detected by the 87P protection, by applying Restricted Ground Fault (RGF) protection. The RGF is designed to detect even small internal ground fault currents, and at the same time provide security on external ones, using a restraint current based on variable symmetrical components parameters. The neutral of the exciting unit secondary winding, is also solidly grounded, and is a source of zero sequence current, where a ground over-current protection 51G can be set to detect phase to ground faults.

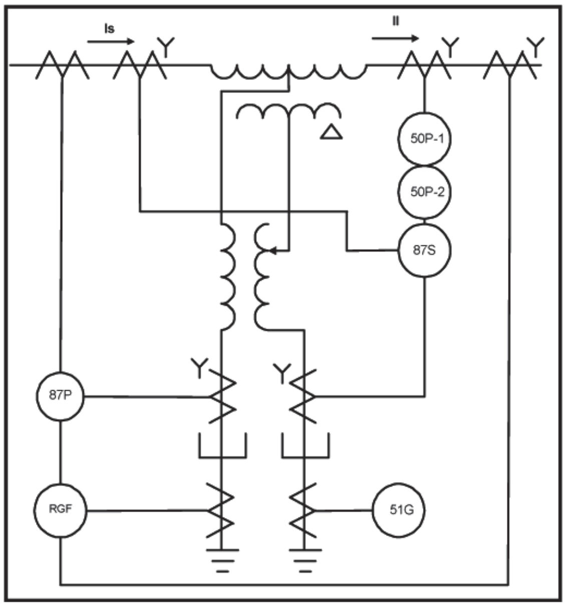


Figure 10.
Ground Fault Protection

5. References

[1] "Protection of Phase Angle Regulating Transformer" IEEE Power System Relaying committee, 1999

[2] "Power Transformer" Principle and Applications, J Winders, 2002

[3] GE Publication GEK-106416, Transformer Management Relay, Instruction Manual