Protection of Phase Angle Regulating Transformers

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Protection of Phase Angle
Regulating Transformers (PAR)

TABLE OF CONTENTS

Protection of Phase Angle Regulating Transformers

Abstract

This paper documents the protection requirements of the phase angle regulating transformer (PAR) and ththeory of operation of the PAR that are currently in service in electric utility power systems. Modeling of PAR in the power frequency domain as well as electromagnetic transient program EMTP simulation are explained.

1.0 Introduction

This document provides insight into the theory and relay protection of phase angle regulating transformers (PAR). Typical phase shifting transformer configurations and current transformer locations are presented.

Topics summarized in this document include the theory of operation of phase angle regulating transformers, the various types of phase regulating transformers, and modeling for use in short circuit studies. Relay protection including differential, overcurrent, and sudden pressure is reviewed.

To aid in the understanding of the current flows within PAR, sample computer studies are provided. Through the use of these sample studies, the relay engineer can determine the correct application of the protection, especially the differential. The concern is not only for installing enough current transformers but also the installation of CTs in the correct location and of the correct ratios. The techniques provided in this guide should help in this determination.

Other sections included in this guide include remedial action schemes and the commissioning of PAR.

2.0 Theory of Phase Angle Regulating Transformers

The power transmitted over a transmission line is represented by:

$$P = (|V1| \bullet |V2 | \sin \theta \ ) / X$$

Where θ is the angle between the sending and receiving end voltages. In a network of parallel paths, but without controlling devices, the division of power flow is determined entirely by the relative impedances of the paths [1]. For example, in Figure 1 below, one path has an impedance of 0.2 pu and a parallel path has an impedance of 0.8 pu. If a total power of 100 MW is flowing through the two lines, the power will always divide as shown.

In some circumstances, the natural division of power flow determined by the network impedances is not desirable. For example, the line with impedance of 0.2 pu might be an underground cable of limited thermal capacity. Another possibility is that one of the paths belongs to another transmission owner who does not wish to have the power flow over their line.

A phase angle regulating transformer can be used to control power in parallel networks. The PAR controls power flow by inserting an out-of-phase (often quadrature) voltage in series with the voltage of the controlled line. In networks whose impedances are largely reactive, the quadrature component of inserted voltage causes a circulating power flow which changes the relative loading in the parallel paths. For example, in Figure 2 below a PAR has been installed in the lower impedance line and adjusted to a phase angle which produces a circulating power flow of 30 MW. The net effect of the through power of 100 MW and the circulating flow of 30 MW is equal power flow in the two lines.

It is important to note that the circulating power flow depends only on the impedance of the loop in which it circulates and the magnitude of the inserted quadrature voltage. It is largely unaffected by the total through power flow. For example, if the 100 MW through flow was removed, the PAR, if not readjusted for the new operating condition, would still circulate 30 MW around the loop.

The amount of quadrature voltage inserted by a phase angle regulating transformer is usually adjustable over a range and is described by the phase angle difference between the transformer's input and output terminals. For example, a quadrature voltage of 0.30 pu of rated voltage produces a phase angle difference of about tan^{-}

^{1} (0.3) = 16.7^{o}. In a loop with a total impedance of 1.0 pu, this quadrature voltage would produce a circulating power flow of about 0.3 pu.

3.0 Types of Phase Angle Regulating Transformers

Phase angle regulating transformers (PAR) can be constructed and configured in various ways to either provide a fixed or a variable phase shift. In addition, some types of PAR can provide voltage regulation by controlling the magnitude of the voltage. The following types of phase angle regulating transformers are commonly used:

3.1 Delta Secondary Series Winding/ Grounded Wye Exciting Windings connections (Conventional)

This is the most commonly used type [B4], [B7], [B10]. It consists of a series unit and an exciting unit. As shown in Figure 3 the units are mounted in separate tanks, with four throat connections between the tanks (three-single phase primary connections and one-three phase secondary connection). The series unit secondary winding is connected in delta while the series primary winding center tap is connected to the primary exciting unit. The exciting unit is connected grounded wye-grounded wye. This configuration offers the advantages of a graded excitation winding insulation, grounded neutral and constant zero sequence impedance. The PAR accomplishes the control of flow of power by adding a regulated quadrature voltage to the source line-to-neutral voltage. Load tap changers (LTC) permit phase angle variations in the advance or the retard power flow directions. A quadrature voltage derived from the phase-to-phase voltages will accomplish the required phase shift. The secondary of the exciting unit is connected in such a way to impress the quadrature voltage to the series winding. The derivation of the quadrature voltage is illustrated in Figure 4. Phase angle shifts of the phase A voltage would be developed by adding a quadrature voltage derived from B & C phase voltages. Changing the magnitude of the quadrature voltage can vary the phase shift. By varying the tap on the load tap changer in the exciting winding, one can control the amount of quadrature voltage impressed on the secondary of the series unit and thus the phase shift across the PAR [B3].

3.2 Wye Secondary Series Winding/Delta primary Exciting Winding Connections

The delta connected phase shifter is very similar to the grounded wye connection, except that the primary winding of the exciting unit is connected in delta and the secondary windings of the exciting and series units are connected in wye. Figure 5 shows the PAR with only phase A connected.

3.3 Delta Hexagonal Connection

The Hexagonal Connection shown in Figure 6 is commonly used for fixed phase shift applications to avoid the use of LTC, which may weaken the PAR design and affect its reliability [B6]. This is a simple design, which uses no-load tap changers and it is normally designed to give one or two constant phase shifts between the source and the load sides. Typical phase shift values are 15, 20, 30 ,or 40 degrees which are accomplished through changes of fixed links. It is designed similar to a two-winding transformer but with a special winding connections. Short windings and long windings are wound on the same core but connected to different phases. The two fixed shifts are normally obtained by dividing the short winding into two smaller windings. The two winding can either be connected in series for maximum shift or in parallel for the minimum phase shift.

3.4 Tapped Series Winding Design

In this PAR design which is shown in Figure 7, all windings involved for phase angle changes and for voltage magnitude corrections are housed in one tank.. Phase shifting is accomplished using quadrature phase-to-phase voltages. The phase shifting process will change the source and load side voltage magnitude. Therefore, regulation of voltage magnitude is required and normally is done using in-phase derived voltage components which are added in series with the winding voltage. Figure 8 shows a three-line AC for 115 kV, 175 MVA single tank design.

3.5 Grounded Wye Connection with Voltage Magnitude Control (voltage regulation)

The impedance of the series winding will produce a voltage drop due to the through current load flow. If this is of concern, voltage regulation can be designed into the scheme. Such an arrangement is shown in Figure 9.

4.0. 60 HZ Modeling of Phase Angle Regulating Transformer for Short Circuit Studies

The positive sequence impedance of PAR varies with the taps and, for a conventional PAR, it is normally minimum at 0^o phase shift and maximum at the maximum design phase shift. The PAR positive sequence impedance can vary by ratio of about (1.5 - 1.7) between the full shift and the 0^o phase shift. Short circuit studies should be simulated using the minimum impedance for fault duty analysis and the maximum impedance for protective relaying sensitivity analysis. Manufacturer test reports should include (as a minimum) PAR positive sequence impedance for the neutral (no shift) and the full phase shift of the PAR.

The zero sequence impedance for the conventional PAR requires careful analysis to determine whether the exciting transformer is a source of zero sequence current. The zero sequence impedance of the PAR remains fairly constant across the tap range [B2]. If the exciting transformer is designed as wye-grounded/wye-grounded (conventional) with a three-legged core construction, the direction of the flux induced by zero sequence current is the same in all three legs. This results in a flux return path through air, creating a relatively low exciting impedance to zero sequence current. The three-legged, three phase core construction is shown in Figure 10. It has an effect of providing a fictitious delta tertiary winding of relatively high impedance, and allows the flow of zero sequence current [10]. The zero sequence equivalent circuit of the conventional PAR is thus similar to a wye-grounded/delta/wye-grounded three winding transformer. Figure 11 shows the zero sequence impedance equivalent circuit for a three-legged conventional PAR. For a five legged core as shown in Figure 12, the flux has a return path through the iron of the PAR resulting in a high winding zero sequence impedance.

5.0 Protection of Conventional Phase Angle Regulating Transformer

Protection systems for the conventional PAR will be described in detail due to the wide application of this type.

5.1 Protection of the Primary Windings of the Series and Exciting Units

Percentage-differential relays with harmonic restraint can be used to provide protection of the primary windings of the PAR. As shown in Figure 13, current transformers for the source and load sides of the series unit as well as the neutral side of the exciting unit primary windings are all connected either in wye or delta. Wye connected current transformers offer advantages in faulted phase identification and current transformer secondary circuit neutral current grounding. In addition, the wye connection will allow the third harmonic to restrain some typesof differential relays for overexcitation conditions. Since the primary differential relay system current transformer connections are all on the series unit primary winding side, the primary differential relay will be unaffected by series unit saturation that could occur during external faults. The primary differential relay system will provide coverage for all PAR primary winding faults. The secondary differential protection system and backup ground overcurrent relaying cover PAR secondary winding faults. The primary differential relays are connected to satisfy Kirchoff's law at the mid point junction of the series unit primary winding [B10] where:

$I_{Source} = I_{Load} + I_{Excitng}$

This relationship will be satisfied when identical CT ratios and connections (wye or delta), and relay taps are selected for the source and load sides of the series unit primary windings and neutral side of the exciting unit primary winding. Figure 14 shows the 3-Line AC connection for the PAR primary differential relay.

5.2 Protection of the Secondary Windings of the PAR Units

Percentage-differential relays with harmonic restraint can be used to provide protection of the series and exciting PAR secondary windings. As shown in Figure 15, CTs for the source and load sides of the primary series winding are connected in delta, while CTs on the neutral side of the secondary exciting units are wye connected.

Since one restraint circuit of the secondary differential relay system is on the secondary side of the series transformer, possible saturation of the series transformer may cause an undesired trip. The saturation of the series transformer would upset the ampere-turns-coupling between the primary and secondary of the series unit and could result in the misoperation of the secondary differential relay system during external faults. Series unit saturation during an external fault could occur due to the low voltage rating of the series unit (40-50 % of the line-to-neutral voltage). Faults on both sides of the phase angle regulating transformer under both maximum short circuit and angular shift (maximum impedance) conditions should be analyzed to determine if series unit saturation is a possibility. EMTP studies could also be used to examine if the PAR series unit can saturate during external faults. If the series unit saturation is a problem, desensitization of the secondary differential relay is required during the overvoltage condition. A scheme may be then applied to discriminate between relay operations caused by overvoltage and operations caused by internal faults. The scheme can delay relay tripping if overexcitation condition is correctable. Volt/ Hertz relays can be used to sense overexcitation and interface with a specially designed differential relay for this condition.

The secondary differential relay system CT connection and ratio requirements must be determined under full load conditions under both neutral and maximum angle shift tap positions. At the neutral tap position, the PAR series unit primary winding source and load currents are equal and in-phase. The current in the series unit secondary winding will be equal to the series unit primary current multiplied by the series unit turns ratio. Under a phase shift condition, the PAR source and load side currents are not equal, and the current in the series unit secondary winding is not as easy to determine. Figure 16 shows the 3-Line AC connection for the secondary differential relay system.

5.2.1 Ampere-Turns Coupling for the Series Unit

Since the exciting unit primary winding connection is at the mid-point of the series unit primary winding, the PAR source side current is only flowing through one-half of the series unit primary winding [B10]. The PAR load side current is flowing through the other half of the series unit primary winding. The current in the series unit delta secondary winding as shown in Figure 17 I_{delta} , is thus

$$I_{delta} = (K/2)\,(I_{source} + I_{load})$$

Where K = Series Unit Turns Ratio = (Series Unit Primary Voltage) / (Series Unit Secondary Voltage)

5.2.2 CT Connections

The series unit secondary delta connection results in the following exciting unit secondary lead currents:

$$I'_{EA} = (K/2)\,(I_{SC\ source} + I_{SC\ load}) - (K/2)(I_{SB\ source} + I_{SB\ load})$$

$$I'_{EB} = (K/2)\,(I_{SA\ source} + I_{SA\ load}) - (K/2)(I_{SC\ source} + I_{SC\ load})$$

$$I'_{EC} = (K/2)\,(I_{SB\ source} + I_{SB\ load}) - (K/2)(I_{SA\ source} + I_{SA\ load})$$

Re-arranging these equations it can be shown that

$$I'_{EA} = (K/2)\,(I_{SC\ source} - I_{SB\ source}) + (K/2)(I_{SC\ load} - I_{SB\ load})$$

$$I'_{EB} = (K/2)\,(I_{SA\ source} - I_{SC\ source}) + (K/2)(I_{SA\ load} - I_{SC\ load})$$

$$I'_{EC} = (K/2)\,(I_{SB\ source} - I_{SA\ source}) + (K/2)(I_{SB\ load} - I_{SA\ load})$$

where

I'_{EA}, I'_{EC}, I'_{EC} = exciting unit secondary A, B, and C phase lead currents

$I_{SA\ source}$, $I_{SB\ source}$, $I_{SC\ source}$ = series unit primary source side A, B, and C phase currents

$I_{SA\ load}$, $I_{SB\ load}$,$I_{SC\ load}$ = series unit primary load side A, B, C phase currents

K = series unit turns ratio

As shown in Figure 16, the connection of the secondary differential relay system will satisfy these equations if the PAR series unit primary source and load side CT's are connected in delta and the exciting unit secondary lead CT's are connected in wye. The secondary differential relays should be connected such that the series unit source and load currents flow into the restraint windings and the exciting unit secondary lead current flows out of the restraint winding. This connection will provide balanced differential operation for external faults as well as all power flows for all PAR tap positions.

5.2.3 CT Ratio and Relay Tap Selection

In a conventional three winding power transformer, CT ratios and relay tap selections are based on balancing the differential relay system two windings at a time. This approach is not feasible for the PAR secondary differential relay system where the exciting unit secondary current is balanced against the **sum** of the series unit primary source and load currents. Relay taps should be selected accordingly.

CT ratios should be chosen to satisfy the relationship

$$(1/n_2)\, I'_{EA} = (1/n_1)\,(I_{SC\ source} - I_{SB\ source}) + (1/n_1)\,(I_{SC\ load} - I_{SB\ load})$$

substituting

$$I'_{EA} = (K/2)\,(I_{SC\ source} - I_{SB\ source}) + (k/2)\,(I_{SC\ load} - I_{SB\ load})$$

it can be shown that

$$n_2 = (k/2)\, n_1$$

where n_1 = series unit primary source and load side CT ratios

n_2 = exciting unit secondary lead CT ratio

k = series unit turns ratio

This formula when followed will result in equal relay tap settings.

5.3 Current Transformer Sizing and Location

Current transformer sizing and location is very much a function of the phase angle regulating transformer design. This section will describe some of the considerations involved using a grounded wye phase angle regulating transformer design as an example.

It is extremely important that the phase angle regulating transformer is analyzed completely at the planning stages of the project. CTs can then be specified before the phase angle regulating transformer is built and incorporated into the final design.

5.3.1 Use of Non-Standard Current Transformer Ratios

For some protection applications for the PAR, it is advantageous to incorporate CTs with a custom CT ratio. One example is for the differential protection which is provided to protect the secondary windings of the series and exciting units. The provision of a custom CT ratio for this protection allows the application of the differential protection at minimum tap for all restraint inputs. This ensures maximum protection sensitivity. As shown in Annex 1, the CT ratio calculation depends on the series unit turns ratio, and the CT ratios selected for the source and load sides to carry the full load of the PAR..

5.3.2 Location of PAR Bushing Current Transformers

It is important that CTs are located properly to give the appropriate coverage for the protection zone involved. For example, CTs on the secondary excitation transformer winding shown in Figure 15 are located on the neutral side of the winding to appropriately protect the secondary winding. Sufficient numbers of CT cores should be provided within each PAR bushing considering protection of the PAR itself as well as the associated protection zones of the substation where the PAR connects.

Again, the importance of studying the protection requirements of the PAR during the planning stages cannot be overemphasized. After the PAR is built it is next to impossible to add additional bushing CTs or change any existing CTs. Some of the CT requirements for protection of the PAR itself may be made up by existing substation CTs or new free standing CTs. Whether or not this is necessary or desirable depends upon the type of PAR specified and the specific substation environment where the PAR is installed.

5.3.3 Load, fault current considerations

For any protection application, the CTs are sized and rated to accommodate the available fault currents and load currents. This aspect is equally important with respect to the protection applied to a phase angle regulating transformer. An important aspect of the analysis is to evaluate the various PAR currents at all tap positions to ensure that the most onerous case is considered for each CT application. A computer spreadsheet is a useful tool to do this analysis. Along with being an aid to understanding the PAR, a spreadsheet derived table is also a useful test tool to evaluate in-service relay currents against the PAR model.

The starting criteria for most CT applications is to limit the steady state load flow to no more than 5 amperes secondaries (for standard 5 ampere secondary rated CTs) and limit the maximum secondary fault current to no more than twenty times rated (i.e., 100 amperes secondary for 5 ampere secondary rated CTs).

5.4 Ground Time Overcurrent Back-up Protection

Inverse or very inverse ground time overcurrent protection when applied in both the exciting unit primary and secondary neutrals will provide back-up ground fault protection for the PAR.

5.4.1 Exciting Unit Primary Ground Protection -

This protection is shown in Figure 18. One of the important aspects of this protection is coordination with primary line side ground relays [5]. This depends upon whether or not the PAR is a source of zero sequence current. In a three phase exciting transformer, with a three-limbed core construction, the direction of the flux is in the same direction in all three legs. The return path for this flux is through the air resulting in a relatively low exciting impedance to zero sequence current. The net result is that the three-legged core construction has the effect of providing a virtual or phantom delta tertiary. Thus, for three-legged core designs, the protection must be coordinated with line side ground relays. For shell form type transformer designs, transformers composed of separate three phase units, or three phase units with a five limbed construction, there is a high exciting impedance to zero sequence current. Thus, for transformers of this type, there is no need to coordinate the protection with line side ground relays.

Another aspect of this protection is security against unbalanced magnetizing inrush currents. This problem is typified by situations in which system fault levels are relatively high, and where the exciting transformer is large. If there are parallel connected phase shifters, the magnetizing inrush currents can even be higher. Solutions to this problem may include: slowing down the protection, or applying second harmonic restraints to the overcurrent relay, or applying 60 Hz tuned relays or a combination of the above.

5.4.2 Exciting Unit Secondary Ground Protection

This ground protection is shown in Figure 19 and does not require coordination with line side ground overcurrent relays.

6.0 Protection of the Wye Secondary Series Winding/ Delta Primary Exciting Winding Connection

The protection of the primary windings of the series and exciting windings can be applied using percentage-differential relays with harmonic restraint. As shown in Figure 20, CTs from the source and load sides of the series unit as well as the delta connected primary windings of the exciting unit are connected to the differential relay. CTs for the primary differential relays are connected to satisfy Kirchoff's law at the mid point junction of the series unit primary winding where:

$I_{Source} = I_{Load} + I_{Excitng}$

Protection of the delta exciting winding can only be accomplished by locating CT's inside the delta. Therefore, to balance the differential connection, CT's for the source and load sides of the series unit should be connected in wye and CT's for the delta exciting winding should be connected in delta. In this case CT ratios for all winding inputs should have equal ratios. This will permit the differential relay to have equal tap settings for all windings. Dual differential protection systems can be used as shown in Figure 20.

The secondary (regulating) windings of the series and exciting units are protected by applying time overcurrent relays located in the neutral of the windings. Fault pressure relays can also be applied to protect the PAR.

7.0 Protection of Delta Hexagonal Phase Angle Regulating Transformer

The PAR can be protected by the application of either differential relaying and/ or distance relaying systems.

7.1 Differential protection

The protection of the delta hexagonal PAR can be simplified by understanding winding configurations and the PAR voltage vector diagram [B6]. The hexagonal PAR is equivalent to a two winding transformer with the short and the long windings being connected in a special way. The short winding “a” and the long winding “A” are wound on the same core, but connected to different phases. Protecting the PAR by a differential scheme that will compensate for the phase shift will require the use of CT’s embedded in the PAR. Each winding in this case will require CT’s located at each end of the winding and this may cause problems for design and manufacturing of the required CT insulation level. This may affect the overall reliability of the PAR.

The PAR protection can be simplified by bringing each winding end outside of the PAR enclosure through a bushing. The winding connections can then be done outside of the PAR tank. As a result, this arrangement will allow the use of bushing type CT's to be located on each end of the windings. This CT arrangement will permit the application of dedicated differential relaying for the short and the long windings. As shown in Figure 21, the overlapping of the “A” and the "B" differential relaying zones will provide complete protection to all six windings of the PAR.

7.2 Distance Protection

A hexagon PAR can be protected by overlapping phase and ground distance relays. The relays can be set to overreach the maximum impedance of the PAR. The zero sequence compensation on the ground distance can be set at 50% although compensation is not really required as Z_0 is approximately equal to Z_1. The phase ground distance relays are supervised by a phase fault detector. The overlapping protection is in service when the source and load sides are energized. As shown in Figure 22, provisions are designed to provide protection for the PAR when energizing from either the source or the load sides. Back-up protection is provided by fault pressure relays and temperature tripping devices.

8.0 Protection of a Single Tank - PAR

The protection of the single tank PAR design can be accomplished by the application of either differential relaying and/ or distance relaying systems.

8.1 Differential Relaying

Design of the PAR differential protection systems must tolerate a continuous phase angle shift between the source and load currents during power flows. Since no CT's are available for any winding inside the PAR tank, the slope setting of the differential relay must accommodate the exciting current component at the full PAR shift angle. Differential protection of a single tank PAR design is shown in Figure 23. Limitations of overall differential protection of a single tank-PAR is documented in Annex-4.

8.2 Distance Protection

A single tank PAR can be protected by overlapping phase and ground distance relays to be located at the source and load sides of the PAR as shown in Figure 22.. The relays can be set to overreach the maximum impedance of the phase shifter. The zero sequence compensation on the ground distance can be set at 50% although compensation is not really required as Z_0 is approximately equal to Z_1. The phase ground distance relays are supervised by a phase fault detector.

9.0 Pressure and Gas Monitoring Devices

Sudden pressure and gas monitoring relays can be placed in a number of different locations within the PAR. The relays can be placed in the series tank, the exciter tank, all three diverted switch columns, and the LTC main compartment [B9]. Experience with the tripping or alarming of sudden pressure and gas monitoring relays varies with each utility. Yet the relays are still a viable protection alternative for transformer fault detection. This is especially true in transformers with complicated circuits like PARs .

10. Parallel Operation of Phase Angle Regulating Transformer

The parallel operation of phase angle regulating transformers introduces an additional protection concern if the PARs were to be operated “out of step”. The operation of parallel phase angle regulating transformers with different phase angle shifts could result in the circulation of large currents between the PARs [8]. If the PARs were directly connected in parallel, the circulating current due to “out of step” operation of the PARs could be limited only by the impedances of the PARs. In some cases, the addition of transformers in the loop will limit the magnitude of the PARs circulating current significantly, such that operation of the PARs one step apart may be tolerated continuously under maximum load conditions.

“Out of step” protection schemes may include sensing of tap positions and/or circulating current. The tap position sensing include hardwiring of the tap position indications to pickup an auxiliary relay when the PARs are at significant taps apart from each other. The scheme can trip associated breakers when the PARs are out of step for greater than certain time delay and the trip can also be conditioned on the PAR temperature hot spot indication. An alarm can also be designed when out of step condition is sensed for a shorter time delay. The scheme can be disabled via supervisory control if one PAR is out of service. As shown in Figure 24, the circulating current sensing includes an overcurrent relay (50) connected to operate on the differential current between the two phase angle regulating transformers [B10]. The overcurrent relay can be set to detect a one step “out of step” condition. Since the differential current which is fed to the overcurrent relay is twice the circulating current, the overcurrent relay which should be utilized may require a significant overcurrent capability.

11. Remedial Action Schemes For PARs

A remedial action scheme may be applied to PAR to limit the power flow. There are two aspects which could be considered in such a scheme.

System Aspect - A remedial action scheme may be applied to automatically limit the power flow to a prescribed amount dependent upon the status of the rest of the network.

PAR aspect - The rating of the PAR tap changer is a severe limiting factor due to the high load currents involved on the secondary of the exciting unit [B7]. If there is a moderate overload condition in the PAR, the PAR can be 'run back' to reduce the power flow through the phase shifter.

For very severe overloads, the tap changer should be automatically blocked, thus saving any added wear and tear or damage to the tap change contacts. An example of a remedial action scheme in block diagram form is shown in Figure 25.

12. Overexcitation Issues

A Phase Angle Regulating Transformer (PAR) is composed of multiple windings. The exciting winding is connected line to ground and is designed for full-L-L voltage. The series winding is connected in series with the line. Having this winding in series with the line brings up many areas of concern, which should be studied through electromagnetic transients program (EMTP). Studies which model this system on both sides of the PAR should be conducted to study the effects on the series winding.

The series unit voltage rating is determined by the amount of phase angle shift of the PAR. This voltage rating is much lower than the system voltage rating. This reduced voltage rating could lead to saturation problems. Since the series winding is in series with the line, the current through it is dynamic.. Any fault that happens external to the transformer produces a current that flows through the PAR. As the fault current increases, the voltage drop across the series unit may be large enough to saturate the series unit. This is especially true if a strong source is on one side of the PAR and a weak source on the other. An external fault on the weak source side of the PAR will saturate the series winding. An EMTP study is recommended to see if series-winding saturation is a problem.

Series winding saturation tends to make the differential relay applied to protect the secondary winding of the PAR susceptible to misoperation. In this case, a method is needed to desensitize the differential relay, thereby preventing misoperation if series-winding saturation. One method employs a potential transformer to monitor the voltage at the series winding. An overvoltage relay is used to supervise the electromechanical differential relays [B5]. As the voltage increases toward the saturation level, the overvoltage relay picks up and blocks the differential relay from operating. Should an internal fault occur during this overexcitation condition, the Sudden Pressure Relay is used to detect and isolate the PAR. With the advent of microprocessor based differential relays, flexibility may exist to steer the differential algorithm with voltage measurements.

13.0 Matrix of Fault Locations seen by Different Protection

13.1 **Fault Types and Protective Devices**

The types of faults, which can occur in phase-angle regulating transformers are similar to those which, occur in conventional transformers.

- winding to ground
- winding to winding (phase-phase)
- windings to winding (primary-secondary)
- turn-to-turn
- tap-changer faults

Also as with conventional transformers, it is generally not possible to calculate the current magnitudes for each fault type because there is insufficient information about the internal construction of the transformer to evaluate the apparent leakage reactance for each fault location. Therefore, the normal protection practice is to provide protection, which is as sensitive as practical consistent with adequate security from false fault signals caused by inrush, ratio changes, or CT errors.

13.2 **Relaying Function**

The principal relaying functions available for the protection of transformers are:

1. **Pressure Relays (ANSI Device 63)** These detect internal faults in transformer windings immersed in oil by sensing changes in the pressure of the oil or the accumulation of gases caused by burning of the insulation by a fault arc.
2. **Ratio-Differential Relays (ANSI Device 87)** Also called transformer-differential relays, these are differential relays with two or more input circuits and are provided with restraining functions to prevent misoperation due to ratio errors and exciting inrush current in the transformers. Typically one three-phase, or three single-phase, relays provide an overall protection for all windings of a conventional transformer. For a phase-angle regulating transformer, they are typically used only to protect a subpart of the transformer. Herein they are referred to as 87T to differentiate them from true differential relays, 87B.
3. **Differential Relays (ANSI Device 87)** These are single-input relays intended for use with paralleled current transformers to provide protection for a zone into which the sum of the currents should always be zero when there is no fault in the zone. Typically these are high-impedance relays intended for bus protection, but other types have been used. In this section, they are referred to as Device 87B to differentiate them from ratio-differential relays, 87T. Compared to ratio-differential relays for transformer protection, they have the following characteristics.
   - greater sensitivity and higher speed
   - protection limited to one winding
   - no protection for turn-to-turn faults within a winding
4. **Neutral Overcurrent Relays (ANSI Device 51N)** When phase-angle regulating transformers have a wye-grounded winding,

neutral overcurrent relays are often used to provide additional back-up protection for faults within the transformer. These relays are actually a form of balance protection which takes advantage of the fact that the neutral current is nearly zero when there is no fault in the transformer, but may increase sharply when one phase winding suffers a fault. Device 51N may also provide significant protection for open-phase conditions, such as a tap-changer contact failure, which are not sensed by other protection.

A careful evaluation of the currents seen by 51N relays during external ground faults or transformer energizing is necessary to be sure that no unwanted trips will occur. The settings necessary to avoid false operations may significantly decrease the speed and sensitivity of this protection.

Application Example

Figure 26 shows an example of protection for the classic phase-angle regulator design using separate series and exciting transformers.

Devices 51N1 and 51N2 are neutral overcurrent relays for the exciting transformer primary

and secondary neutrals, respectively. Devices 63E and 63S are the pressure relays for the exciting and series unit transformer tanks.

Device 87B is a single-input differential relay of the high-impedance type. Its zone consists of the series and exciting transformers' primary windings which are electrically connected at the center tap of the series primary. Its three CTs monitor all inputs to the zone, providing a true differential protection.

Device 87T is a three-input ratio-differential relay for the series transformer. Its ratio settings are determined by the ratio of the series transformer which has a constant value regardless of the tap position of the phase-angle regulator. The exciting transformer is not provided with a ratio-differential relay because its ratio varies widely depending on the tap position. Note that the polarities of the CTs for 87T on the series winding are such that through current does not sum to zero at the relay; instead it enters the relay twice. This is done in order that the relay can provide protection even if the phase angle regulator is energized from only one side. The secondary side CTs of 87T are connected in delta to accommodate the phase shift introduced by the delta connection of the series transformer secondary winding.

The table below shows the protection afforded by the various relays. “P” indicates that this device provides the primary (most sensitive) protection for this fault type. “B” indicates back-up. Protection designated “B” may or may not be slower or less sensitive than the “P” protection.

Fault Location	Series Primary	Series Secondary	Exciting Primary	Exciting Sec.
Winding-Ground	P:87B B:87T, 63S, 51N1	P:63S B:87T, 51N2	P:87B B:63E	P:63E B:87T, 51N2
Winding-Winding	P:87B B:87T, 63S	P:63S; B:87T	P:87B B:63E	P:63E B:87T
Turn-to-Turn	P:63S B:87T	P:63S B:87T	P:63E B:51N1	P:63E B:51N2

Relays other than those listed for a particular fault may also have a tendency to operate. The sensitivity of 87T and 51N2 for faults in the secondary of either transformer is variable depending on the tap changer position.

14. Operating Procedures for Phase Angle Regulating Transformers

The Phase Angle Regulating Transformers (PARs) may be switched in and out of service while the lines remain energized. In order to perform this switching, the regulators need to be adjusted to the neutral or Tap “0” position. After adjusting the taps, it is important to check the tap indicators at the regulator and control panels.

Each regulator tap changer must be regulated alternately to keep tap positions of parallel transformers no more than one tap apart until the final tap position is reached. Schemes exist where SCADA will have group control of the tap changers to guarantee that parallel transformers are always on the same tap. Simultaneous adjustment to tap settings is a major operating concern.

Another operating concern deals with switching procedures when it comes to energizing a line with PARs. Transient switching studies, to address overvoltage concerns, are sometimes required to determine the operating restrictions when energizing a line with PARs.

The PARs are designed so that they can be bypassed via a circuit switchers. The general procedure is to bypass only under emergency conditions. Once again, prior to bypassing a PAR with a circuit switchers, the regulator taps must be adjusted to the neutral position.

ANNEX A

Sample Calculations of Differential Protection for Conventional PAR

- PAR is rated at 240/320/400 MVA OA/FA/FA 230 kV, 3 phase. [7]
- Angle variation is - 40 to +40 degrees
- Series unit is rated 91.41/66.96 KV.
- Exciting unit is rated 230/ 38.66 kV.

Primary differential relaying system shown in Figure 27 can be set as follows:Maximum loading current =

$400 \text{ X } 10^6 / \sqrt{3}\ 230 \text{ x} 10^3 = 1004 \text{ A}$

CT ratio should be 200/ 1 or higher if CT's are connected in wye

CT ratio should be 200 x / $\sqrt{3}$ /1or higher if CT's are connected in delta

A ratio of 1200/5 or 2000/ 5 can be selected.

Since $I_{Source} = I_{load} + I_{exciting}$

Therefore, all CT ratios should be either1200/ 5 or 2000/ 5

Differential relay taps can be set at minimum to provide more sensitivity. For electromechanical differential relay, a tap of 2.9 A can be selected.

- Secondary differential relaying system shown in Figure 28 can be set as follows:

  PAR should be first analyzed at its neutral tap position

  Since primary source and load side CT ratios are chosen to be 2000/5 (400/1).

  The series unit turns ratio K = 344 turns/ 252 turns = 91410 V/ 66960 V =1.365

  Therefore the ideal secondary lead CT ratio is:

$$n_2 = K /2 \ (n_1)$$

$n_1 = 400/1$
$K = 1.365$
$\Rightarrow n_2 = 273/1$ or $1365/5$

With I_{sec} lead $= 1004 * K * \sqrt{3} = 2373.6$ A

This CT ratio would result in the following current ratio:

Current ratio = $\{(1004 * \sqrt{3})/400) + (1004 \sqrt{3}) / 400)\}/(2373.6/273) = 1$

A current ratio of one (1) will allow all differential relay tap settings to be set at the same value. The non-standard ratio of 273/ 1 would result in a current of

$2373.6/273 = 8.7$ A

The PAR was designed with a CT ratio of 2750/ 5 resulting in a current ratio of:

Current ratio = $\{(1004/\sqrt{3} / 400 + 1004/\sqrt{3} / 400) / 2373.6/550\} = 2.0146$

If differential relay taps of 8.7 amps were chosen for the series unit primary source and load restraint windings, an exciting unit secondary lead restraint winding tap of 8.7/ 2.0146 = 4.318 would result in a Zero mismatch. The nearest available relay tap is 4.2 Amps.

Mismatch = { (current ratio) - (tap ratio) }/ smallest of the two

$M = \{(2.0146 - 2.0714)/(2.0146)\} \times 100 = 2.8\,\% < 5\%$ O.K.

Figure 29 illustrates the design of an auxiliary current transformer to balance the PAR secondary differential relaying without the use of the ampere-turns coupling and current ratio concepts. The differential relaying system is balanced using an additional auxiliary current transformers specified at 10/ 5. The design shown in Figure 27 avoids the use of auxiliary CTs and therefore is superior and is recommended.

ANNEX B

Flexible AC Transmission System (FACTS) Devices

FACTS allow the transmission system to be the active element. It provides the flexibility to change power flows and improve stability for dynamic, integrated power systems. FACTS incorporate shunt and/or series devices that can vary the power flow by changing line impedance, phase angle (between line ends) and voltage magnitude at the station bus.

FACTS devices typically utilize switched thyristor power controllers to control particular system parameters. Examples of FACTS device applications include: Series Capacitors, Static Var Compensators, Phase Angle Regulators, Static Synchronous Series Compensators, and Unified Power Flow Controllers (UPFC). The UPFC regulate line impedance, voltage, and phase angle via a voltage-source, injection in series with the line. The UPFC is roughly equivalent in function to a thyristor-controlled tap-changing transformer for phase angle control together with a static var compensator for reactive control. It is configured with a shunt element (s) for VAR/ voltage support and a series element for power flow/ phase shift. The series transformer (static synchronous series compensator) provides the controllable series compensation and incorporates the phase angle regulation capability. It injects a voltage with controllable magnitude and phase angle in series with the line, instantaneously if required. The real and reactive power are exchanged with the AC system. The conventional phase shifter cannot generate reactive power, which has to be supplied by the line or a separate VAR source. The thyristor controlled phase angle regulator is functionally the same as the mechanically controlled regulator. The UPFC is the most similar, of FACTS devices, to the PAR.

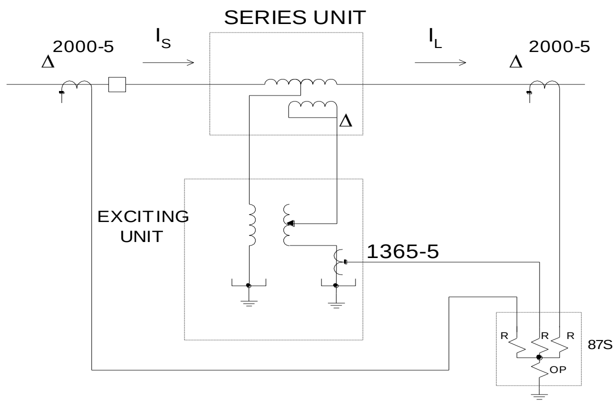
Protection of Flexible AC Transmission System(FACTS) Devices

The UPFC is protected using conventional transformer and bus relaying methods. Dual transformer differential protection systems and pressure relays are used for the protection of the series and shunt transformer. Bus differential relaying, overcurrent relays and over voltage relays responding to zero-sequence voltage are also used. Microprocessor distance relays can be used to protect the line which include the series transformer.

The UPFC is physically and functionally different than a basic mechanically controlled PAR. The UPFC incorporates somewhat different protection requirements. Its unique differential protection schemes involve different considerations than the PAR. Therefore, details on UPFC protection schemes and considerations will not be included in this document

ANNEX C

Tabular Description of PAR Currents at Various Tap Positions



The table below shows the excitation transformer secondary winding currents, and CT currents which facilitates setting the 87S type protection

	Exciting Unit CT Ratio 1365* 5A		**S1 CT Ratio 2000 5A Delta**		**L1 CT Ratio 2000 5A Delta**			
	Exciting Unit CT Secondary Current		**S1 CT Secondary Current**		**L1 CT Secondary Current**			
Tap Pos.	**IB - IC CURRENT**		**IB - IC CURRENT**		**IB - IC CURRENT**		**A phase relay difference current**	
	real	**imag**	**real**	**imag**	**real**	**imag**	**real**	**imag**
33	2.798538	-7.63497609	1.705E-15	-4.33013	2.8	-3.3	-0.00016	0.000444
32	2.661876	-7.74601848	1.705E-15	-4.33013	2.7	-3.4	-0.00015	0.00045
31	2.518969	-7.85273248	1.705E-15	-4.33013	2.5	-3.5	-0.00015	0.000457
30	2.369259	-7.95512625	1.705E-15	-4.33013	2.4	-3.6	-0.00014	0.000463
29	2.213443	-8.05232045	1.705E-15	-4.33013	2.2	-3.7	-0.00013	0.000468
28	2.052316	-8.14353749	1.705E-15	-4.33013	2.1	-3.8	-0.00012	0.000473
27	1.885396	-8.22877109	1.705E-15	-4.33013	1.9	-3.9	-0.00011	0.000478
26	1.714944	-8.30670211	1.705E-15	-4.33013	1.7	-4.0	-1E-04	0.000483
25	1.535628	-8.37933267	1.705E-15	-4.33013	1.5	-4.0	-8.9E-05	0.000487
24	1.353964	-8.44364523	1.705E-15	-4.33013	1.4	-4.1	-7.9E-05	0.000491
23	1.168164	-8.5002197	1.705E-15	-4.33013	1.2	-4.2	-6.8E-05	0.000494
22	0.979278	-8.54857698	1.705E-15	-4.33013	1.0	-4.2	-5.7E-05	0.000497
21	0.786919	-8.58865759	1.705E-15	-4.33013	0.8	-4.3	-4.6E-05	0.000499
20	0.592192	-8.62007442	1.705E-15	-4.33013	0.6	-4.3	-3.4E-05	0.000501
19	0.396237	-8.64259132	1.705E-15	-4.33013	0.4	-4.3	-2.3E-05	0.000502
18	0.197949	-8.65623091	1.705E-15	-4.33013	0.2	-4.3	-1.2E-05	0.000503
17	3.33E-15	-8.66075757	1.705E-15	-4.33013	0.0	-4.3	7.91E-17	0.000504

Notes:

* 1365 - 5 ratio is the equvalent ratio for the auxilary and main cts choosen for the exciting tranformer secondary winding in figure 29.

Annex D

Limitations of Overall Differential Protection

Overall differential protection, when applied to a PAR transformer using only source and load side ct's as shown in Figure 23, has certain limitations. These must be carefully studied to avoid misoperation of the protection on load or through-fault conditions.

Balanced Conditions

For balanced load or three-phase fault conditions, the phase shift of the PAR transformer causes a error current to appear in the overall differential relay. This error current is proportional to the through current and varies with the phase shift. The magnitude of the error current is:

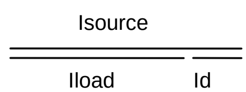
$$I_d = I_{thru} \cdot 2 \cdot \sin\left(\frac{\theta}{2}\right)$$

where θ is the angle between the source and load side currents and I_{thru} is the magnitude of the source or load current.

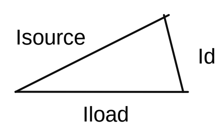
The table at the right gives the per-unit magnitude of I_d for typical phase shifts:

Note that at 30 degrees phase shift the differential current is more than 50% of the through current and at 60 degrees it is equal to the through current. This indicates that a very strong restraint characteristic (high slope) is required to prevent misoperation, especially if the maximum phase shift is large.

θ	$\frac{I_d}{I_{thru}}$
0	0.00
10	0.17
20	0.35
30	0.52
40	0.68
50	0.85
60	1.00



Ratio Difference



Phase Angle Difference

Another aspect of the differential current is its phase angle. When the source and load currents are out of phase, the difference current is approximately 90 degrees out of phase with either the source or load side currents. This situation is in contrast to a ratio difference which causes a differential current which is in phase with the source and load side currents.

With some types of differential relays, the restraint produced by the source and load currents may be less effective when it is out of phase with the differential current. This needs to be checked before assuming that a relay’s published restraint characteristics are applicable to out-of-phase current conditions.

Unbalanced Currents

PAR transformers operate by means of mixing currents and voltages from the three phases in order to produce an apparent phase shift. For single phase through currents, the PAR does not produce its rated phase shift; instead it produces a mixing of the single phase current into an unbalanced three-phase current condition. This effect can produce through-fault conditions in which an overall differential relay sees current in only one of its two input circuits, thus leaving it vulnerable to misoperation.

Unbalanced currents in phase shifters can be analyzed by means of symmetrical components:

- Positive sequence currents are shifted in accordance with the set phase angle shift of the PAR.
- Negative sequence currents are shifted *opposite* to the set phase shift.
- Zero-sequence currents are not shifted at all.

For example, the table below shows the source and load side currents and differential current for an assumed bc phase-phase fault, with no load current, on the load side of a PAR, for various phase angle shifts. Fault current on the load side is assumed to be Ia=0, Ib = -Ic = 1.0 . Since this is a single-phase condition, all currents are either in phase or 180 degrees out of phase with the fault current, regardless of the PAR phase angle. Differential currents are calculated from IdA = IA - Ia, etc. Slope A is the apparent slope of the fault condition given by Slope A = IdA/0.5*(|Ia|+|IA|). Details of the calculation using

Differential Currents for b-c Load Side Through Fault

	Load Side			Source Side			Differential			Slope
Shift	**Ia**	**Ib**	**Ic**	**IA**	**IB**	**IC**	**|IdA|**	**|IdB|**	**|IdC|**	**A**
-60	0	1	-1	-1.000	1.000	0.000	1.000	0.000	1.000	200%
-50	0	1	-1	-0.885	1.085	-0.201	0.885	0.085	0.799	“
-40	0	1	-1	-0.742	1.137	-0.395	0.742	0.137	0.605	“
-30	0	1	-1	-0.577	1.155	-0.577	0.577	0.155	0.423	“
-20	0	1	-1	-0.395	1.137	-0.742	0.395	0.137	0.258	“
-10	0	1	-1	-0.201	1.085	-0.885	0.201	0.085	0.115	“
0	0	1	-1	0.00	1.000	-1.000	0.00	0.000	0.000	-
10	0	1	-1	0.201	0.885	-1.085	0.201	0.115	0.085	200%
20	0	1	-1	0.395	0.742	-1.137	0.395	0.258	0.137	“
30	0	1	-1	0.577	0.577	-1.155	0.577	0.423	0.155	“
40	0	1	-1	0.742	0.395	-1.137	0.742	0.605	0.137	“
50	0	1	-1	0.885	0.201	-1.085	0.885	0.799	0.085	“
60	0	1	-1	1.000	0.000	-1.000	1.000	1.000	0.000	“

symmetrical components are given in the spreadsheet at the end of this Annex.

Note that at ±30 degrees conditions are similar to those for a through phase-phase fault through an ordinary delta/wye transformer bank, i.e. the high current phase has twice the current and opposite sign to the other two phases. Connecting the overall differential ct’s in delta/wye configuration could correct the phase error for this one phase shift setting, but would have higher errors at some other phase shifts.

For all phase shifts except 0 degrees, there is A phase current on the source side of the phase-shifter but no corresponding “a” phase current on the load side. Thus an overall differential relay can be expected to operate whenever the A phase current reaches the relay’s minimum operating current. These results indicate that high slope settings (large effective restraint) are not sufficient to stabilize overall differential relays for certain types of through-fault conditions.

Phase-to-Ground Through Faults

Through faults to ground can be analyzed in a similar manner, following the rules for symmetrical component phase shifts as given above. The analysis is more complex and depends on the location of system positive and zero-sequence current sources, whether the differential CTs are wye or delta connected, and whether the PAR is itself a source of zero-sequence current. For PARs which are not a zero-sequence source, wye-connected CTs help to stabilize the overall differential protection for through faults to ground because the zero-sequence currents are not subject to phase shifting and thus contribute restraint without producing any differential curren

Bibliography

B1."Regulating Transformers in Power System Analysis" by: J.E. Hobson, W. A. Lewis, AIEE Transactions, May 1939

B2."Equivalent Circuit Impedance of Regulating Transformers" by: C. E. Clem, AIEE Transactions, May 1939

B3."The Phase Angle Regulating Transformer on the PSE&G System - application and relay protection" by: K. H. Chang and D. J. O'Neill, Pennsylvania Electric Association, February 1974

B4."Westinghouse shell form Phase Angle Regulating Transformers" by: L. S. McCormick, Pennsylvania Electric Association, February 1974

B5."Protective Relaying for Phase Angle Regulator" by: Hung Jen L1, Western Protective Relay Conference, October 1975

B6."Protection Aspects and Operating Experience of the Mississippi Power Company 500 kV Tie line to Gulf states utilities using two 230 kV 1000 MVA Delta Hexagonal phase shifters" by: W. J. Marsh, Jr. and H. S. Smith, 1985, Protective Relaying Conference Georgia Institute of Technology May 1985

B7."Nelway Substation phase shifting transformer protection" by: F. P. Plumptre, P. Eng Seventeenth Annual Western Protective Relay Conference October 1990

B8."Experience with Parallel EHV phase shifting transformers" by: J. Bladow, A. Montoya, IEEE/PES July 1991, Winter meeting

B9."Problems Protecting Phase-shifting Transformer" by: Peter E. Krause and C. S. Miller Transmission and Distribution, November 1991

B10."Phase Angle Regulating Transformer Protection" by: M. A. Ibrahim, F. P. Stacom, IEEE Transaction, Vol. 9, No. 1, January 1994

Figures

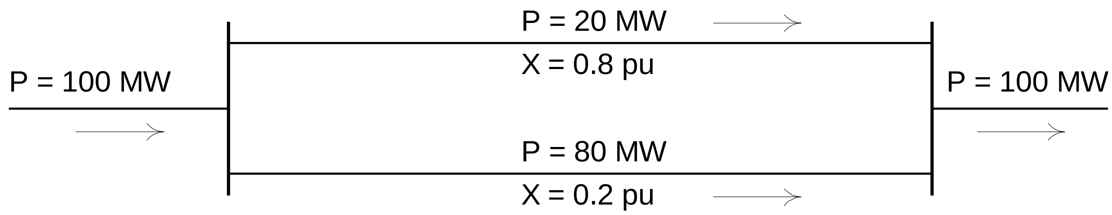


Figure 1 - Parallel Lines Free Flowing Flows

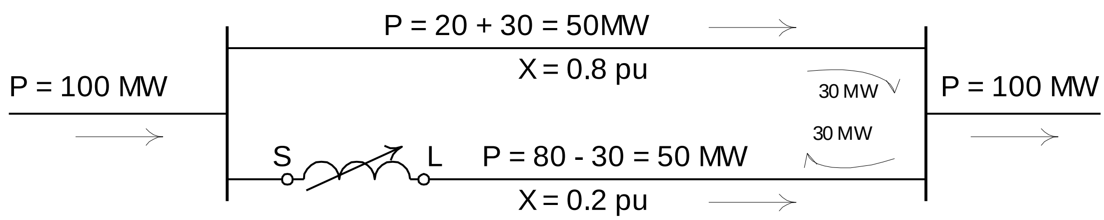


Figure 2 - Controlling of Flows using PAR

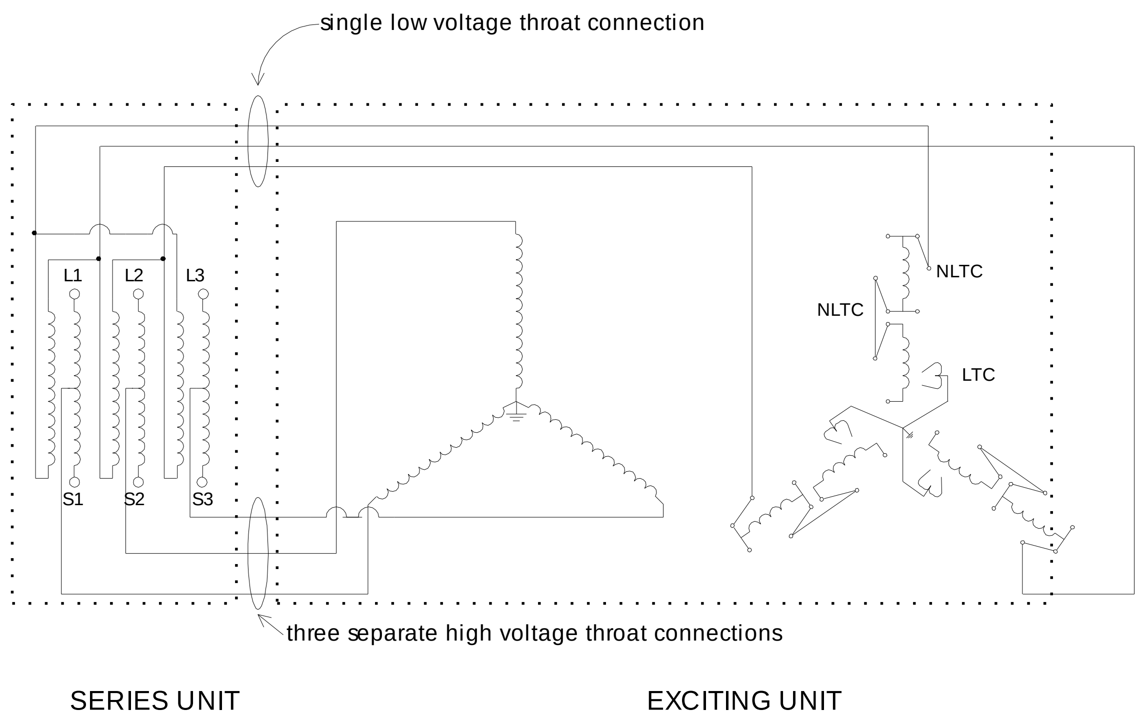
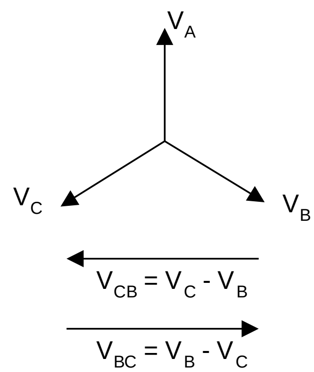
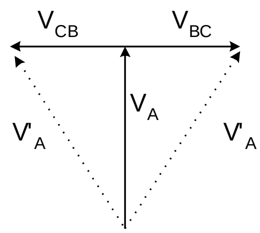


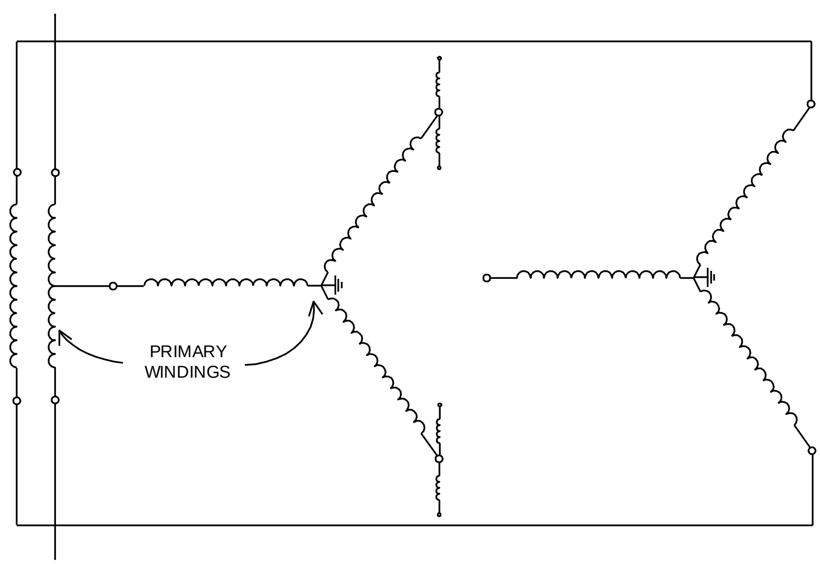
Figure 3 - Conventional PAR (Grounded Wye Exciting Transformer)



Qudrature voltage



V'_A due to quadrature voltage adding to V_A



Development of qudrature voltage within phase shifting transformer

Figure 4 - Development of quadrature voltage for ‘A’ phase

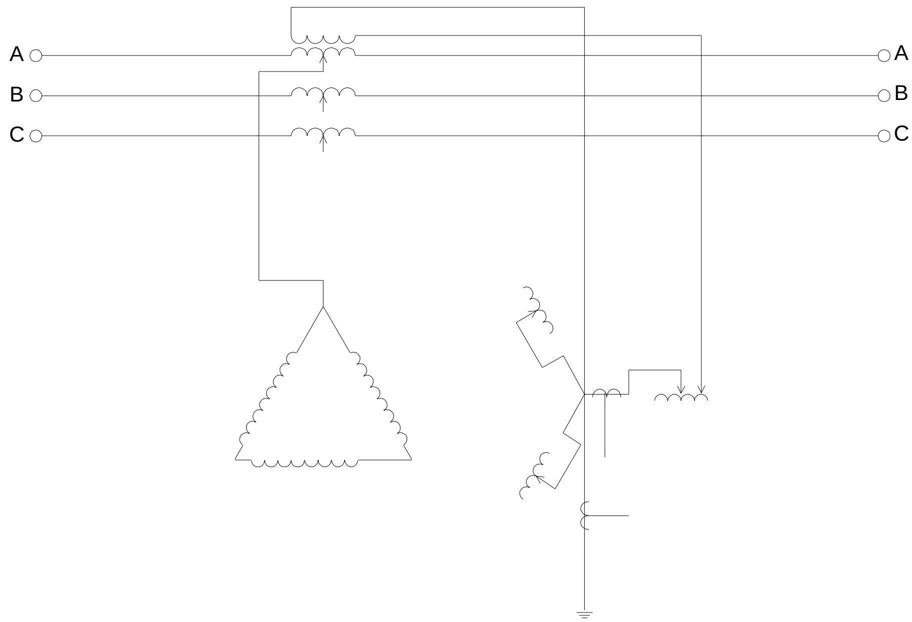
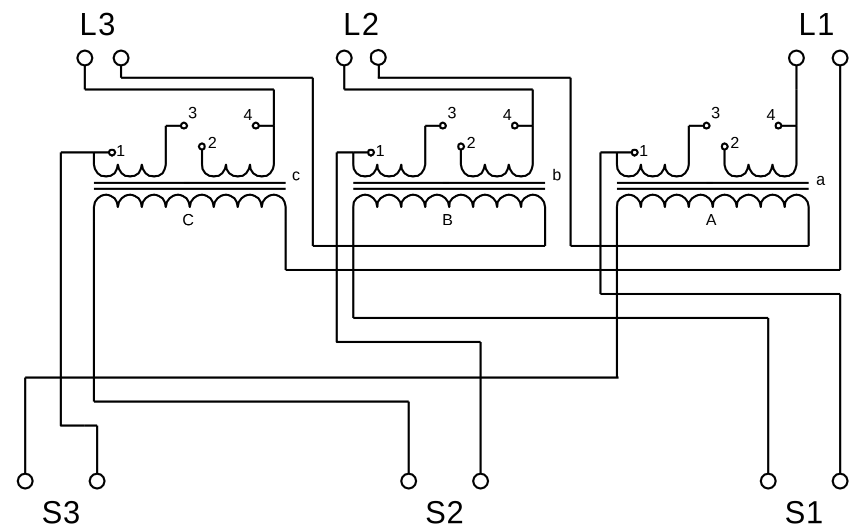
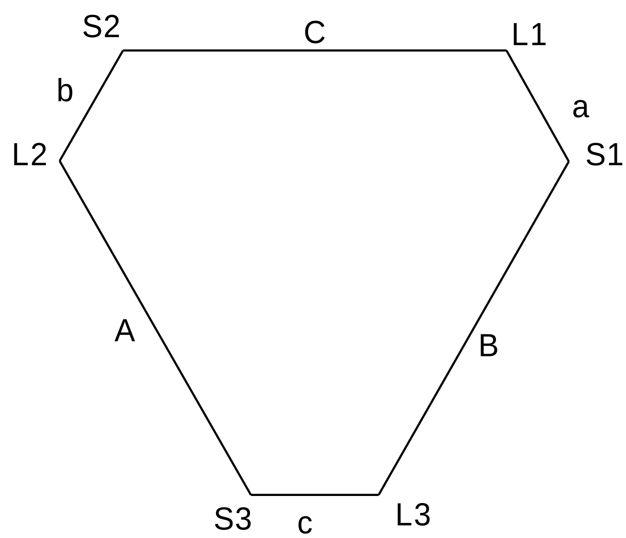


Figure 5 - PAR with delta/wye exciting unit



(a) Winding Connections



(b) Phasor Diagram

Figure 6 - Hexagonal design

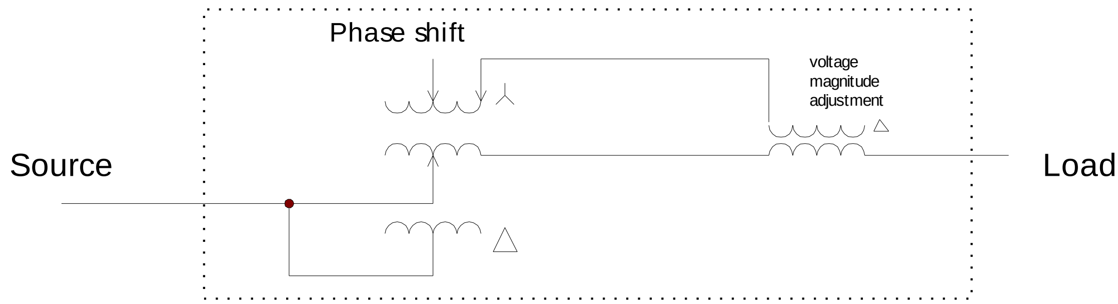


Figure 7 - One line diagram for single tank design

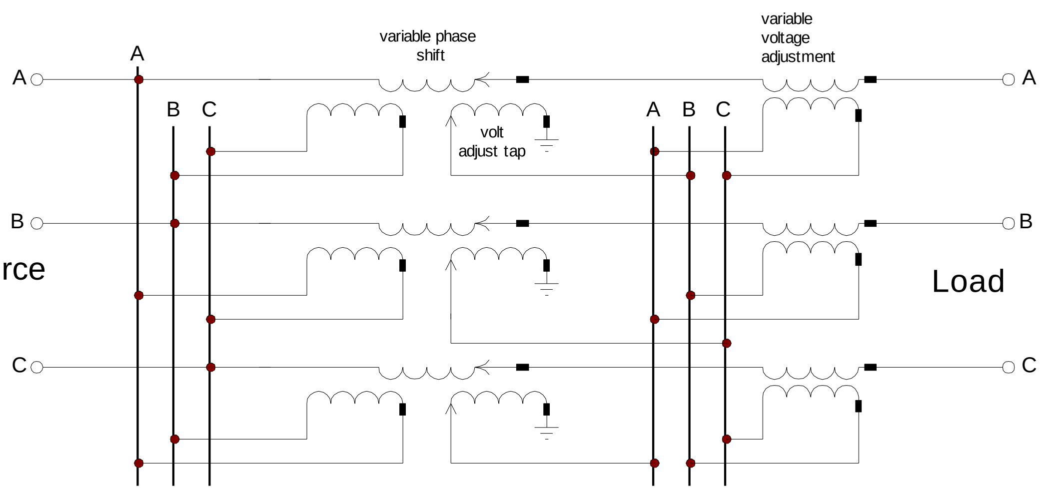
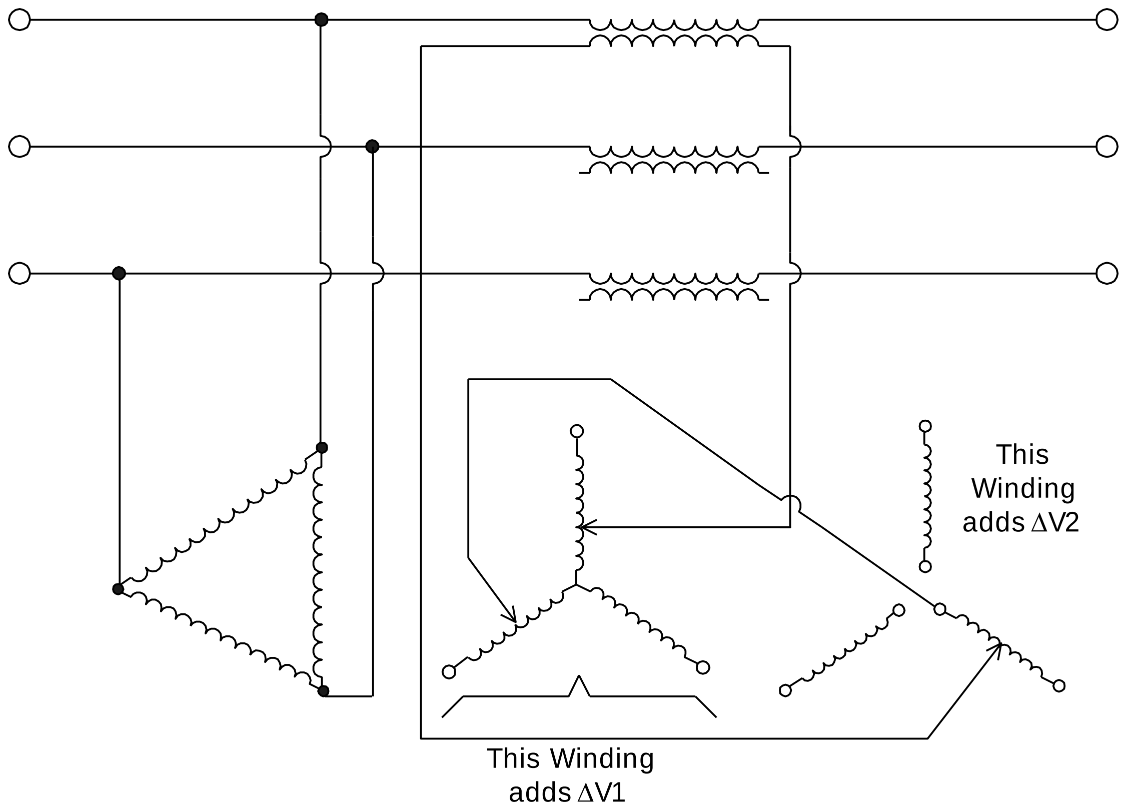
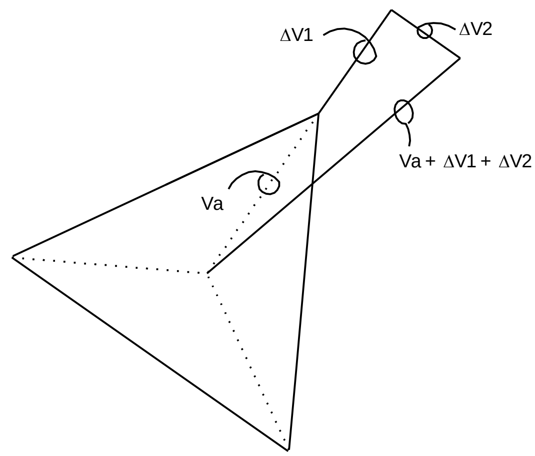


Figure 8 - Three line ac for single tank PAR design



(a) Connection Diagram



(b) Phasor Diagram

Figure 9 - Grounded wye with voltage magnitude control

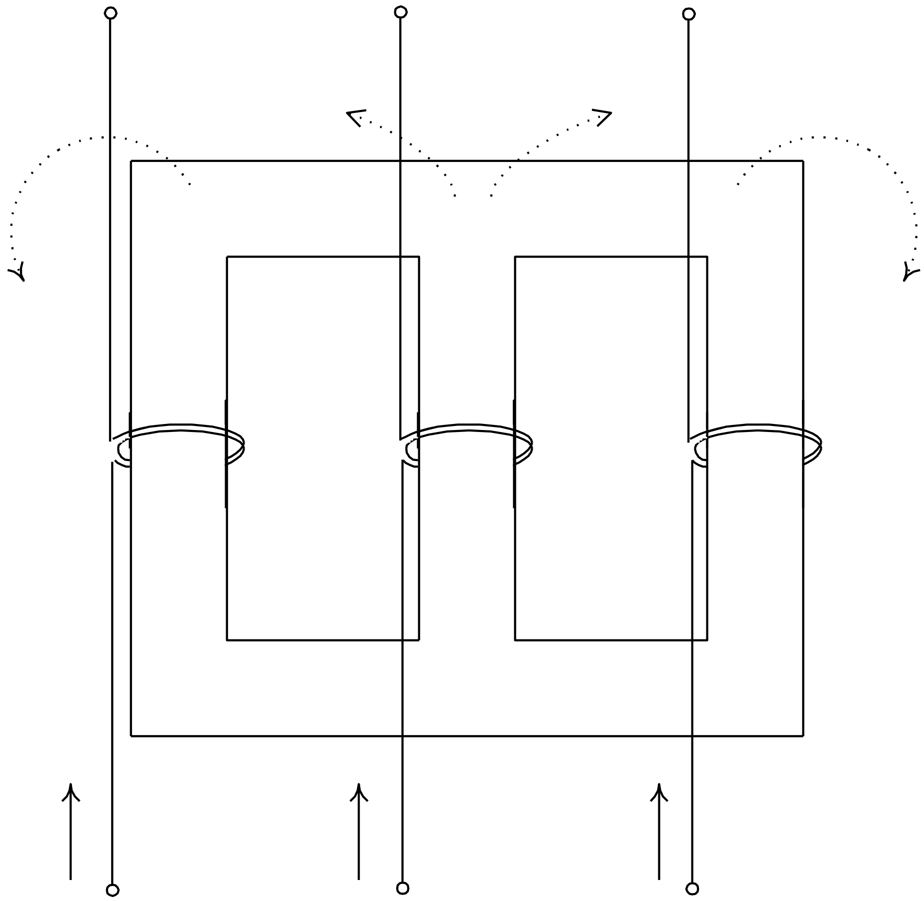


Figure 10 Three legged core PAR

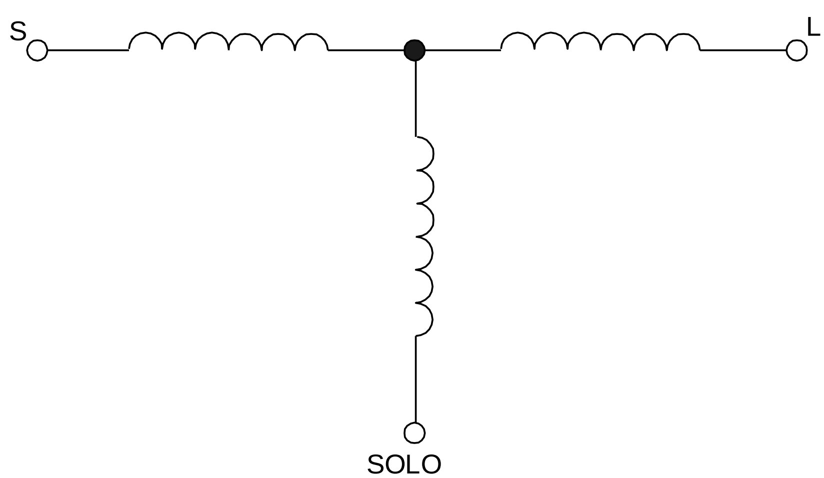


Figure 11 - Zero sequence equivalent impedance circuit

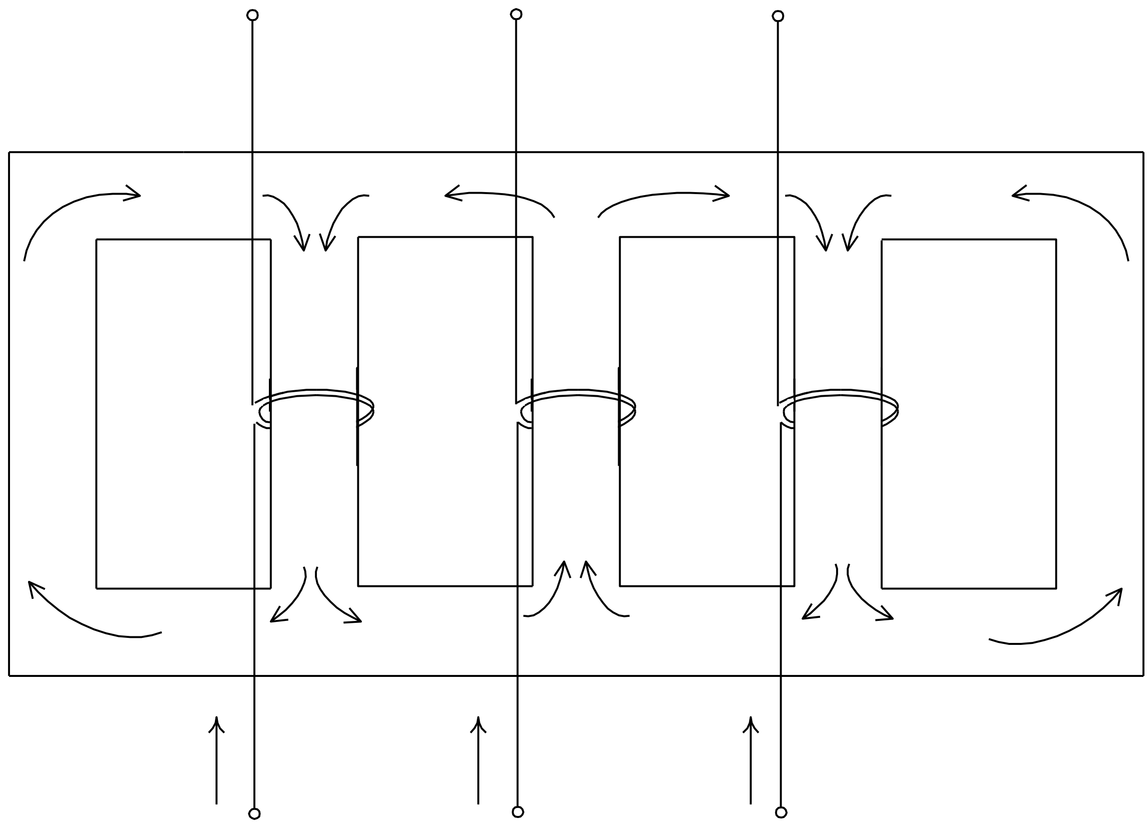
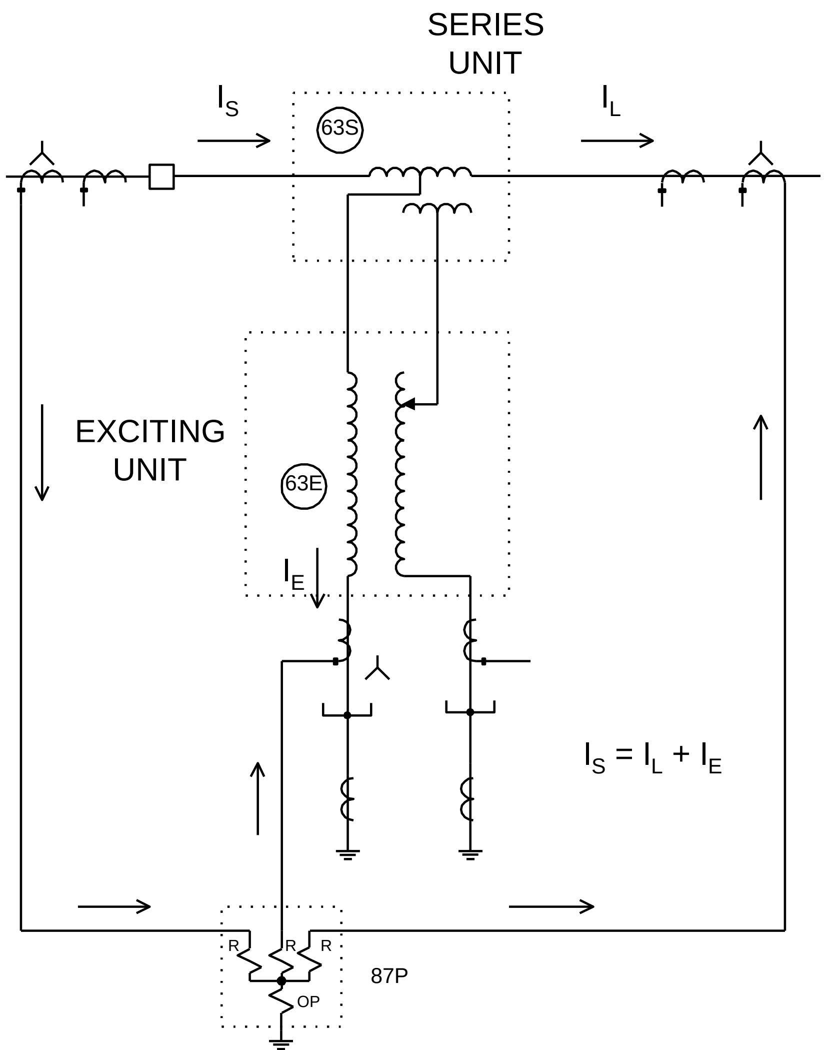


Figure 12 - Five legged core PAR

PHASE ANGLE REGULATOR



A.C. One line for primary differential relaying system

Figure 13 - CT connections

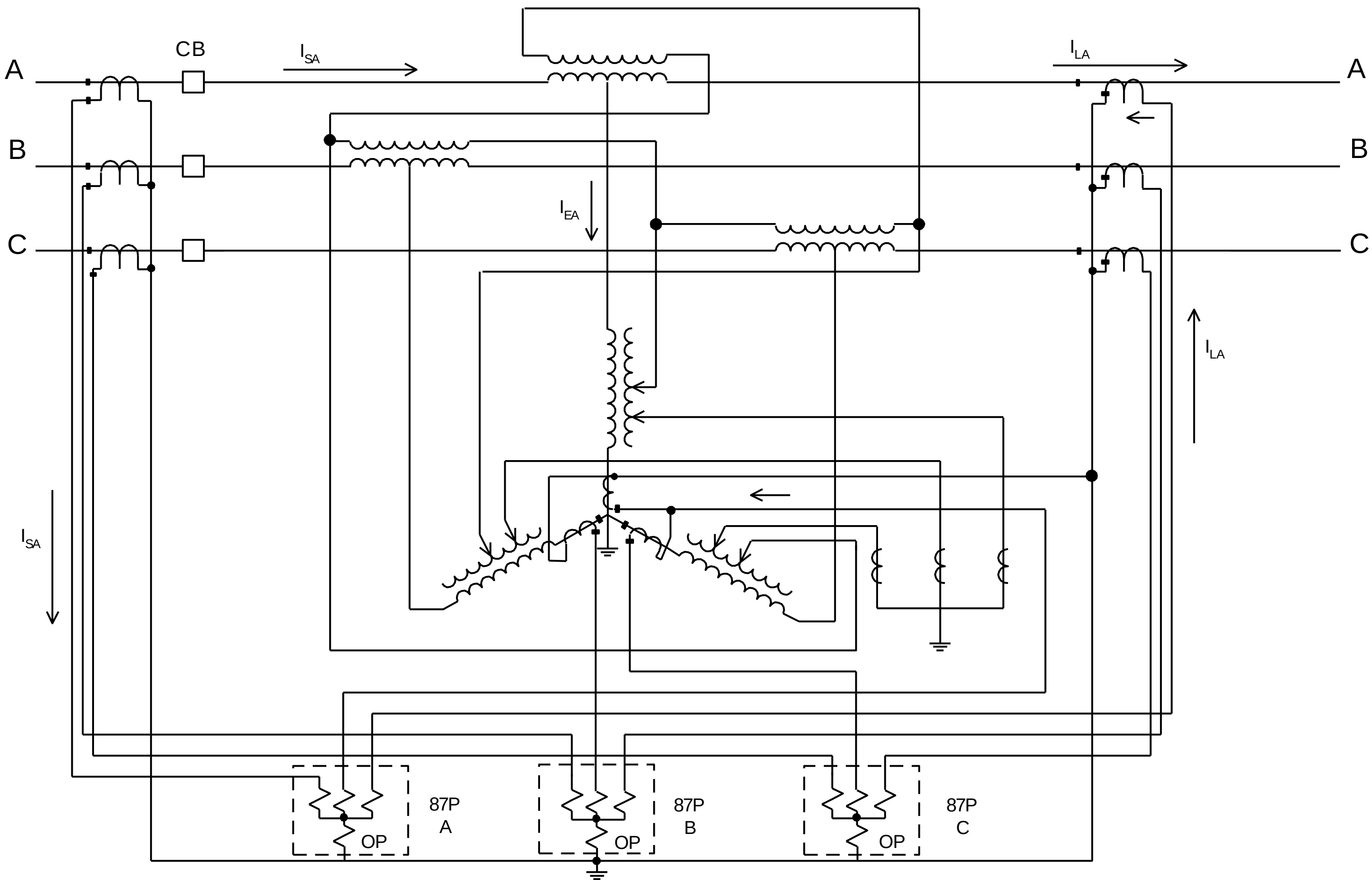


Figure 14 - 3 Line AC Connection for PAR primary differential relay

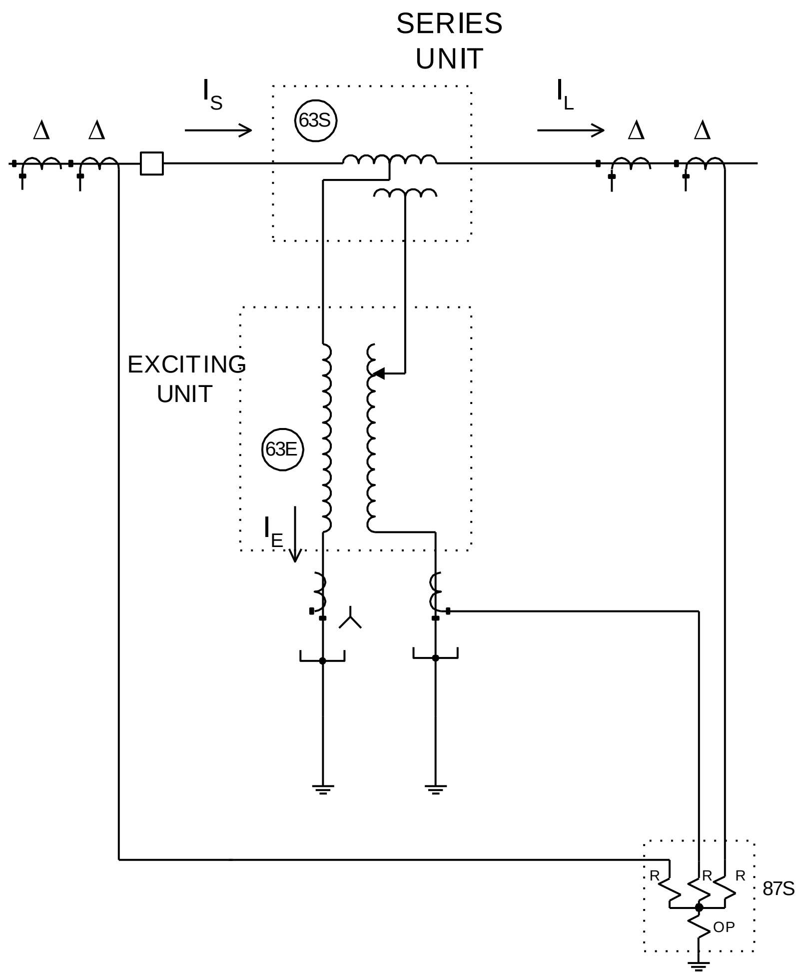


Figure 15 - AC one line for secondary differential relaying system

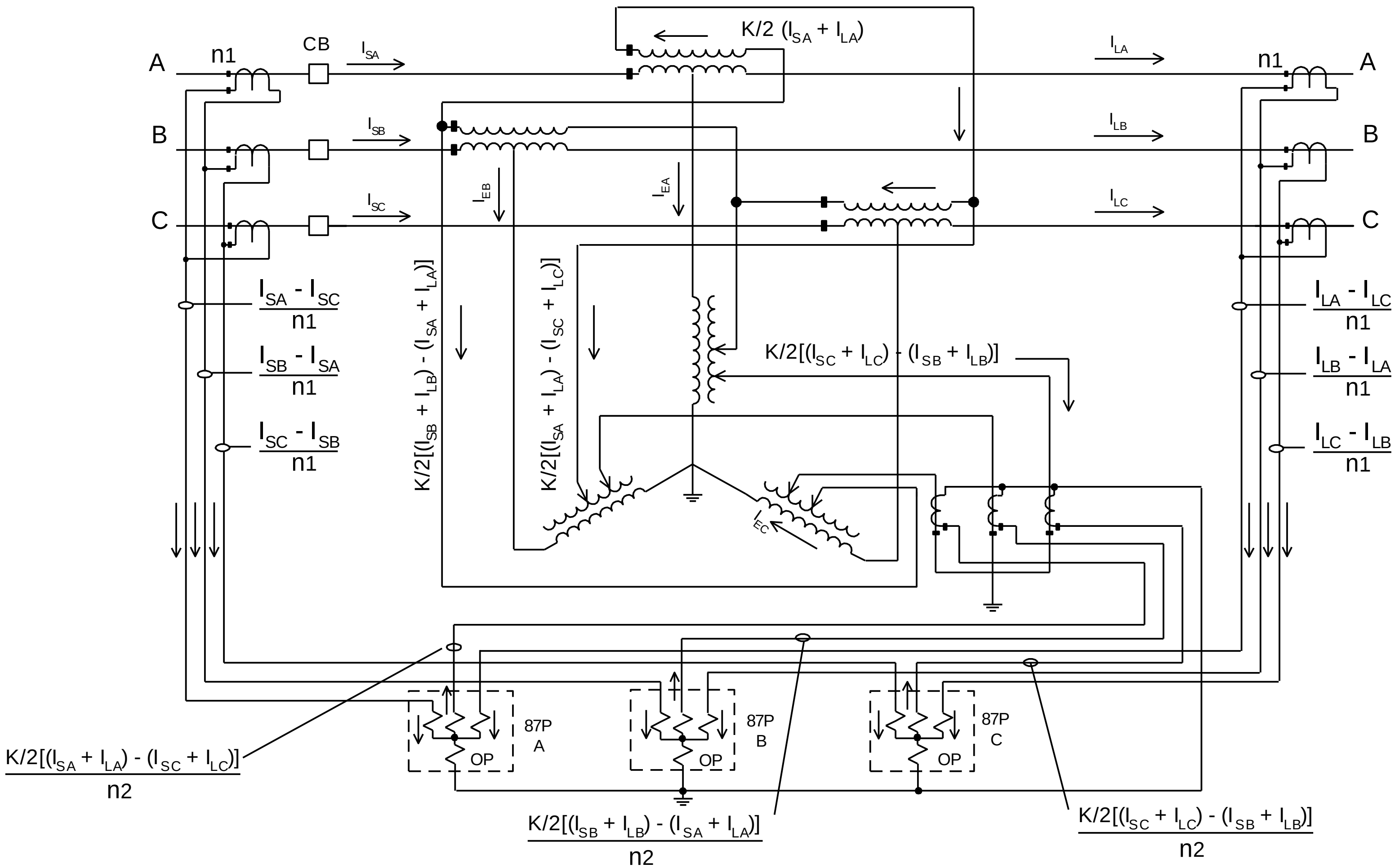


Figure 16 - 3 line ac connections for secondary differential relaying system

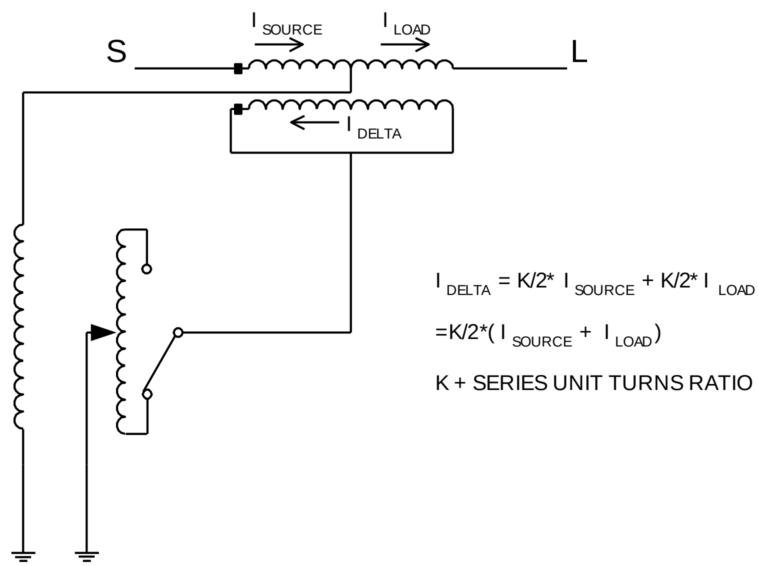


Figure 17 - Ampere turns coupling of series unit

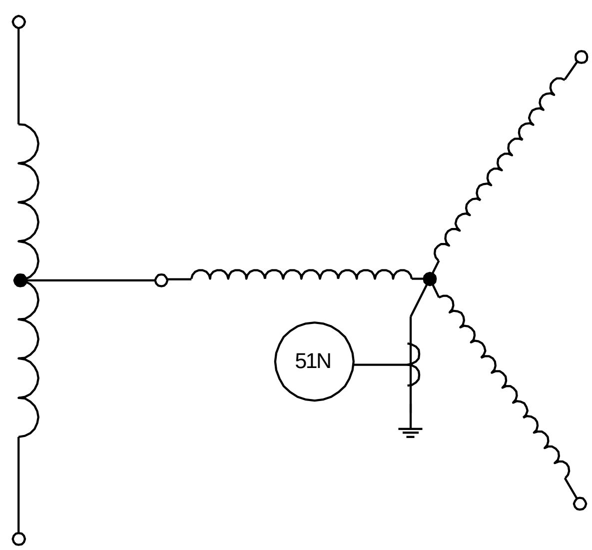


Figure 18 - Exciting unit primary protection

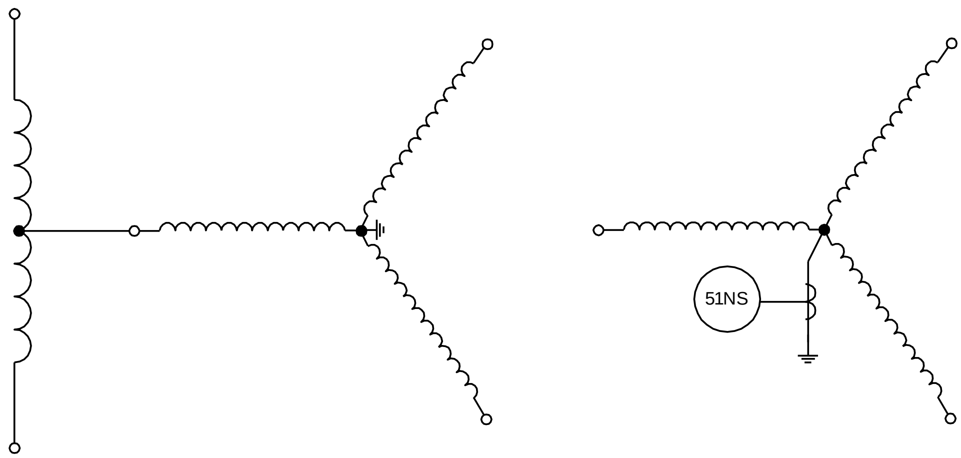


Figure 19 - Exciting unit secondary ground protection

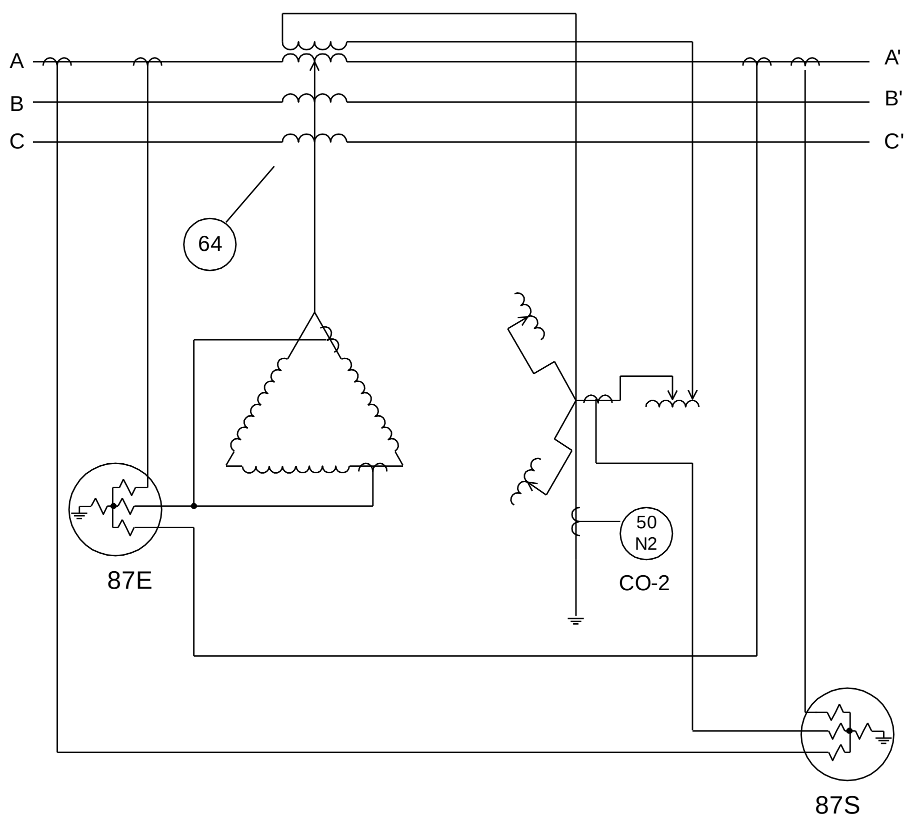


Figure 20 - PAR with delta/wye exciting unit

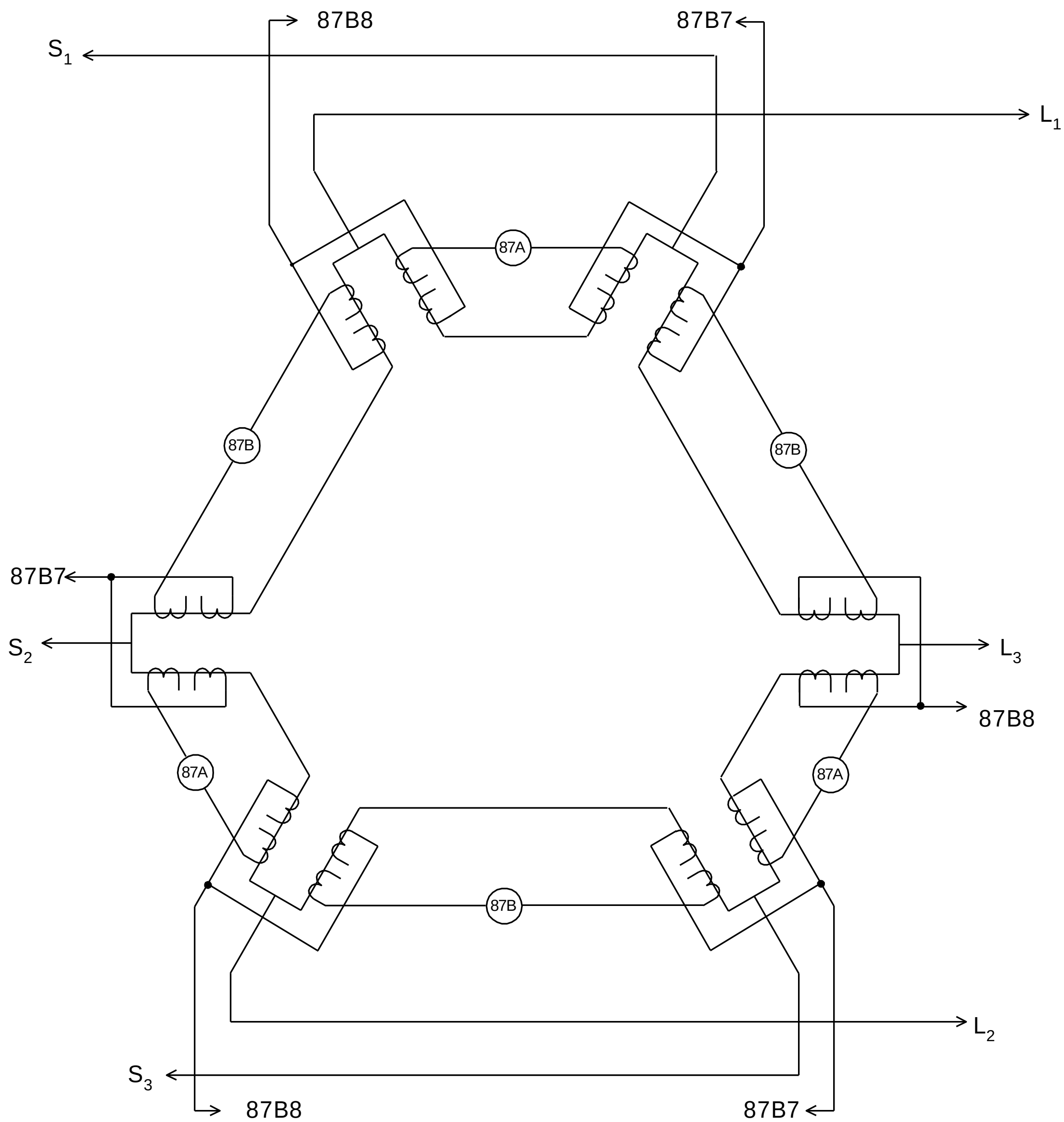


Figure 21 - Windings brought out to bushings

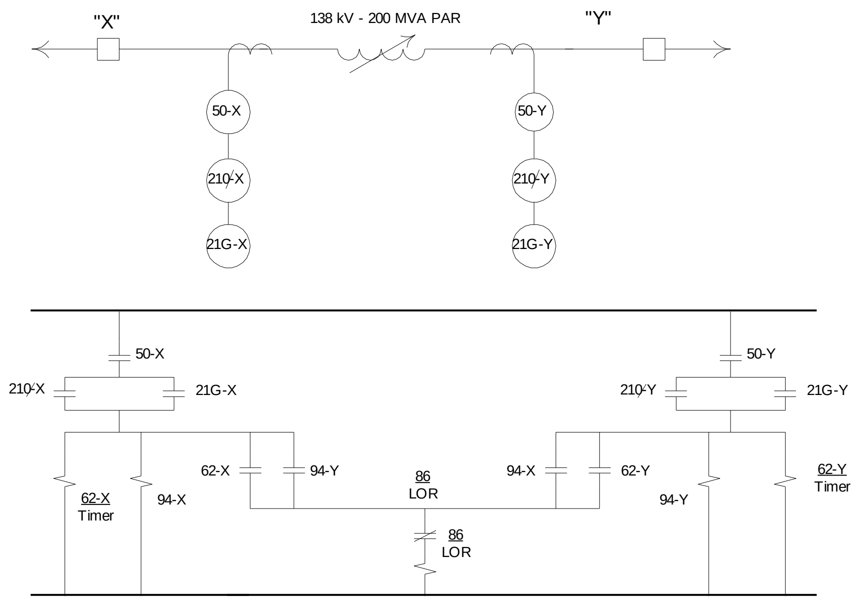


Figure 22 - Distance protection scheme for PAR

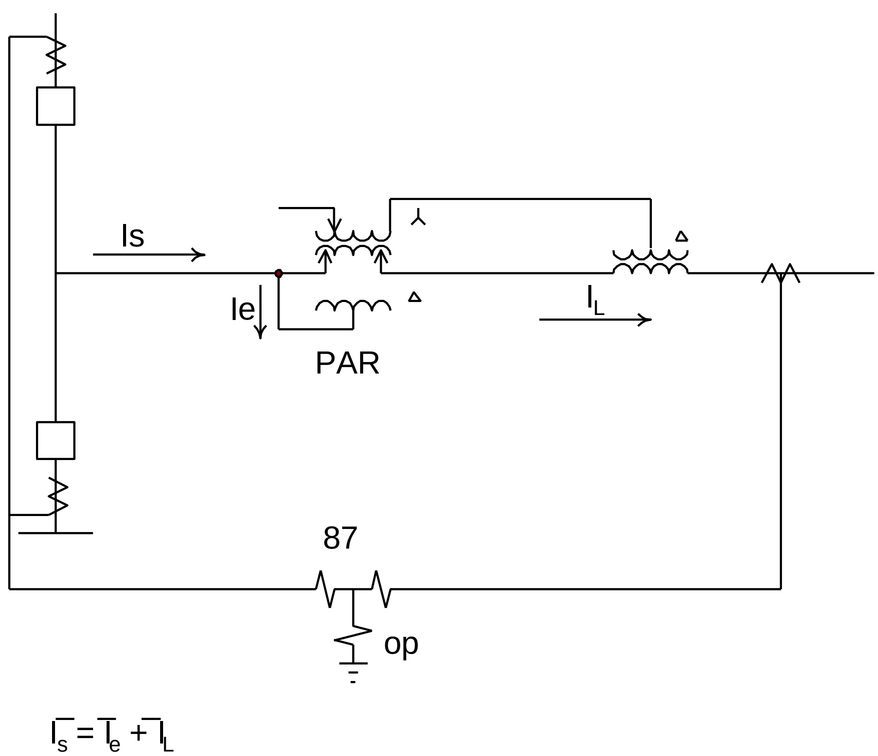


Figure 23 - Single tank PAR differential connection

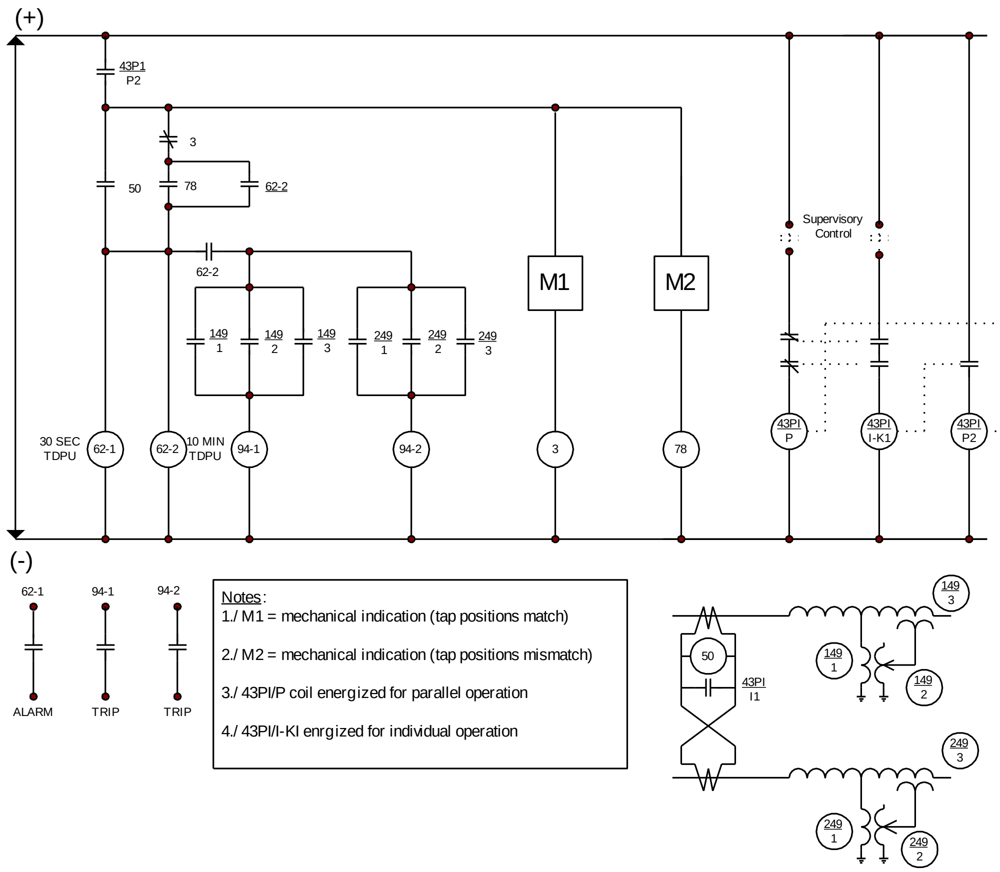
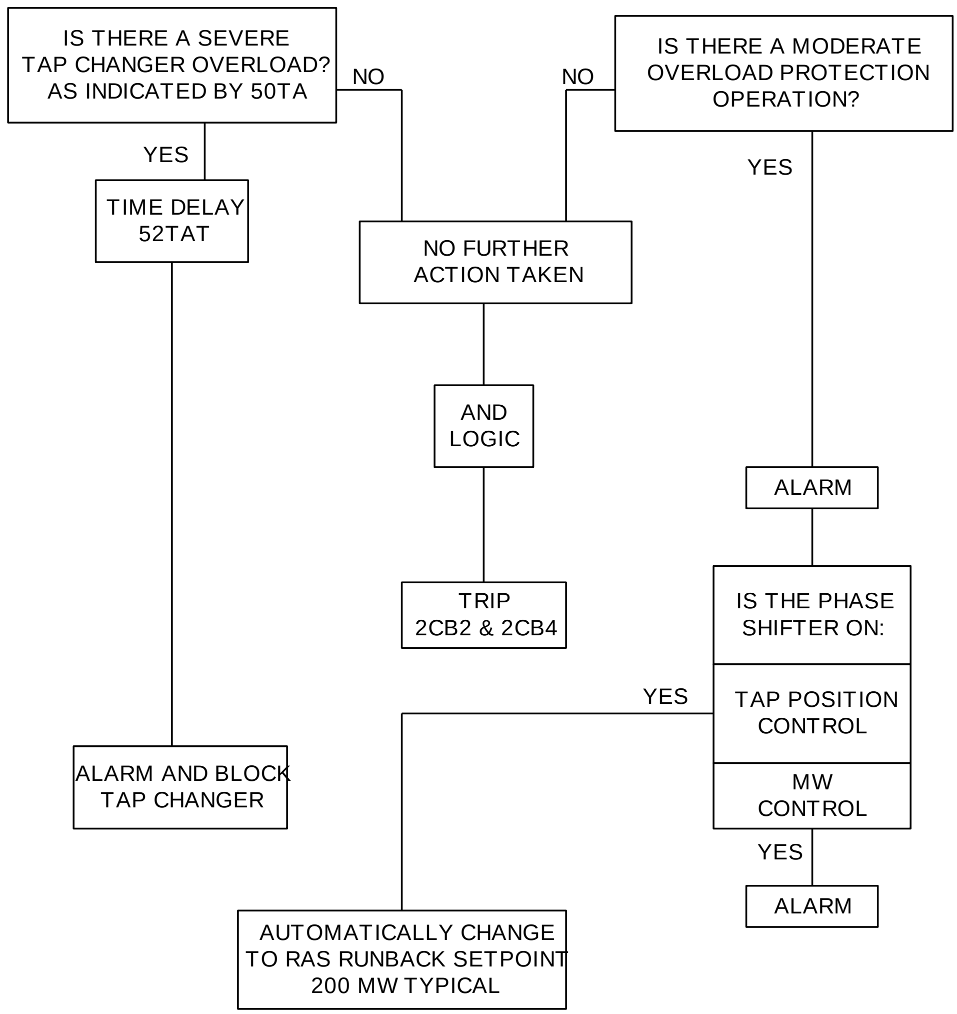


Figure 24 - PAR “out of step” protection

REMEDIAL ACTION SCHEME (RAS)
T0 LIMIT T2 TAP CHANGER OVERLOAD



NOTES:
1. Alarms are annunciated locally as well as sent to the control center

2. The relay settings and RAS runback setpoint are local manual adjustments at the substation. Once they have been optimized they will not be altered.

3. Normal MW setpoint is set remotely at the control center.

4. All functions are non-lockout

Figure 25 - Example remedial action scheme

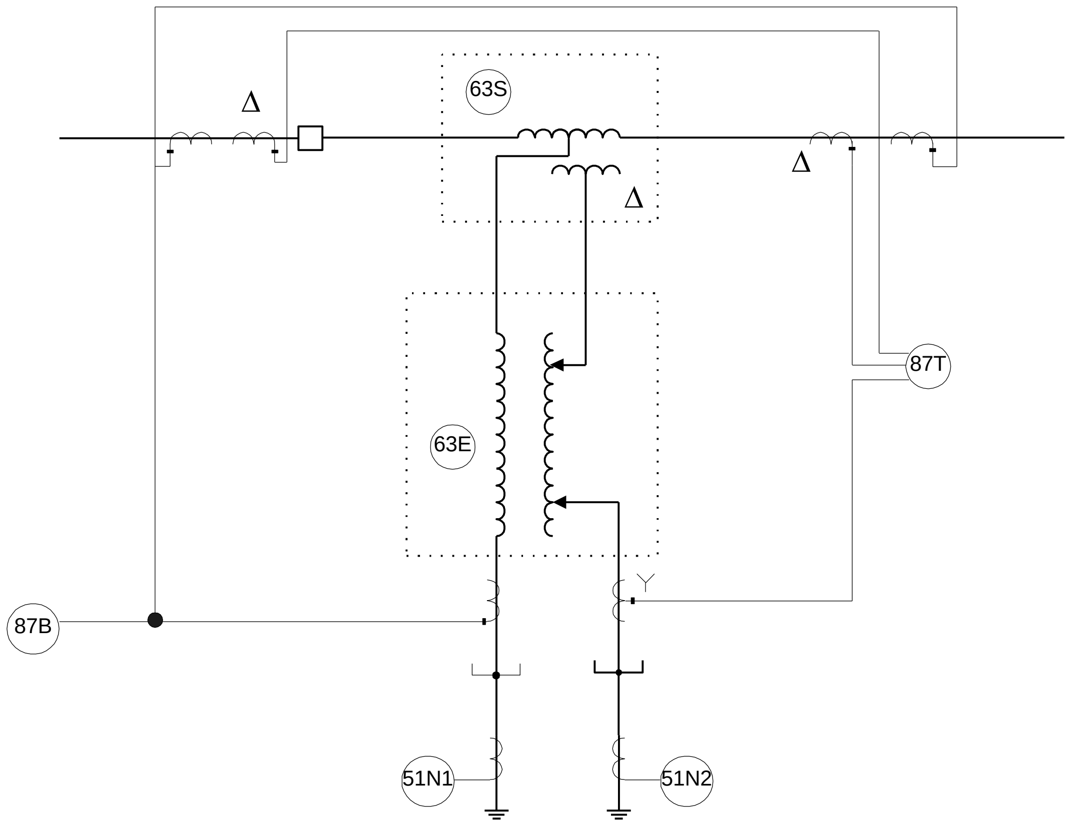


Figure 26 - Phase angle regulator

with series and exciting transformers, showing possible protection

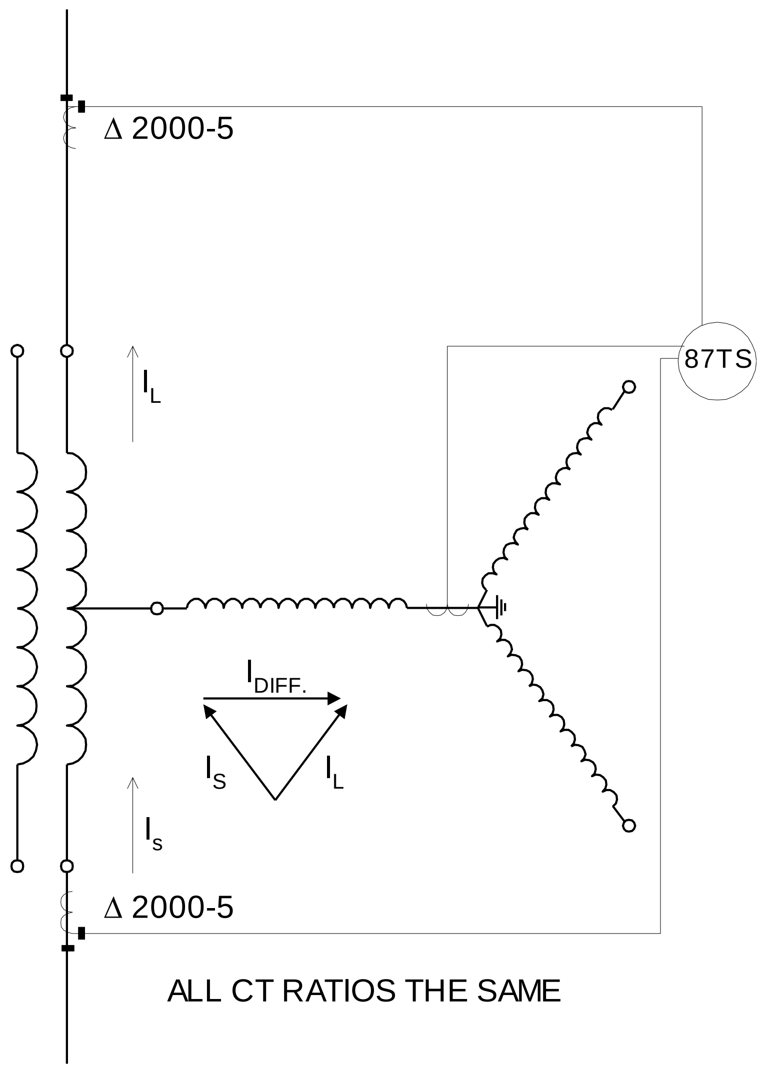


Figure 27 - Primary differential relaying for Annex 1

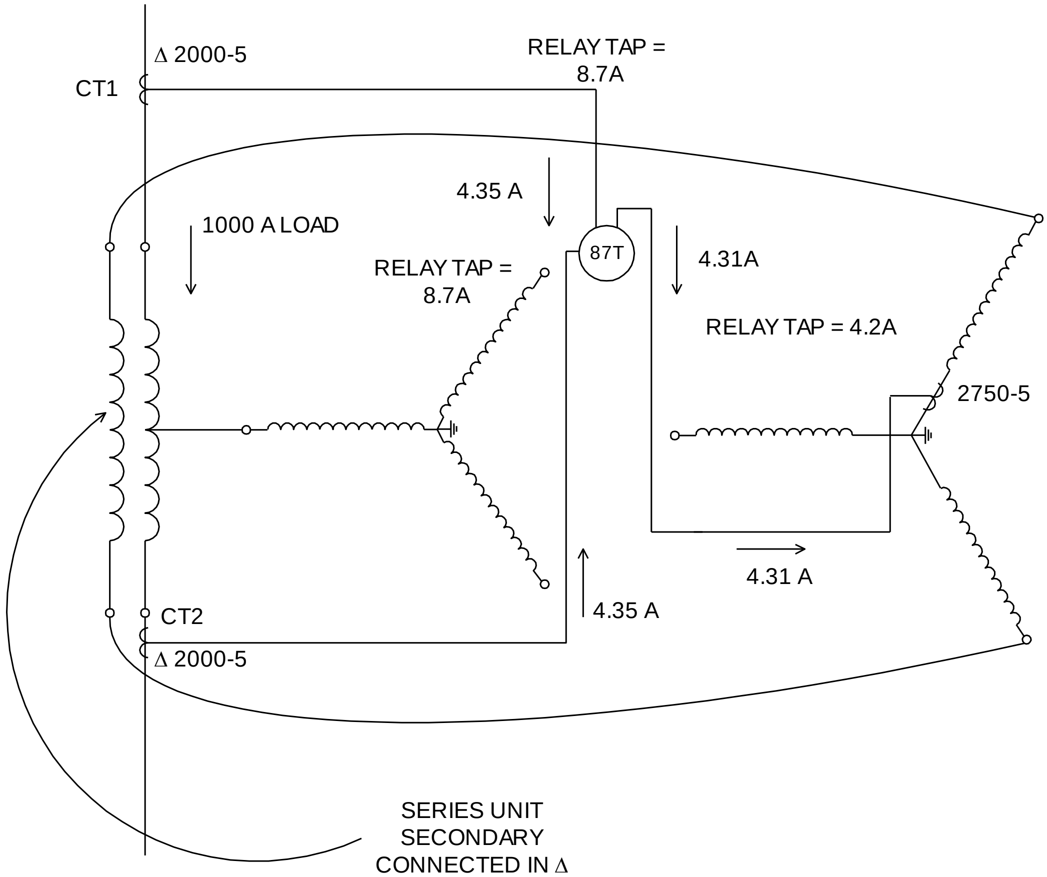


Figure 28 - Secondary differential relaying for Annex 1

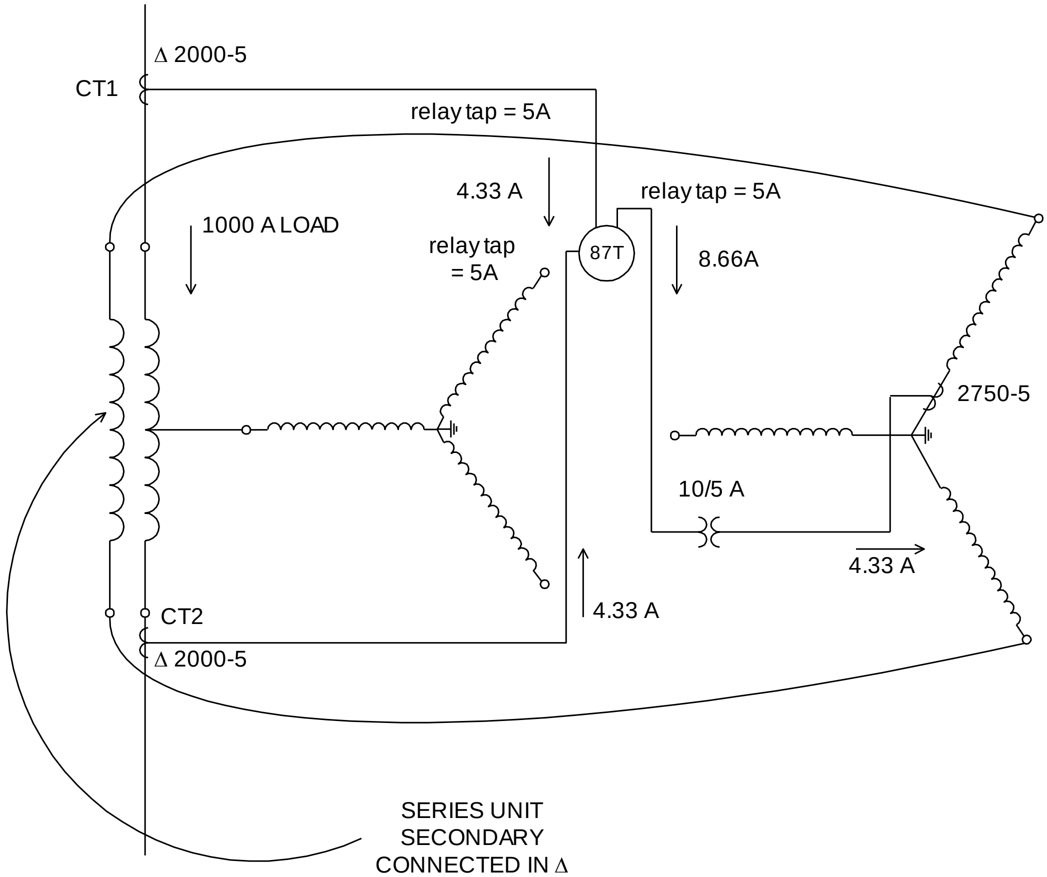


Figure 29 - Use of auxiliary current transformer to balance secondary differential relaying system - Annex 1 example