Some Old and New thoughts on Phase Angle Regulator Protection

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Abstract

"Smart Grid" can be defined as getting the power to the customer the smartest way possible with the least amount of losses. One of the ways to control the power flow over the transmission line is to insert a phase angle regulating transformer (PAR) in the line. PAR's have long been dreaded by the protection engineer as a very complex device with many different currents that make it tedious at best to develop a complete protection scheme. The problem is compounded by currents changing with tap position on the load tap changer. This paper will review the theory and application of phase angle regulating transformers. Then review the classical protection given PAR's. finally, suggesting new approaches to the protection problem made easier by the use of microprocessor based transformer differential relays.

Introduction

Phase angle regulating transformers have been a part of the planner's arsenal for years. Yet, every time one is installed the protection engineer has to seemingly "reinvent the wheel" to come up with the appropriate protection scheme. There have been many papers written about the protection of phase angle regulating transformers (PAR's). Some are listed in the references. This paper will discuss the application of PAR's, the design of PAR's, and the protection of PAR's with emphasis on advances in protection with microprocessor relays.

Application

In power systems, power doesn't always flow the way we desire it to flow. Rather, it flows based on the impedances in the network, following the path of least impedance. The general equation for power flow across a network is:

$$P = \frac{V_s V_R}{Z} \cdot \sin\theta \text{ ....(1)}$$

Where : P = the power flow through the system
V_S = Sending end voltage
V_R = Receiving end voltage
Z = Impedance of the line
Sin θ = The angle between V_S, and V_R

From equation (1) it can be seen that to change the power flow one can either lower the impedance of the line, or increase the angle between the sending and receiving voltages. Lowering the impedance is often done by applying of series capacitors to the line. Phase angle regulators change the angle between the sending and receiving ends by introducing a voltage that is in quadrature to the sending end voltage. The power flow is directly proportional to the angle change which is directly proportional to the amount of quadrature voltage added to the source voltage. The relationship between the amount of quadrature voltage added, and the resulting phase shift is shown in figure 1.

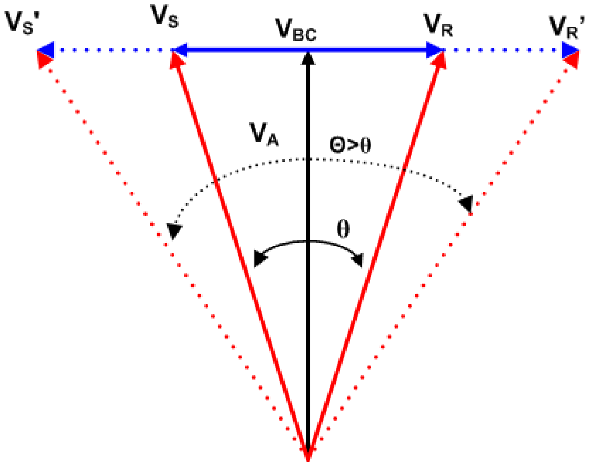


Figure 1
Phase Angle Shift from Quadrature Voltage

An application for the phase angle regulator is the multiple interconnected system. Figure 2a. A phase angle regulator is placed between points 1 and 2. An equivalent loop impedance can be calculated looking into the system from points 1 and 2. This is the parallel combination of all the lines in the intertie. Assuming a 1 per unit power flow, the equivalent circuit looks like figure 2b.

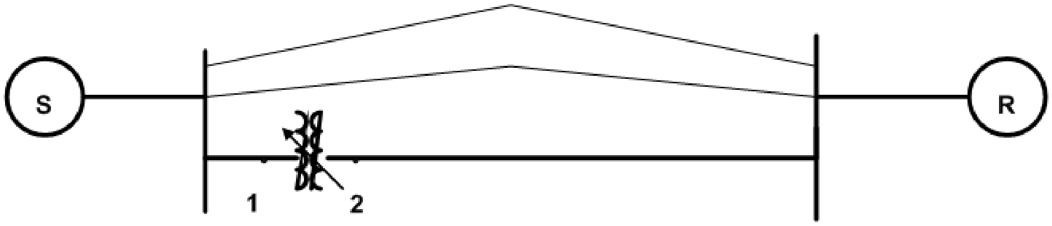


Figure 2a
Sample Network

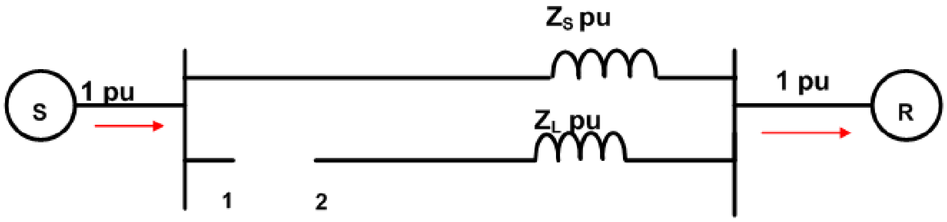


Figure 2b
Network Equivalent

A PAR is placed between points 1 and 2. The power division between the two lines is inversely proportional to the impedances of the two lines when the PAR is at the mid tap position, as shown in figure 2c.

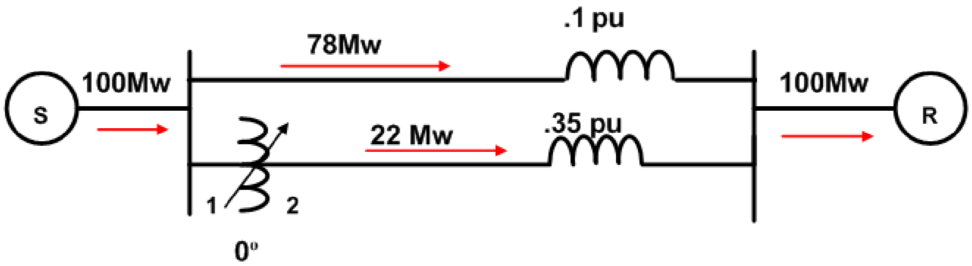


Figure 2c
Flows on Network

When the PAR tapchanger is moved to the + position, a certain amount of power will flow in the loop acting to add to the power flow in one line, and subtract from the flow in the other line. The end result is the power flow in both lines change yet the total power transmitted remains unchanged. Figure 2d shows the change in power flows for a 5 degree advance of the tapchanger position.

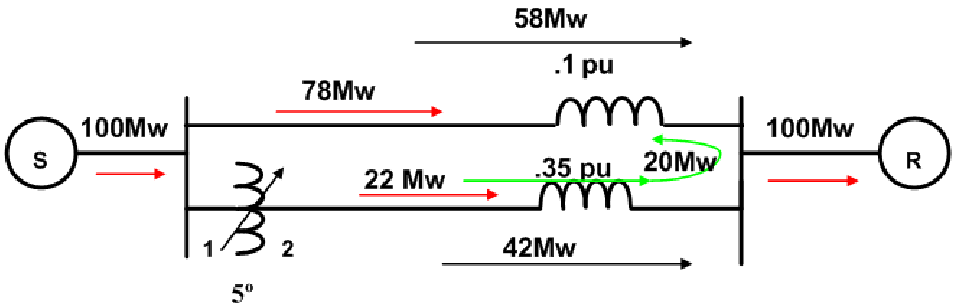


Figure 2d
Resulting flows from PAR

The relationship between the loop impedance, loop circulating power in per cent of the base power, and the PAR setting can be derived. This is shown in figure 3.

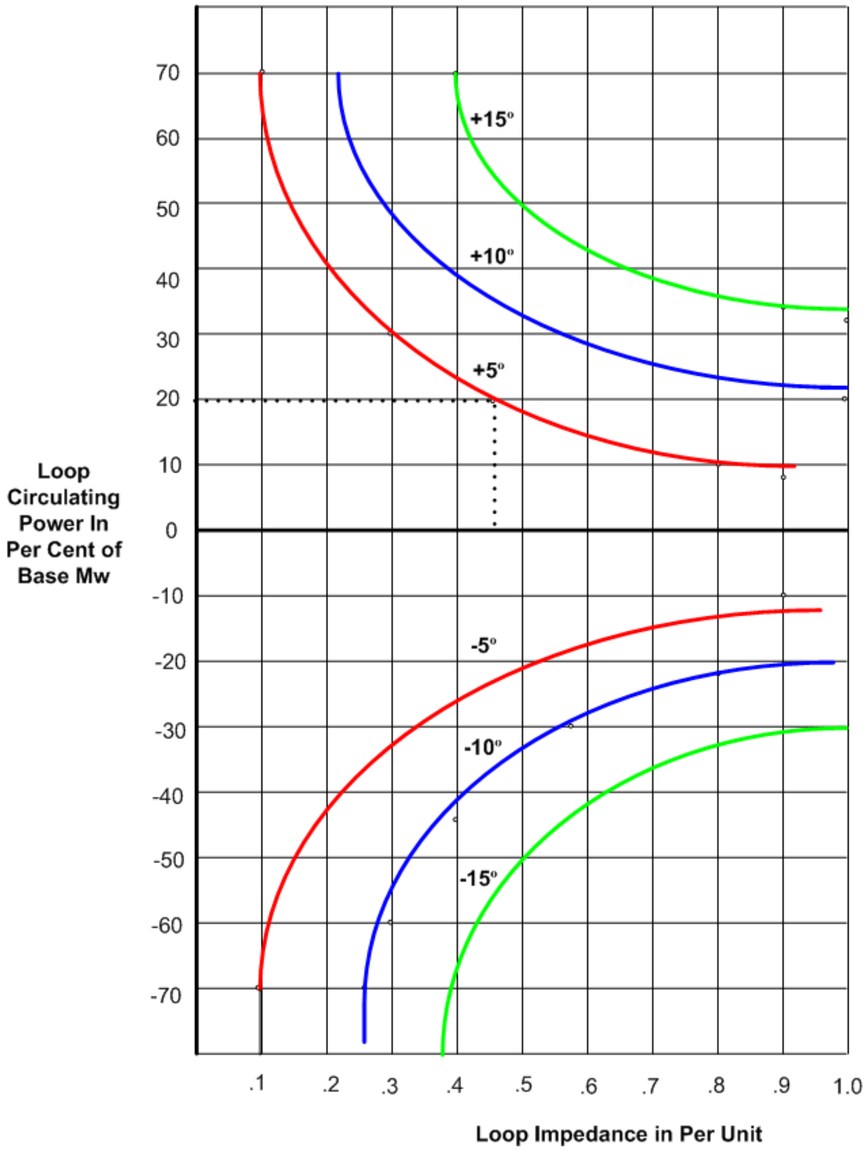


Figure 3
Desired Angle Chart

If one wanted to increase the power flow through one of the lines by 20 percent, as is the case in figure 2d, then the total loop impedance is calculated, .45 per unit. The intersection of the .45 per unit loop impedance with the desired 20 per cent change in power, yields a phase angle regulator setting of +5º.

Phase Angle Regulator Design

A phase angle regulator inserts a quadrature voltage in series with the source voltage to attain the proper phase shift. The protection engineer needs to understand how this is done before deciding on the protection for the PAR. The classic PAR consists of two transformers. An exciting transformer, and a series transformer. The exciting transformer is connected in a Wye – Wye configuration. The secondary of the series transformer is connected in delta.

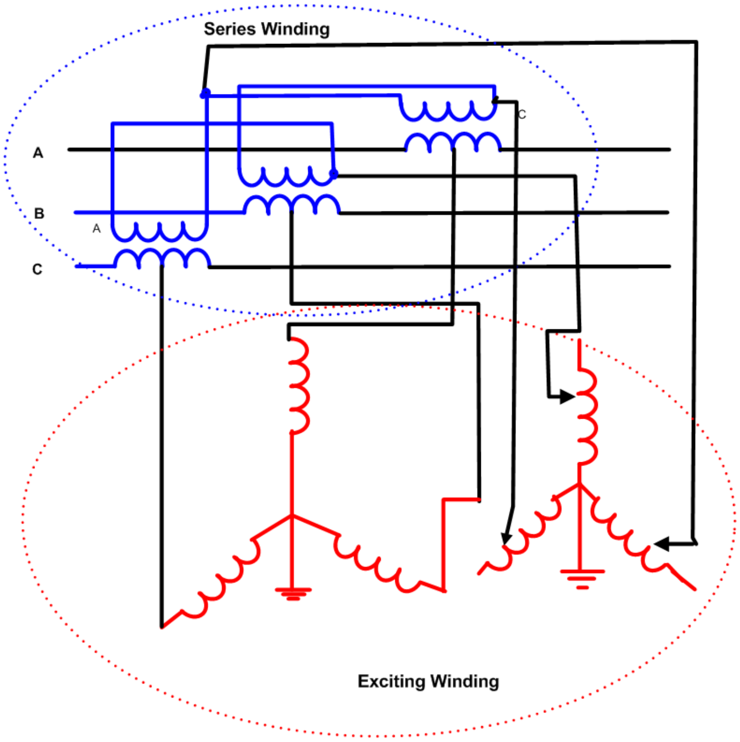


Figure 4
Conventional Phase Angle Regulator

As shown in figure 4, the secondary of the exciting transformer has a load tap changer. As the load tap changer advances position, a voltage is impressed across the secondary of the series transformer. This voltage is the quadrature voltage, V_{BC} for A phase, V_{CA} for B phase, and V_{AB} for C phase. The higher the tap changer position, the larger the quadrature voltage. The larger the quadrature voltage, the larger the phase angle shift as shown in Figure 1.

Although the classic design has many installations worldwide, it is a costly design which required two tanks. In recent years other less expensive designs have started to appear. One of the alternative configurations is the extended delta design.

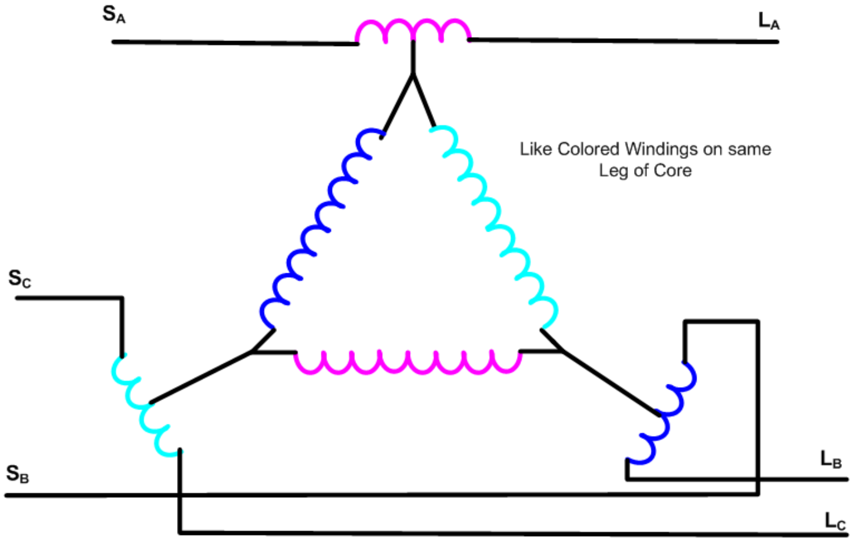


Figure 5
Extended Delta Design

This is a single tank design with a delta exciting winding with a fixed number of turns. The series winding has a tapchanger. The series winding is split into two identical parts, each with it's own tapchanger. As the tapchangers moves from center position, a quadrature voltage is inserted between the source and load terminals.

Protection of Phase Angle Regulators

The protection of a phase angle regulator is dependent on it's design and the location of the current transformers. To understand how to protect a PAR one must first understand the current flow in the PAR.. Looking at the current flow on the conventional, Grounded Wye exciting winding.

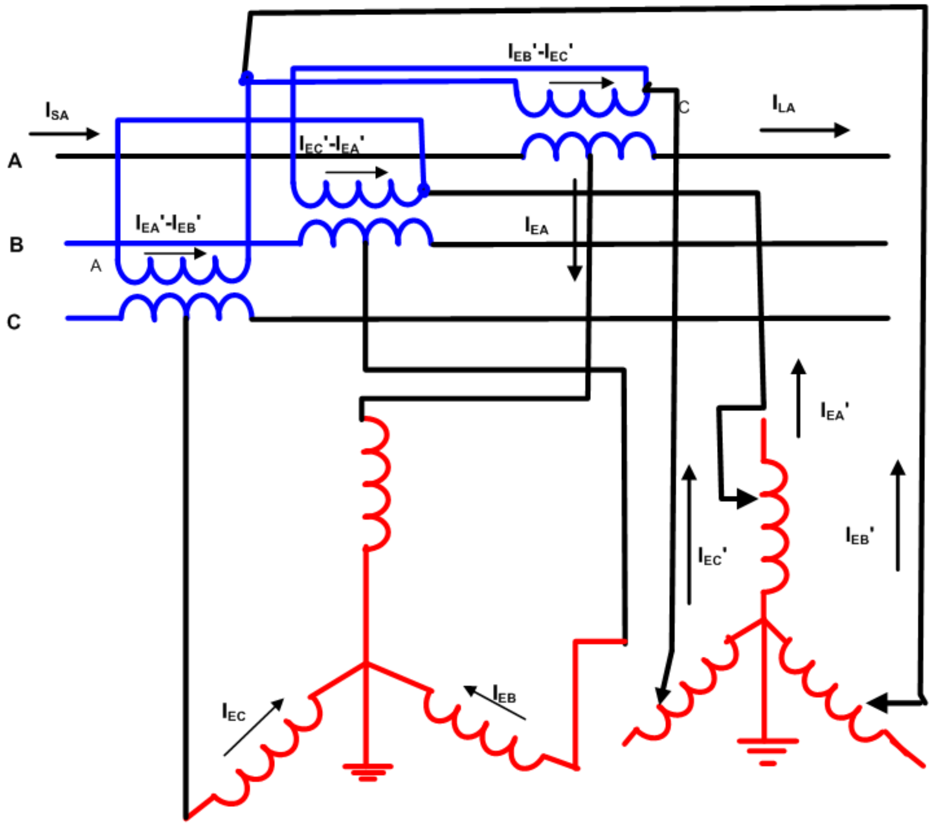


Figure 6
Currents in Conventional PAR

Looking closer at the current flow in the primary of the Series winding and the primary of the exciting winding, and using Kirchoff's law :

$$I_{SA} - I_{EA} - I_{LA} = 0$$

A simple differential protection encompassing these windings can be applied. This is shown in Figure 7.

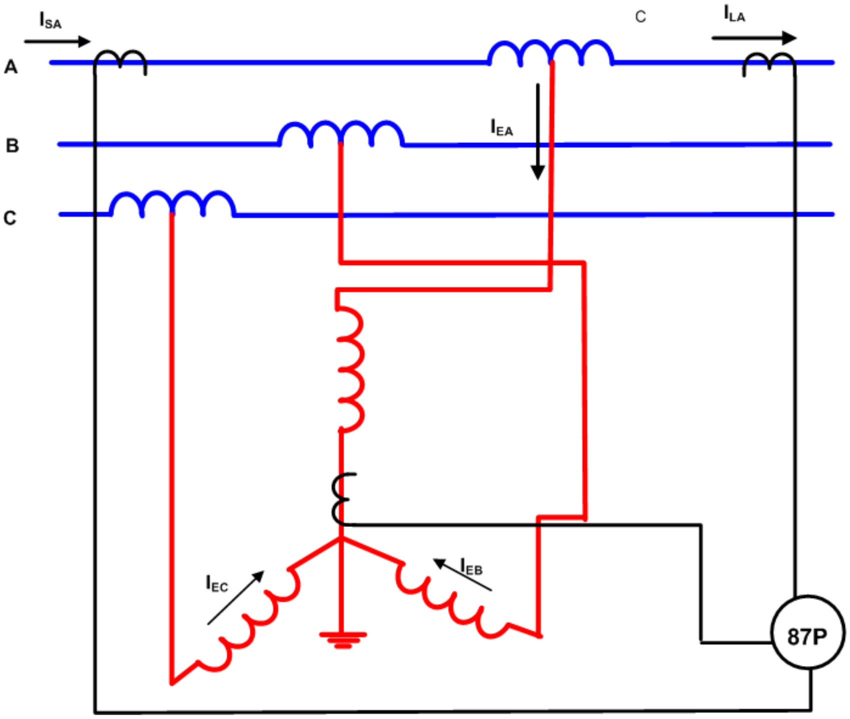


Figure 7
Protection for Primary of Series and Exciting Winding

Protection for the secondary windings of the PAR is not quite as easy. The primary of the series winding is center tapped. The current flowing through the primary of the series winding is I_S on the source side of the winding, and I_L on the load side of the winding. Therefore, the current flowing in the delta secondary of the series winding is :

$$I_{delta\ sec} = (N/2)\ (I_S + I_L)$$

Where: N = series unit turns ratio = (Series Primary Voltage) / (Series Secondary V)

Due to the series unit secondary delta connection, the current flowing at the leads of the secondary of the exciting unit are:

$$I_{EA}' = (N/2)(I_{SB} + I_{LB}) - (N/2)(I_{SC} + I_{LC})$$
$$I_{EB}' = (N/2)(I_{SC} + I_{LC}) - (N/2)(I_{SA} + I_{LA})$$
$$I_{EC}' = (N/2)(I_{SA} + I_{LA}) - (N/2)(I_{SB} + I_{LB})$$

Where: I_{EA}', I_{EB}', I_{EC}' = exciting unit secondary A, B, and C phase lead currents
I_{SA}, I_{SB}, I_{SC} = series unit primary source side A, B, and C phase currents
$I_{LA,}$ $I_{LB,}$ I_{LC} = series unit primary load side A,B,C phase currents
N = Series unit turns ratio

These equations can be satisfied in the protection by connecting the current transformers and the source, and load side in Delta, and the current transformers in the secondary of the exciting winding in Wye. Note the polarities in figure 8.

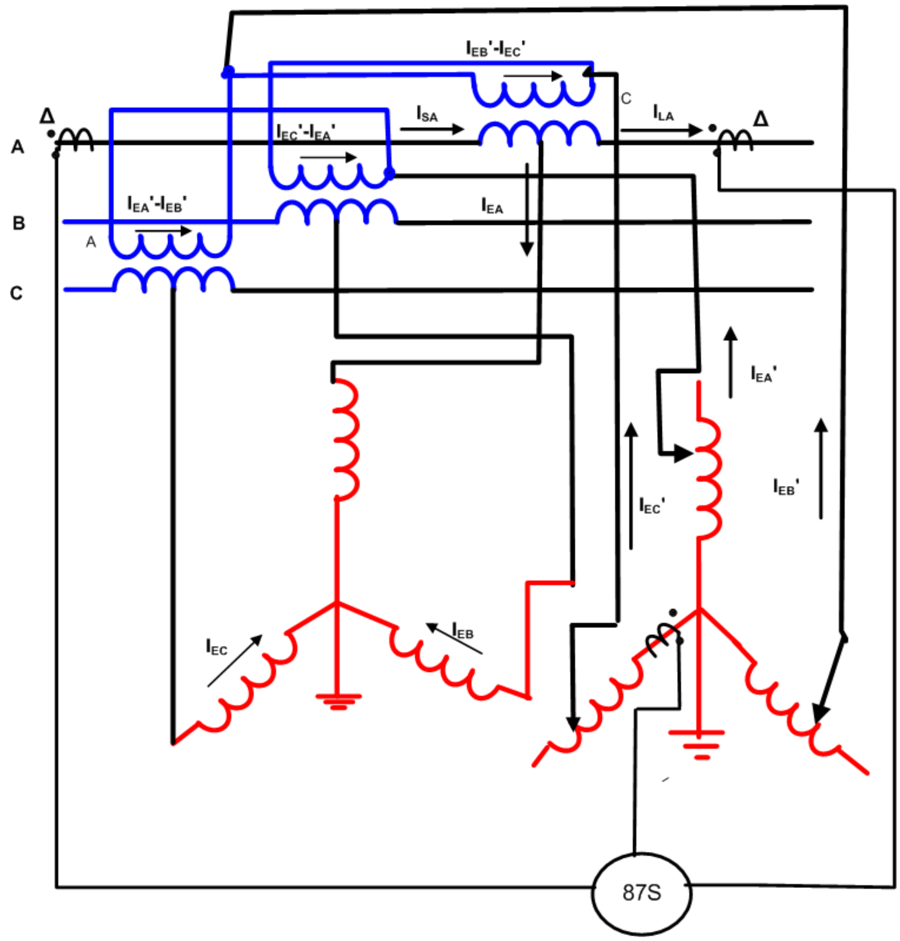


Figure 8
Secondary differential relay protection

At this point a word needs to be said about the potential saturation of the series winding. Most transformers are applied in shunt to the power system, so the maximum voltage it can see is a function of the maximum system voltage. Very rarely would a grounded wye winding see a voltage greater than 1.4 per unit of the transformer rating. However, a series transformer has a relatively small rating which is a function of the maximum phase shift. . e.g a 345kV transformer with a 20º shift would have a series winding sized at $345/\sqrt{3}\,\sin(20^{\circ})$x margin . For a margin of 20%, the rating would be 81kV. Depending on the source impedances on either side of the transformer, it's possible that the series winding could saturate under through fault conditions. Since under saturation conditions, the ampere turns balance is violated, there is a chance that the differential relay may maloperate for this through fault condition. EMTP studies should be done to verify if this condition can exist. If it can, than the differential can be supervised by an overvoltage element such that if the overvoltage is seen, the differential is blocked.

One other word of caution is with respect to the ratio of the current transformer used. The PSRC report listed in the references goes through the derivation of the ratio for the secondary exciting winding current transformer. The report concludes the ratio should be:

$$n_2 = K/2 \times n_1$$

where: K is the turns ratio of the series winding,
n_1 is the series unit source and load side ct ratios.
n_2 is the ratio of the current transformer on the secondary of the exciting winding.

In addition to the differential protection, overcurrent protection is usually added to each winding, and sudden pressure relays are added to each tank.

Now we’ll look at the winding currents in the extended delta design.

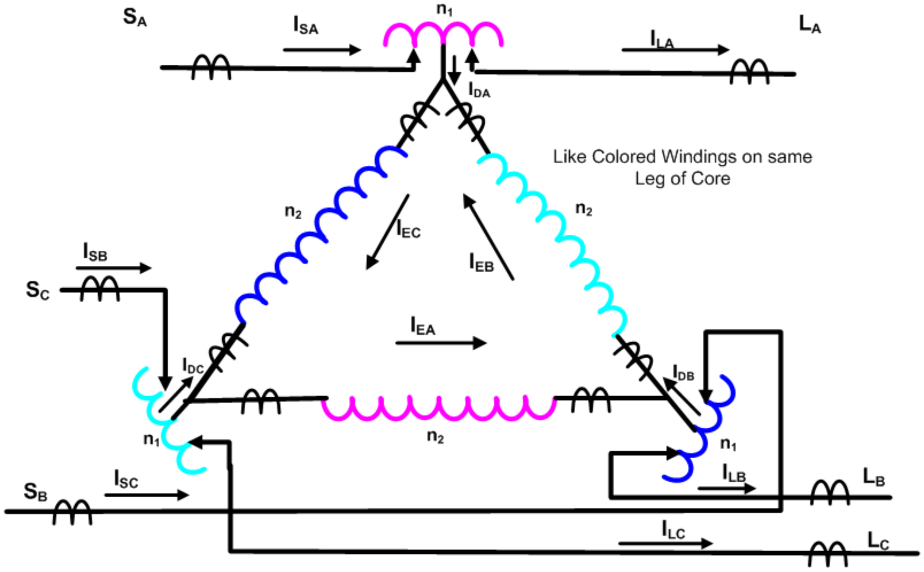


Figure 9
Currents in Extended Delta PAR

Providing a differential protection for this PAR is the same as providing a three winding transformer differential to any three winding transformer with one difference. The ampere turn equation for windings located on the first core leg can be written as:

$$n_1 I_{LA} + n_1 I_{SA} + n2\, I_{EA} = 0$$

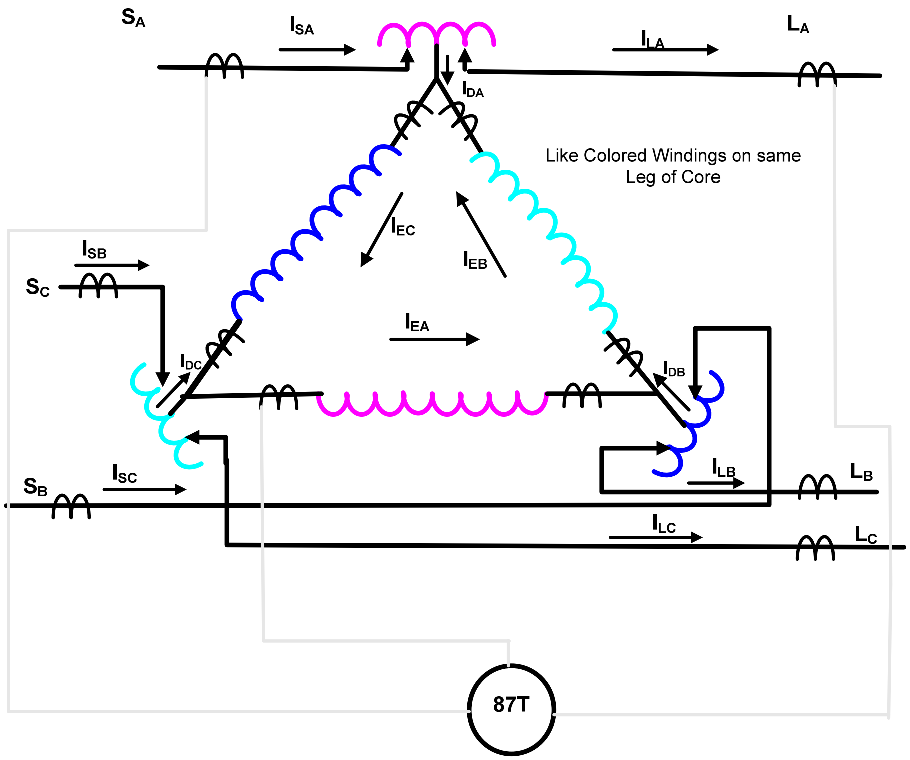
after rearranging terms :

$$I_{LA} + I_{SA} + n_2/n_1\, I_{EA} = 0$$

The last equation will be used to calculate the differential current for phase A. In a similar way the differential currents can be calculated for phases B, and C. Notice n_2 has a fixed number of turns, and n_1 has a variable number of turns depending on tap changer position. Fortunately, all the tap changers move together, so each phase winding will have the same number of turns, and the number of turns on the two series windings are kept identical throughout the tap range. If the actual n_1 is known, one could compensate on line for any tapchanger position. Modern numerical relays can accept inputs in the form of 4 – 20ma signal, or BCD coded binary signals which are readily available from tap changer remote position indicators. Using this information, a modern transformer differential relay can respond to the change tap position, and modify its setting accordingly.

This differential protection protects all three windings from phase to phase and phase to ground faults. It also offers protection for turn to turn faults. However, the sensitivity for this type of fault will be dependent on the number of turns shorted.

In order to use the equations described earlier, the vector group for this transformer would be set to Dd0. Where "D" represents the delta connected high voltage winding. "d" represents the delta connected low voltage winding. "0" represents the clock number of how much the "A" phase high side winding leads the "A" phase low side winding of the transformer. One clock number equals 30º. If there is a reversing switch on the tapchanger, such that the phase shift could go from boost to retard, then the relay would need two setting groups, both identical, but with the vector group for the latter case of Dd6. where "6" represents 180º (6 x 30º). This would compensate for the reverse current direction through two windings of the PAR. The position of the reversing switch on the tapchanger would be brought back to the relay as an input. Upon seeing the input, the relay would change setting groups. Figure 11 shows the differential protection for "A" phase.



Future Protection with Numerical Relays

In normal transformer differential protection, the phase shift across the transformer is fixed and known. This information is set in the relay. Relays use inputs from current transformers placed on the terminals of the transformer to provide protection. In a phase angle regulating transformer the phase shift across the transformer is variable. Summing the currents at the transformer terminals won't work. Current transformers must be located buried in the internal connections between windings with special current transformer ratios in order to obtain the complete currents for differential protection.

In cases where these current transformers weren't available, or forgotten about when ordering the transformer, protection engineers would resort to impedance relays looking into the transformer, and overcurrent relays to obtain some degree of protection.

It's possible to write equations for the current at all terminals based on the tap position, and therefore phase shift, of the phase angle regulating transformer. The differential function can be carried out solely with the currents at the terminals of the PAR, and the tap position derived from a transducer, or BCD input from the tapchanger mechanism.

The use of such an algorithm will eliminate the need for buried current transformers, or special ratio current transformers.

Conclusions

In today's environment "Smart Grid" is the buzzword. Regulating flows over transmission lines is one component of the Smart Grid. A component used to regulating these flows is the phase angle regulator. PAR's are very expensive pieces of equipment that are critical to controlling power flows. The protection of a PAR is a complex issue, but made easier by understanding the current flow through the windings. With the proper placement, and sizing of current transformers at the time of order, adequate protection can be provided. In some circumstances it is necessary to know the exact position of the load tap changer to provide transformer current differential protection. Remote position indicators for the tapchanger position are available to feed into the modern numerical relay. New protection algorithms can be developed to provide protection without the use of current transformers buried in the windings. When implemented, PAR protection will be simplified..

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Biography

Roger Hedding graduated from Marquette University and joined Westinghouse Electric Corp. After receiving a Masters degree in Electrical Engineering from the University of Pittsburgh, Roger became a District Engineer, and eventually moved to Milwaukee where he currently resides. As a Regional Technical Manager for ABB Inc, he's responsible for the application, and technical issues associated with ABB Transmission relays in the Great Lakes region. Roger is a IEEE senior member, and Secretary of the IEEE Power Systems Relay Committee. Roger has authored or co authored many papers in power systems protection. His hobbies include playing golf, traveling with his wife, and playing with his grandchildren