EE493 Protection of Power Systems I

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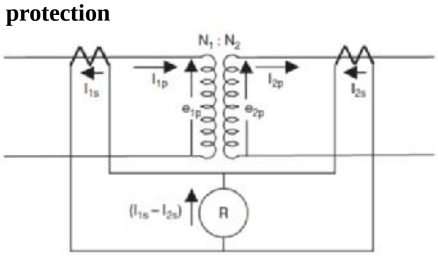
- Slides 2-6 are from Chapter 8 of "Power System Relaying", 4th Edition, Wiley, 2014, by S. Horowitz and A. G. Phadke
- Slides 7-11 are from chapter 8 of "Protection of Electricity Distribution Networks", 3rd Edition, 2011, by Juan Gers

Percentage differential protection



In normal condition

$$N_1 i_{1p} = N_2 i_{2p}$$

If the current transformers have turns ratios of 1 : n_1 and 1 : n_2 on the primary and the secondary side respectively, under normal conditions the currents in the secondary windings of the current transformers are related by

$$N_1 n_1 i_{1s} = N_2 n_2 i_{2s}$$

If we select the CTs appropriately, we may make $N_1 n_1 = N_2 n_2$, and then, for a normal transformer, $i_{1s} = i_{2s}$. However, if an internal fault develops, this condition is no longer satisfied, and the difference of i_{ls} and i_{2s} becomes much larger; in fact, it is proportional to the fault current. The differential current

$$I_d = i_{1s} - i_{2s}$$

Possible sources of errors in differential relays:

1) It may not be possible to obtain the CT ratios on the primary and the secondary side which satisfy the condition N1n1 = N2n2, as we must select CTs with standard ratios. The problem can be alleviated by the fact that most relays themselves provide different tap positions for each of the CT inputs to the relay, thus, providing auxiliary CTs which can correct any deviation from the desired ratios. Even with these adjustments, there still remains some residual ratio mismatch, which leads to a small differential current Id during normal conditions.

2) The errors associated to two CTs may differ from each other, thus leading to significant differential current when there is normal load flow, or an external fault.

3) If the power transformer is equipped with a tap changer, it will introduce a main transformer ratio change when the taps are changed.

These three effects cause a differential current to flow in the overcurrent relay, and the relay design must accommodate these differential currents without causing a trip. Since each of these causes leads to a differential current which is proportional to the actual current flowing in the transformer primary and secondary windings, a percentage differential relay provides an excellent solution to this problem.

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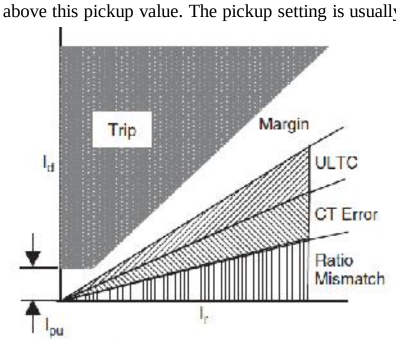
In a percentage differential relay, the differential current must exceed a fixed percentage of the 'through' current in the transformer. The through current is defined as the average of the primary and the secondary currents:

$$i_r = \frac{i_{1s} + i_{2s}}{2}$$

The current i_r is known as the restraint current – a name that comes from the electromechanical relay design, where this current produced a restraint torque on the moving disc, while the differential current produced the operating torque. The relay operates when

$$i_d \geq K i_r$$

where *K* is the slope of the percentage differential characteristic. *K* is generally expressed as a percent value: typically 10, 20 and 40 %. A relay with a slope of 10% is far more sensitive than a relay with a slope of 40 %. A practical percentage differential characteristic is shown in the following figure. The relay slope determines the trip zone. The three sources of differential current during normal transformer operation are shown, as is the margin of safety used in arriving at the slope. The relay has a small pickup current setting, i.e. the relay does not operate unless the differential current is above this pickup value. The pickup setting is usually set very low: typical values are 0.25 A secondary



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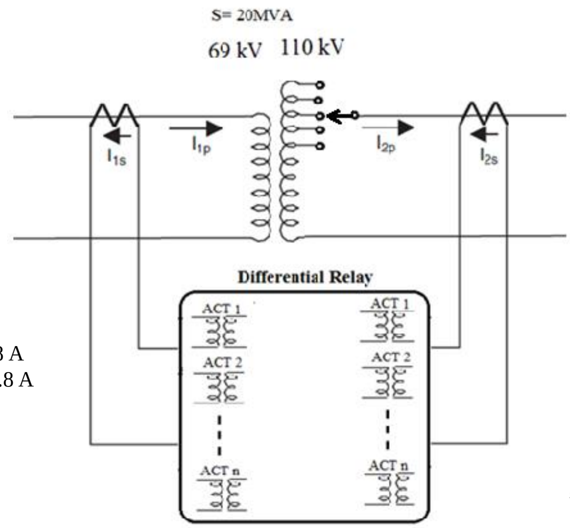
Percentage differential relay characteristic

Example: A single-phase transformer is rated at 69/110 kV, 20 MVA. It is to be protected by a differential relay, with input taps (auxiliary current transformer (ACT)) of 3/5, 4/5, 4.5/5, 4.8/5, 4.9/5, 5/5, 5.1/5, 5.2/5, 5.5/5 A secondary. The transformer has an under load tap changer (ULTC) with a turns ratio of −5% to +5% . Specify the CTs, the pickup setting and the percentage differential slope for the relay. The available slopes are 10, 20 and 40 %. Assume a 10% errors due to the errors in the CTs.



$S_{1\phi}=V\times I \rightarrow$
$20\times10^6=69\times10^3\times I_{1p} \rightarrow I_{1p}=289.8$ A
$20\times10^6=110\times10^3\times I_{2p} \rightarrow I_{2p}=181.8$ A

We may select CT ratios of 300 : 5 and 200 : 5 for the two sides. These will produce $289.8 \times 5/300 = 4.83$ A, and $181.8 \times 5/200 = 4.54$ A in the two CT secondaries. In order to reduce a mismatch between these currents, we should use the relay auxiliary CTs. The standard taps for Auxiliary CTs around 4.45 A are 4.5 and 4.8. As 4.5 is closer to 4.45 we choose 4.45 as the tap for auxiliary CT. Tap of 4.45 means if you provide 4.5 A to that CT the output would be 5 A. Therefore for 4.54 A the output of the auxiliary CT is

$$\frac{4.54}{4.5}\times 5 = 1.009\times 5$$

Standard taps around 4.83 A are 4.8 and 4.9. As 4.8 is closer to 4.83 we should select 4.8. Therefore, the output of auxiliary CT for 4.83 A is

$$\frac{4.83}{4.8}\times 5 = 1.0062\times 5$$

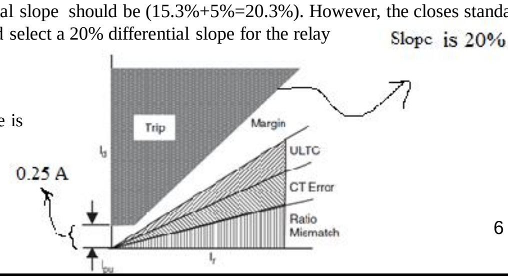
Thus, the differential current in the relay due to CT ratio mismatch would amount to $(1.009 - 1.006)\times 5$ or about 0.3 % (i.e. 0.003 of 5 A)

The tap changer will change the main transformer ratio by 5 %, when it is in its extreme tap position. Therefore, it causes 5% errors as well.

The problem also assumes 10% errors due to CTs errors. Therefore the total error is
3%+5%+10%=15.3%

With about a 5% margin of safety, the differential slope should be (15.3%+5%=20.3%). However, the closes standard slope to this value is 20%. Therefore, we should select a 20% differential slope for the relay

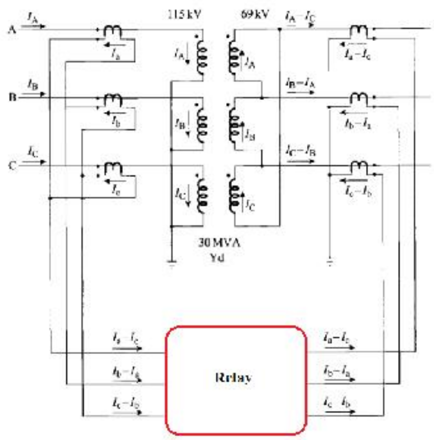
For the pickup setting, a typical available value is 0.25 A.



Percentage differential protection

In general, the CTs on the star side of a star/delta transformer should be connected in delta, and those on the delta side should be connected in star. This arrangement compensates for the phase shift across the transformer.

Example: Consider a 30 MVA, 11.5/69 kV, Yd transformer as shown in the following figure. Determine the transformation ratio and connections of the CTs required in order to set the differential relays.
CTs with ratios in steps of 50/5 up to 250/5, and in steps of 100/5 thereafter, should be used(it means the standard CT ratios are 50/5, 100/5,…200/5, 250/5, 350/5, 450/5,…).
The standard ratios of auxiliary CT of the relays are: 5/5, 5.5/5, 6/5, 6.6/5, 7.3/5, 8/5, 9/5, and 10/5 A



$$I_{load}(69\,\mathrm{kV}) = \frac{30\,\mathrm{MVA}}{\sqrt{3}\times 69\,\mathrm{kV}} = 251.0\,\mathrm{A}$$

$$I_{load}(11.5\,\mathrm{kV}) = \frac{30\,\mathrm{MVA}}{\sqrt{3}\times 11.5\,\mathrm{kV}} = 1506.13\,\mathrm{A}$$

The CT ratios are selected as follows
the CT ratio at 11.5 kV is selected as 1500/5
The CT ratio at 69 kV is selected as 250/5.
It should be noted that 1506.13 is between two CT standard ratios 1500/5 and 1600/5. In general when the current is between two CT ratios we should select the higher one (in this case 1600/5). However, as 1506.13 is very close to 1500 we chose 1500 not 1600. For example if the current was 1540 we should have selected 1600/5.
The same argument holds for choosing 250/5 rather that selecting 350/5 ratio for 69 kV side.

With the two ratios selected in this way, the currents in the windings of the relay for nominal conditions are

$$I_{relay} \text{ at } 69\,\mathrm{kV} = 251 \times (5/250) = 5.02\,\mathrm{A}$$

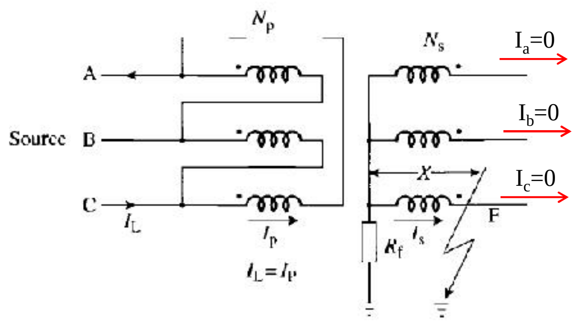
$$I_{relay} \text{ at } 11.5\,\mathrm{kV} = 1506.13 \times (5/1500) \times \sqrt{3} = 8.69\,\mathrm{A}$$

In above equation $\sqrt{3}$ is due to the fact that the CTs are 11.5 kV side are connected in delta configuration.
Now, we should select the tap of auxulіry CT such that the difference between two above values is minimized.

This means we should find x such that the following equation become zero or very small value
5.02-(5/x)×8.69
Therefore, standard auxiliary CT ratio 9/5 (i.e. X=9) should be selected

Percentage of winding protected by the differential relay during an earth fault

Although differential protection is very reliable for protecting power transformers, the windings are not always fully protected, especially in the case of single-phase faults. Consider the case of a delta/star transformer as shown in the following figure in which the star winding has been earthed via a resistor. Assume an internal earth fault occurs at point F at a distance X from the neutral point, involving X percent turns, and that the resistor has been set so that nominal current I_{nom} will flow for a fault on the terminals, (with full line-to-neutral voltage applied between phase and earth). The numbers of primary and secondary turns are Np and Ns respectively. It is assumed the secondary side of transformer is open (not loaded). Therefore, $I_a=I_b=I_c=0$



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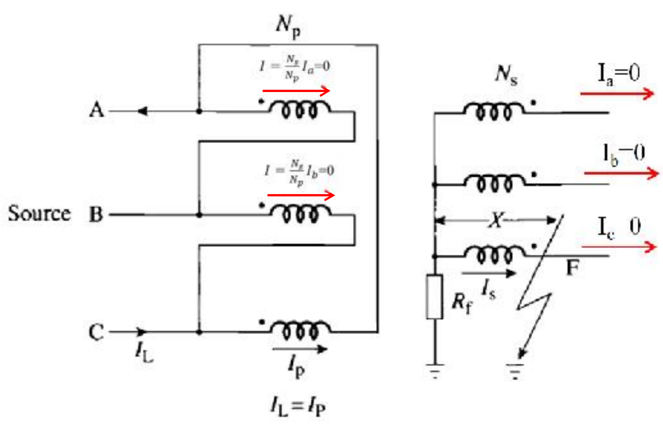
The secondary current for a fault at F is produced by X percent of the line-to neutral voltage. Therefore, by direct ratio, the current will be XI_{nom}. In addition, the number of turns involved in the fault is *XNs*. The distribution of current in the delta side for an earth fault on the star side results in a line current



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$$I'_L = X I_{nom} \times (X N_s / N_p) = X^2 I_{nom} (N_s / N_p)$$

Under normal conditions, the line current in the delta side, I_L, is

$$I_L = \sqrt{3} I_{nom} \times (N_s / N_p)$$

If the differential relay is set to operate for 20 percent of the nominal line current then, for operation of the relay, the following should apply:

$$I'_L \geq 0.2 \times I_L$$

i.e.

$$X^2 I_{nom} (N_s / N_p) \geq 0.2 \times \sqrt{3} \times I_{nom} \times (N_s / N_p)$$

$$X^2 \geq 0.2\sqrt{3}, \quad \text{i.e. } X \geq 59 \text{ per cent}$$

Therefore, 59 percent of the secondary winding will remain unprotected. It should be noted that to protect 80 per cent of the winding ($X > 0.2$) would require an effective relay setting of 2.3 per cent of the nominal primary current. This level of setting can be very difficult to achieve with certain types of differential relays.