EE493 Protection of Power Systems I

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Chapter 9 of "Protection of Electricity Distribution Networks", 3rd Edition, 2011, by Juan Gers
Chapter 5 of "Power System Relaying", 4th Edition, Wiley, 2014, by S. Horowitz and A. G. Phadke

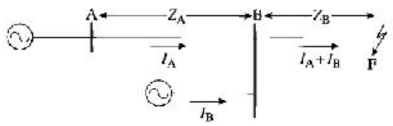
The effect of infeeds on distance relays

The effect of infeeds needs to be taken into account when there are one or more generation sources within the protection zone of a distance relay which can contribute to the fault current without being seen by the distance relay. Analyzing the case illustrated in the following, it can be appreciated that the impedance seen by the distance relay at A for a fault beyond busbar B is greater than actually occurs. In fact, if a solid earth-fault is present at F, the voltage at the relay at A would be

$$V_A = I_A Z_A + (I_A + I_B) Z_B$$

from which

$$\frac{V_A}{I_A} = Z_A + \left[1 + \frac{I_B}{I_A}\right] Z_B$$



Effect of an infeed on distance protection

The relay therefore sees an impedance of KZ_B, the infeed constant K being equal to I_B/I_A, in addition to the line impedance Z_A, which implies that its reach is reduced.

The setting of zones 2 and 3 for the relay at A should then take the following form:

$$Z_{relay} = Z_A + (1 + K) Z_B$$

where K is given as

$$K = \frac{I_{total\ infeed}}{I_{relay}}$$

Since the value of the infeed constant depends on the zone under consideration, several infeed constants, referred to as K1, K2 and K3, need to be calculated. K1 is used to calculate the infeed for the second zone (i.e. for faults at second shortest line). K2 and K3 are used for zone 3, K2 taking account of the infeed on the adjacent line (i.e. for faults at longest second line) and K3 that in the remote line (i.e. for faults at shortest third line). Therefore, to take into account the impact of infeeds:

Zone 1 = 80-85% of protected line impedance with delay of zero second (instantaneously)
Zone 2 = Protected line + $(1+K_1)\times 50\%$ of shortest second line
With the delay of typically 0.25 to 0.4 second.
Zone 3 = protected line + $(1+K_2)\times$ longest second line + $(1+K_3)\times$ 25% of shortest third line
With the delay typically between 0.6 to 1.5 second

For example in the following network

$Z_1 = 0.8$ to 0.85 times Z_{CB}

$Z_2 = Z_{CB} + 0.5(1+K_1)Z_{BD}$

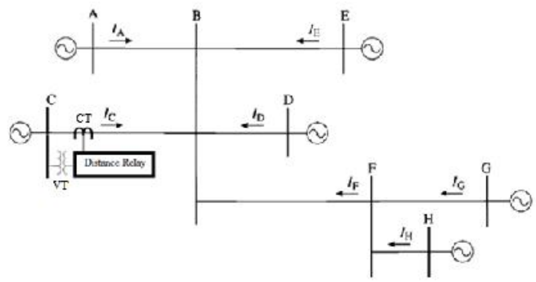
$Z_3 = Z_{CB} + (1+K_2)Z_{BF} + 0.25(1+K_3)Z_{FH}$

where

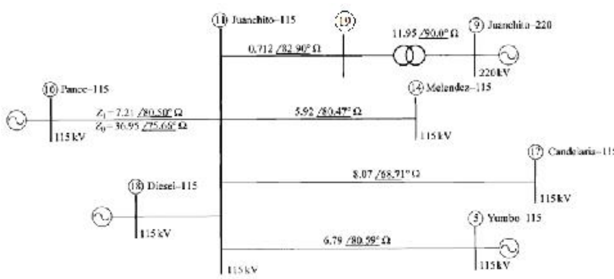
$$K_1 = \frac{I_A + I_E + I_F}{I_C}$$

$$K_2 = \frac{I_A + I_D + I_E}{I_C}$$

$$K_3 = \frac{I_A + I_D + I_E + I_G}{I_C}$$



Example: Consider a distance relay installed at the Pance substation (bus 10) in the circuit to Juanchito substation (bus 11) in the system shown in the following figure. The CT and VT transformation ratios of relays are 600/5 and 1000/1 respectively.



From the criterion for setting zone 1

$Z_1 = 0.85Z_{10-11} = 0.85(7.21\angle 80.5^\circ) = 6.13\angle 80.5^\circ$ primary ohms

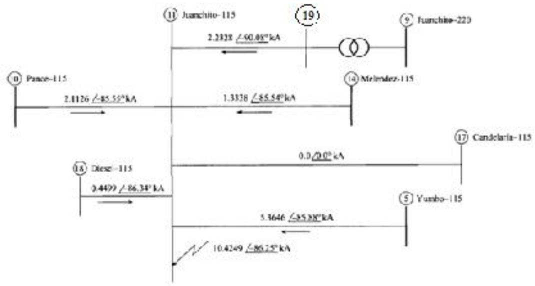
and for zone 2

$Z_2 = Z_{10-11} + 0.5(1+K_1)Z_{11-19}$

In this case the infeed constant is defined as:

$$K_1 = \frac{I_{14-11} + I_{17-11} + I_{5-11} + I_{18-11}}{I_{10-11}}$$

To calculate K_1 a fault is applied at busbar 11 which is at the beginning of the shortest second line



The above figure shows short-circuit analysis results

From the short-circuit values

$$K_1 = \frac{1333.8\angle -85.54^\circ + 0 + 5364.6\angle -85.88^\circ + 449.9\angle -86.34^\circ}{2112.6\angle(-85.55^\circ)}$$

$$K_1 = \frac{7148.27\angle -85.87^\circ}{2112.6\angle -85.5^\circ} = 3.38\angle -0.37^\circ$$

so that $1 + K_1 = 4.38\angle -0.36^\circ$

Therefore, the setting for zone 2 is

$$Z_2 = 7.21\angle 80.50^\circ + (4.38\angle -0.36^\circ \times 0.356\angle 82.90^\circ) = 8.75\angle 82.12^\circ \text{ primary ohms}$$

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and the setting for zone 3 is

$$Z_3 = Z_{10-11} + (1 + K_2)Z_{11-17} + 0.25(1 + K_3)Z_{\text{transformer}}$$

K2 is defined for the fault at the beginning of longest second line (here is line between buses 11 and 17

$$K_2 = \frac{I_{19-11} + I_{14-11} + I_{5-11} + I_{18-11}}{I_{10-11}}$$

K3 is defined for the fault at the beginning of shortest third line(which here is the transformer)

$$K_3 = \frac{I_{17-11} + I_{14-11} + I_{5-11} + I_{18-11}}{I_{10-11}}$$

When setting zone 3, it is common to assume K3 is the same as K2. Therefore, we do not need to so short-circuit analysis to calculate K3.

For a fault on busbar 11, the infeed constant is defined as

$$K_2 = \frac{I_{19-11} + I_{14-11} + I_{5-11} + I_{18-11}}{I_{10-11}}$$

Thus:

$$K_2 = \frac{+1333.8\angle -85.54^\circ + 5364.6\angle -85.88^\circ + 449.9\angle -86.34^\circ}{2112.6\angle -85.5^\circ}$$

i.e.

$$K_2 = \frac{9376.72\angle -86.86^\circ}{2112.6\angle -85.5^\circ} = 4.44\angle -1.36^\circ$$

so that

$$1 + K_2 = 5.44\angle -1.10^\circ$$

Therefore the setting for zone 3 is

$$Z_3 = 7.21\angle 80.50^\circ + (5.44\angle -1.10^\circ \times 8.07\angle 68.71^\circ) + 0.25 \times (1 + 4.44\angle -1.36^\circ)11.95\angle 90^\circ = 66.61\angle 73.92^\circ$$

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The relay settings, in primary ohms, can be summed up as follows:

$Z_1 = 6.13\angle 80.5^\circ$

$Z_2 = 8.75\angle 82.12^\circ$

$Z_3 = 66.61\angle 73.92^\circ$

When someone sets relays, the values should be the values seen by the relays

$$Z_{sec} = \frac{V_{sec}}{I_{sec}} = \frac{V_{primary} \times \dfrac{\text{Number of turns at secondary side of voltage transformer}}{\text{Number of turns at primary side of voltage transformer}}}{I_{primary} \times \dfrac{\text{Number of turns at primary side of current transformer}}{\text{Number of turns at secondary side of current transformer}}} = Z_{primary} \times \frac{CTR}{VTR}$$

$$CTR = \frac{\text{Number of turns at secondary side of voltage transformer}}{\text{Number of turns at primary side of voltage transformer}}$$

$$VTR = \frac{\text{Number of turns at primary side of current transformer}}{\text{Number of turns at secondary side of current transformer}}$$

The secondary ohms are calculated using the following expression:

$$Z_{sec} = Z_{prim} \times \frac{CTR}{VTR}$$

In this case $CTR/VTR = 120/1000 = 0.12$, and, therefore, $Z_1 = 0.736\,\Omega$, $Z_2 = 1.05\,\Omega$, and $Z_3 = 7.99\,\Omega$

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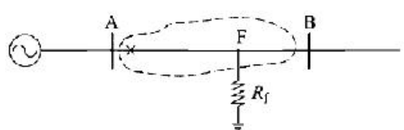
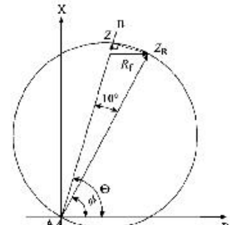
The effect of fault resistance on distance protection

For a solid fault, the impedance measured by the relay is equal to the impedance up to the fault point. However, the fault may not be solid, i.e. it might involve an impedance. Fault impedances are critical when they are located close to the limits of the relay protection zones since, although the line impedance is inside the operating characteristic, the fault impedance can take the total resistance seen by the relay outside this characteristic resulting in under reaching in the relay. If the characteristic angle of the relay, ϕ, has been adjusted to be equal to the characteristic angle of the line θ then, under fault conditions with fault impedance, the relay will under reach. For this reason it is common practice to set ϕ a little behind θ (by approximately ten degrees) in order to be able to accept a small amount of fault impedance without producing under reaching.
From the following figure:

$$Z = Z_R \cos(\Theta - \phi)$$

Where Z_R is the projected value of line impedance Z over the relay direction.
It should be noted Z_R is the value that should be plugged into the relay as the setting value





$Z = Z_R \cos(\Theta - \phi)$

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The effect of fault resistance on distance protection

Example: If the line impedance is 0.027+j*0.2783 ohm/mile and it is 120 miles and characteristic angle of the relay is 80 degrees set the Zone 1 of the relay

Z1=0.85*(0.027+j*0.2783)*120=2.754+j*28.3866=28.5199∠84.458 (characteristic angle of the line is 84.458 degrees)

Relay characteristic angle is 80 degrees. Therefore

$Z_1 = \frac{28.5199}{\cos(84.458-80)}$ =28.6064

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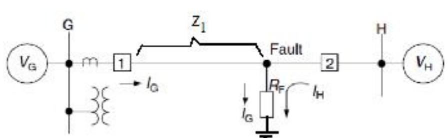
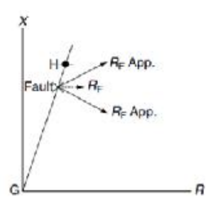
The effect of fault resistance on distance protection when fault is fed bu a source at remote end

Fault resistance, as seen by distance-type relays, is not a pure resistance, except on a radial line (i.e. there is no source at remote end of the line). If the faults is fed from the remote terminal(s), it produces a very large apparent impedance (i.e. the fault appears as a complex number with real and imaginary parts). A large apparent impedance can result in failure to operate or misoperation of relays as the total impedance of a fault that occurs insides the zone of relay may appear to relay as a fault out of the relay zone, or the faults out side the relay may appear as a fault inside the relay zone.





$$V_{relay} = Z_1 I_G + R_f(I_G + I_H)$$

$$Z_{Relay} = \frac{V_{relay}}{I_G} = Z_1 + R_f\left(1 + \frac{I_H}{I_G}\right)$$

R_F will appear as either tilted up when V_H (I_H) leads V_G (I_H) or tilted down when V_G (I_G) leads V_H (I_H).

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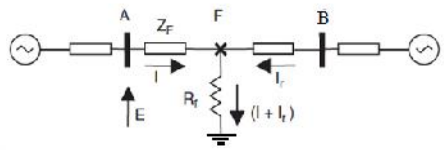
Example: Assume a single-phase circuit as shown in the following figure, and let the line impedance to the fault point be (4 + j40) Ω , while the fault resistance is 10 Ω. Let the current to the fault in the line in question be 400∠− 85◦ amps, while the current contribution to the fault from the remote end is 600∠− 90◦ amps. Then, the apparent impedance seen by the relay is



$$Z_{Relay} = \frac{V_{relay}}{I_G} = Z_1 + R_f(1+\frac{I_H}{I_G})$$

$$Z_a = (4+j40) + 10\left(1 + \frac{600\angle\ \ 90^{\circ}}{400\angle - 85^{\circ}}\right)$$

=(4+j40)+10*(1+(1.494-j0.131))=4+j40+10+14.94-j1.31=28.94+j38.69

the receiving end current contribution is in phase with the sending end current, the error in *Z*a will be in the real part only. That is not the case here, and hence the reactance also is in error.

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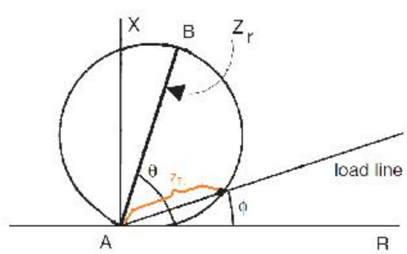
Loadability of relays (Load encroachment)



When load value increases, the impedance seen by the relay reduces. This is because for the same voltage level when the load increases the load current increases as well. Therefore, impedance reduces as Z=V/I. If the impedance seen by the relay in normal condition (Zload) reduces, at some point the impedance enters the operation zone of the relay (i.e. Zload becomes less that Z_L in above figure) and the relay mis-operates as the load impedance appears to the relay as a fault.

In above figure Θ is angle of line impedance, and ϕ is angle of load (i.e. the power factor of the load is equal to Cos(ϕ)). In above figure

$$Z_L = Z_r \times \cos(\Theta - \phi)$$

It is notable that Zr is the value of largest zone of the relay. For example, if the relay has 3 zones, Zr is the reach of zone 3.

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It is notable if we assume the single phase apparent power of load is $S_1\varphi$ and three-phase apparent power of the load is $S_3\varphi$, the equivalent impedance is

$$Z_{load} = \frac{E_{load}}{I_{load}} \text{ and } S_{1\varphi} = E_{load} \times I_{load} \text{ therefore } Z_{load} = \frac{E^2}{S_{1\varphi}}$$

As $S_3\varphi = 3\times S_1\varphi$, the above equation is equivalent to

$$Z_{load} = \frac{E^2}{\frac{S_{3\varphi}}{3}} = \frac{3 \times E^2}{S_{3\varphi}}$$

The above impedance seem by the relay is

$$Z_{load(\text{ Secondary })} = Z_{load(\text{Primary })} \times \frac{CTR}{VTR} = \frac{E^2}{\frac{S_{3\varphi}}{3}} \times \frac{CTR}{VTR} = \frac{3 \times E^2}{S_{3\varphi}} \times \frac{CTR}{VTR}$$

The primary impedance is impedance of the load before applying the CT and VT ratios at relay location and secondary impedance is the impedance of the line after applying the CT and VT ratios at relay location

If Z_{load} becomes less than Z_L (in previous figure) the relay trips. Therefore:

$$\frac{E^2}{\frac{S_{3\varphi}}{3}} = Z_r \times \cos(\Theta - \phi)$$

Therefore, the maximum load that still does not cause mis-trip is defined as follows

$$S_{3\varphi} = \frac{3 \times E^2}{Z_r \times \cos(\Theta - \phi)}$$

It is notable in above equation Zr is the primary impedance of the relay. If the secondary impedance of the relay is provided, at first primary impedance Z should be calculated and then the above equation is used

$$Z_{r(secondary)} = Z_{r(primary)} \times \frac{CTR}{VTR} \longrightarrow Z_{r(primary)} = Z_{r(secondary)} \times \frac{VTR}{CTR}$$

Therefore:

$$S_{3\varphi} = \frac{3\times E^2}{Z_{r\,(primary)} \times \cos(\Theta - \phi)} = \frac{3\times E^2}{Z_{r(secondary)} \times \frac{VTR}{CTR} \times \cos(\Theta - \phi)} = \frac{3\times E^2}{Z_{r(secondary)} \times \cos(\Theta - \phi)} \times \frac{CTR}{VTR}$$

Example: In a network with line-ground voltage of 20kV, the current and voltage transformer ratios for the relay are determined to be CTR = 100 and VTR= 288.6. Assume the setting of the zone 3 of the relay is 1.17 + j8.84 = 8.917∠82.46◦ (this is a secondary impedance which is inserted in the relay as the setting of the relay). Moreover assume a power factor of 0.8 lagging for load which means cos(ϕ)= 0.8 and as a result ϕ = 36.870.

As the impedance of the 3rd zone of the is 1.17 + j8.84 = 8.917∠82.46◦ the angle of the line impedance is Θ = 82.46◦

$$S_{3\varphi} = \frac{3\times E^2}{Z_{r(secondary)}\times\cos(\Theta-\phi)} \times \frac{CTR}{VTR}$$

$$S_{3\varphi} = \frac{3\times 20^2}{8.917\times cos(82.46-36.87)} \times \frac{100}{288.6} = 66.63\ MVA$$

Therefore $S_{3\varphi}$=66.63 MVA is the maximum load that still does not cause relay mis-operation

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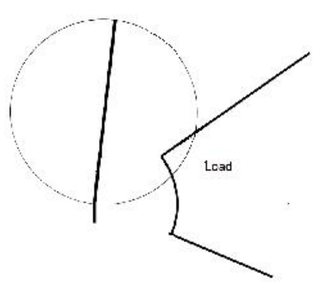
The loading of the network should be less than the maximum load that is calculated in previous slides. If for some reasons we need to supply loads more than the maximum allowable load, the size of the relay zone should be reduced. It is also possible to define another zone around the load area as shown in the following figure. If the impedance seen by the relay falls inside this zone the relay operation is blocked and mis-operation of the relay is prevented



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