

Last Topics #2: Out-of-step Relays

1.0 Introduction

There are some additional topics that are appropriate to include in a course on power systems dynamics, and I do so here because they are highly relevant to what might be called “current events.” The topic of this set of notes is “Out-of-step relays.”

2.0 Impedance relays

Impedance, or “distance” relays are the most common transmission network relay and are used to detect faulted conditions. They operate by measuring voltage \mathbf{V} at a bus and current \mathbf{I} flowing into or out of a particular circuit connected to that bus, and then taking the ratio $Z=\mathbf{V}/\mathbf{I}$. They work because under faulted conditions, V typically decreases and I increases, and so Z_{faulted} , compared to Z_{normal} , is typically much smaller.

For example, suppose $\Delta V=0.5(V_{\text{normal}})$ and $\Delta I=2(I_{\text{normal}})$.

$$\text{Before fault: } \frac{V}{I} = \frac{V_{\text{normal}}}{I_{\text{normal}}} = Z_{\text{normal}} .$$

$$\text{After fault: } \frac{V}{I} = \frac{0.5(V_{\text{normal}})}{2(I_{\text{normal}})} = \frac{1}{4} \frac{V_{\text{normal}}}{I_{\text{normal}}} = Z_{\text{fault}}$$

From this, we can see that:

$$Z_{\text{fault}} = \frac{1}{4} Z_{\text{normal}}$$

To illustrate, consider the network of Fig. 1. Plot the impedance as seen by the impedance relay looking into the circuit for (a) normal

load conditions, (b) 3-phase fault F_1 , (c) 3-phase fault F_2 . The values given are impedance in per-unit.

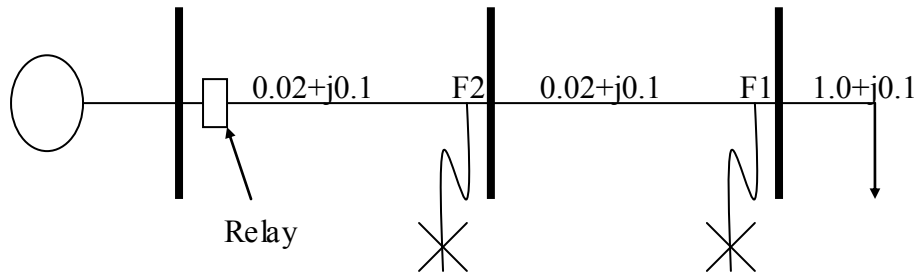


Fig. 1

The per-phase circuit is shown in Fig. 2.

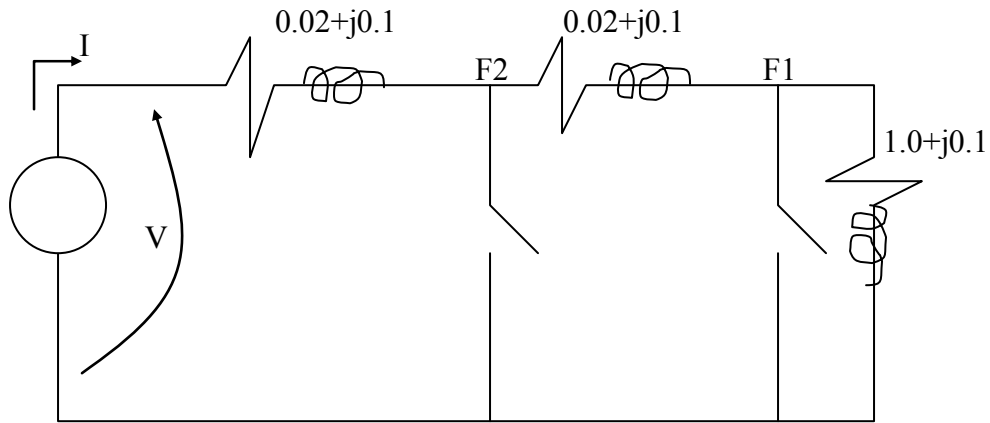


Fig. 2

The desired impedance is

$$Z = \frac{V}{I} \tag{1}$$

(a) Under normal load,

$$Z_n = \frac{V}{I} = 1.04 + j0.3$$

(b) For a fault at F_1 ,

$$Z_{F1} = \frac{V}{I} = 0.04 + j0.2$$

(c) For a fault at F_2 ,

$$Z_{F2} = \frac{V}{I} = 0.02 + j0.1$$

Let's plot these on what we will call the Z-plane, or the R-X plane, as shown in Fig. 3.

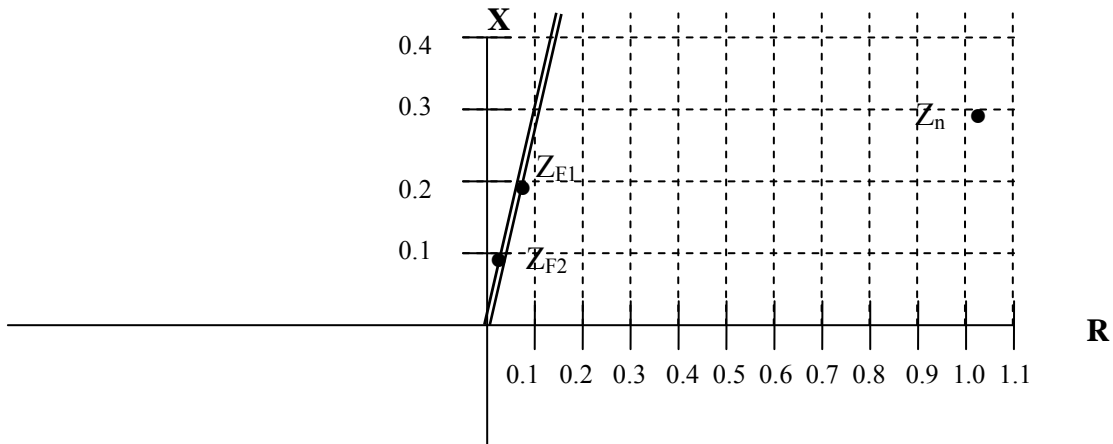


Fig. 3

Some observations:

1. The faulted conditions are located relatively near the origin in the Z-plane, whereas the normal load conditions are located far to the right on the Z-plane. We can use this to our advantage in designing relays to discriminate between faulted conditions and normal load conditions.
2. The points corresponding to the faulted conditions, Z_{F1} and Z_{F2} , are positioned on a line extending from the origin. This will be the case as long as the impedance per unit length is uniform over the length of the line.
3. Z_{F1} is farther from the relay than Z_{F2} ; it is also farther from the origin than Z_{F2} . This consistency reflects the relation between

“distance” and “impedance.” That is, the farther in distance from the relay, the larger will be the impedance.

The third observation is significant. It implies that the relay can accurately judge the fault location based on the impedance it sees.

2.0 Impedance relay tripping characteristic

The simplest impedance relay is one that operates with the following logic:

$$\left| \frac{V}{I} \right| \leq |Z_t| \rightarrow \text{Trip}$$

$$\left| \frac{V}{I} \right| > |Z_t| \rightarrow \text{Block}$$

This logic can be illustrated in the impedance plane as in Fig. 4.

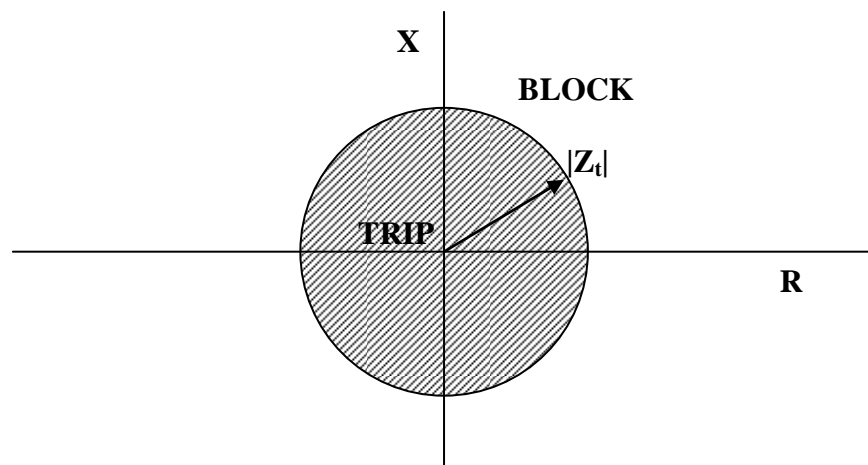


Fig. 4

We may also plot the locus of impedance values corresponding to the particular circuit we are protecting (the line impedance locus), as we move from one end of the circuit to the other. This can be helpful in identifying the relationship between the tripping logic and the possible impedance values seen by the relay.

As an example of this, consider the portion of a transmission system in Fig. 5.

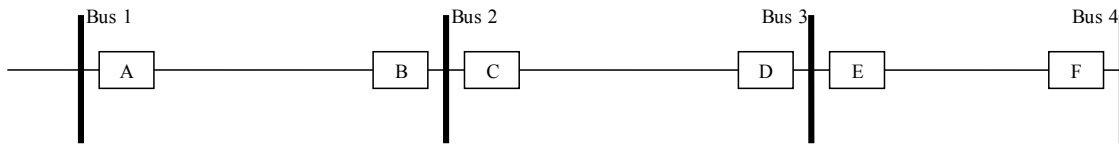


Fig. 5

Consider the relay C. Assuming the same tripping logic as in Fig. 4, and assuming uniform impedance per unit length of the two circuits to the right and to the left of it, the line impedance locus seen by relay C are shown in Fig. 6.

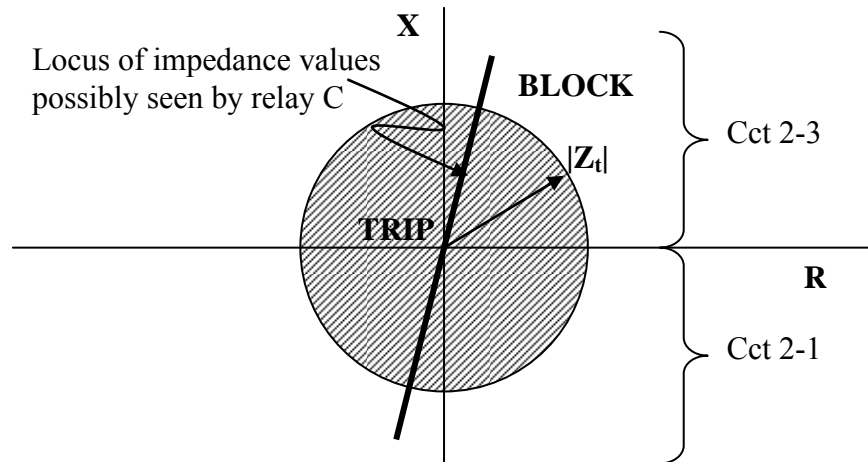


Fig. 6

There are two observations in relation to Fig. 6:

Directionality: The portion of the relay-impedance-locus in the upper half of the plane corresponds to what the relay sees when a fault is on cct. 2-3; the portion of the relay-impedance-locus in the lower half of the plane corresponds to what the relay sees when a fault is on cct. 2-1.

Therefore, relay C trips looking right or left. This is generally not acceptable because if it trips for faults on cct. 2-1, it will unnecessarily deenergize bus 2.

The conceptually simplest approach to providing directionality is to use both an impedance relay and a directional relay. The tripping logic would then be:

$$-180 < \theta < 0, \text{ and } |Z| \leq Z_t \rightarrow \text{Trip}$$

$$0 < \theta < 180, \text{ or } |Z| > Z_t \rightarrow \text{Block}$$

where θ is the angle of the current phasor relative to the angle of the voltage phasor.

The tripping characteristic would then be as illustrated in Fig. 7.

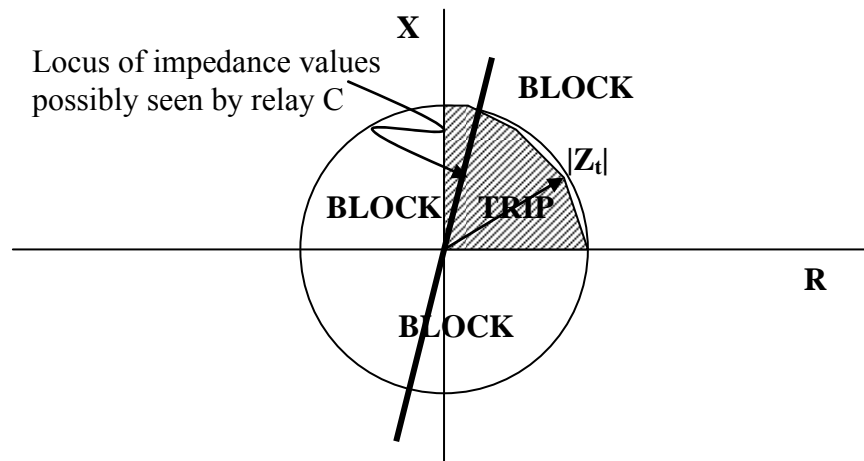


Fig. 7

3.0 Mho relay

Another approach to providing directionality in impedance relays results in the Mho relay. The Mho relay characteristic is achieved by offsetting the impedance relay tripping characteristic by an amount $R_t + jX_t$ such that $|R_t + jX_t| = |Z_t|$. This is illustrated in Fig. 8. A detailed derivation is provided in [1], pp. 472-473.

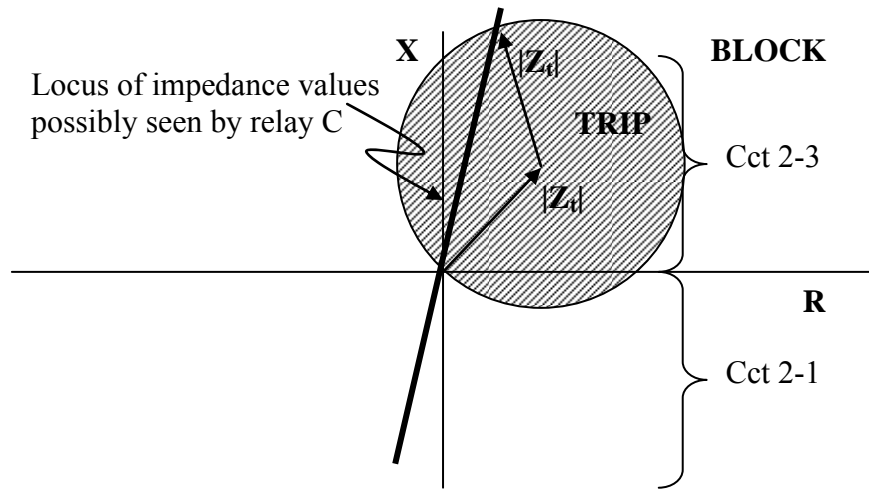


Fig. 8

One observes from Fig. 8 that the Mho relay is directional.

3.0 Impedance during swings

The remaining sections are adapted from [2,³]. Consider the simplified system of Fig. 9 [2], with the equivalent circuit of Fig. 10 [2].

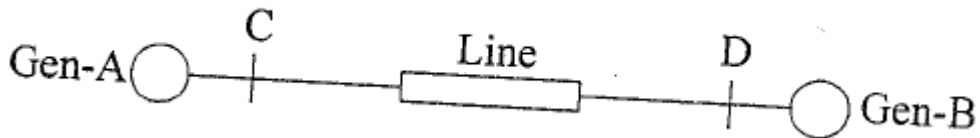


Fig. 9 [2]

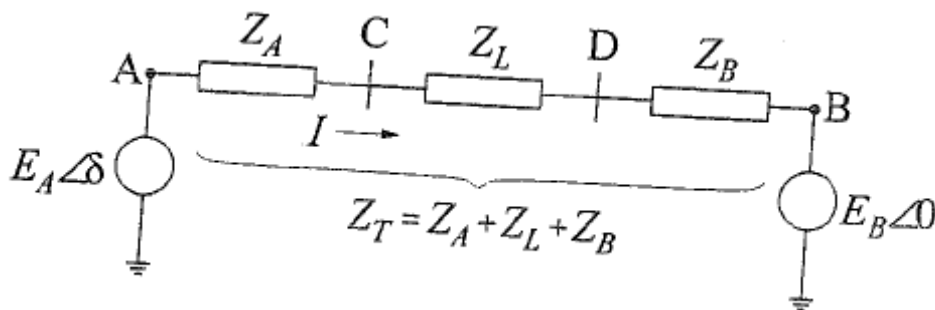


Fig. 10 [2]

The current \mathbf{I} is given by

$$\bar{I} = \frac{E_A \angle \delta - E_B \angle 0}{Z_T} \quad (1)$$

The voltage at bus C can be expressed as

$$\bar{E}_C = \bar{E}_A - Z_A \bar{I} \quad (2)$$

The impedance seen by an impedance relay at bus C protecting line CD is

$$Z_C = \frac{\bar{E}_C}{\bar{I}} = \frac{\bar{E}_A - Z_A \bar{I}}{\bar{I}} = \frac{E_A \angle \delta}{\bar{I}} - Z_A \quad (3)$$

Substituting (1) into (3) yields

$$Z_C = \frac{Z_T E_A \angle \delta}{E_A \angle \delta - E_B \angle 0} - Z_A \quad (4)$$

Now let's assume that $E_A = E_B = 1.0$ (magnitude only). In this case, (4) becomes

$$Z_C = \frac{Z_T \angle \delta}{1 \angle \delta - 1 \angle 0} - Z_A \quad (5)$$

Kunder in [2], pg. 915, shows that this can be written as

$$Z_C = \left(\frac{Z_T}{2} - Z_A \right) - j \left(\frac{Z_T}{2} \cot \frac{\delta}{2} \right) \quad (6)$$

We know from our previous work in this course that during a disturbance, the rotor “swings” resulting in a change to δ .

We can use (6) to plot the locus of points for Z_C as the angle changes from $\delta=0$ to $\delta=360$. Fig. 11 results.

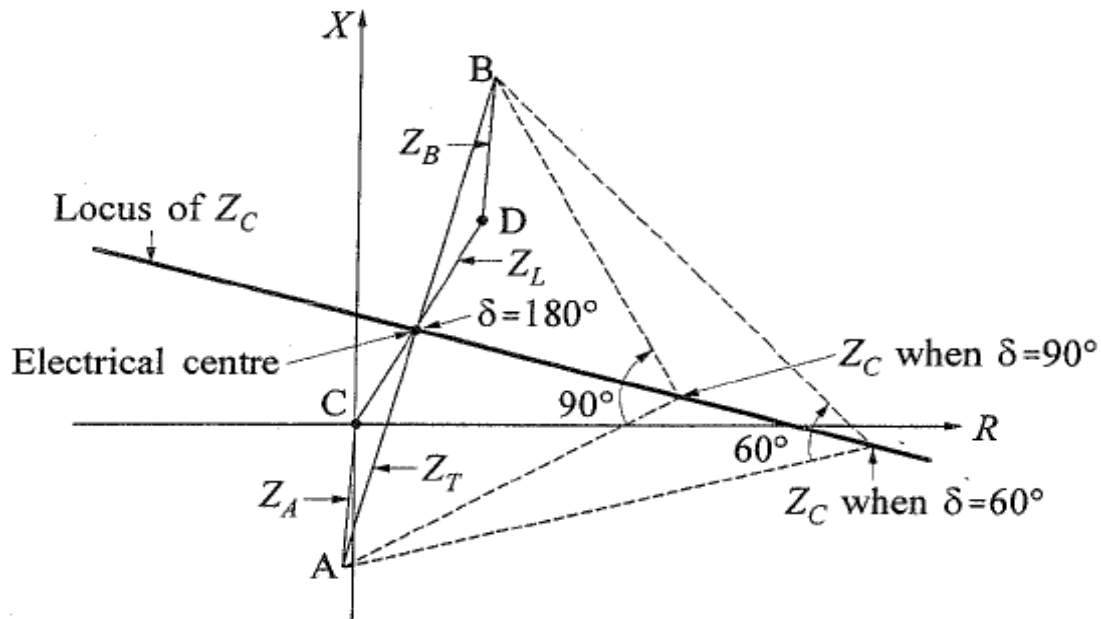


Fig. 11

The following can be proven, but here we simply observe:

- Segment C-A represents impedance between bus C and bus A, typically highly reactive since it includes transformer and synchronous machine. It is in the negative direction because we have defined “positive” current out of bus C towards bus D.
- Segment C-D represents impedance between bus C and bus D, more resistive than C-A since it represents a transmission line.
- Segment D-B represents impedance between points D and B, also highly reactive because it, like C-A, includes transformer and synchronous machine.
- Segment A-B represents impedance between points A and B. This is the impedance of the entire transmission between the internal voltages E_A and E_B .
- The angle formed by lines from A and B to any point on the Z_C locus is equal to the angle δ corresponding to the point of intersection on the Z_C locus. Fig. 11 illustrates this for three angles: $\delta=60^\circ$, $\delta=90^\circ$, and $\delta=180^\circ$.
- The locus of Z_C is a perpendicular bisector to segment A-B. It is the middle of segment A-B. As a result, we say it represents the *electrical center* of the network.

- When $\delta=180$, the voltage at the electrical center becomes zero, and therefore the impedance relay at bus C sees a three-phase fault at the electrical center.

If E_A is not equal to E_B , then the apparent impedance loci are circles with centers on extensions of the impedance line A-B, as illustrated in Figure 12 [2].

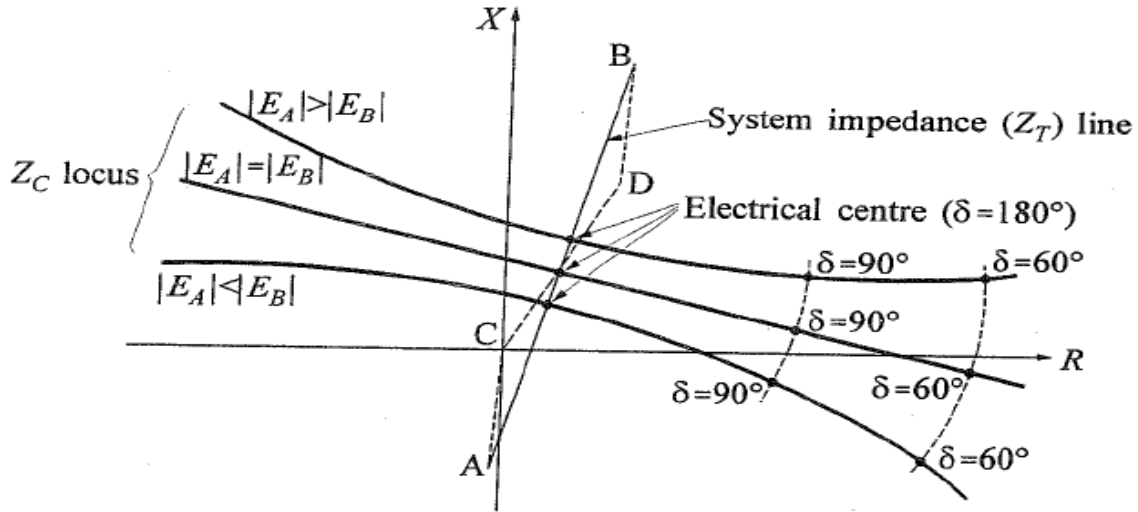


Fig. 12 [2]

Figure 12 represents the situation when the electrical center is out in the transmission system relative to bus C. In this case, inspecting a Mho relay trip characteristic, Fig. 13, we observe that a swing could trip it.

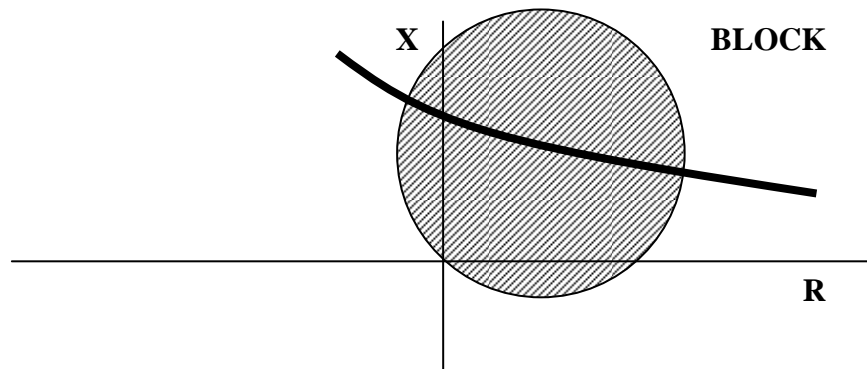


Fig. 13

The critical issue here is that we would like to trip if indeed there is an instability, i.e., if the swing is going to pass through the electrical center.

But we do not want to trip if a stable swing enters the trip region.

So here is what we desire the Mho relay to do:

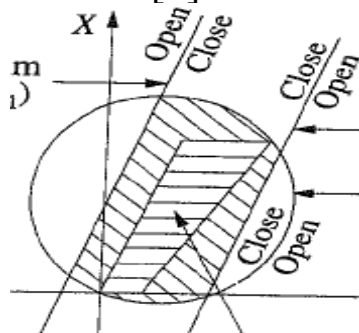
- TRIP for
 - fault conditions that enter the trip characteristic
 - unstable swings
- BLOCK for
 - Swings that are not from fault conditions and that are stable

This leads to the principle of out-of-step relaying [2]:

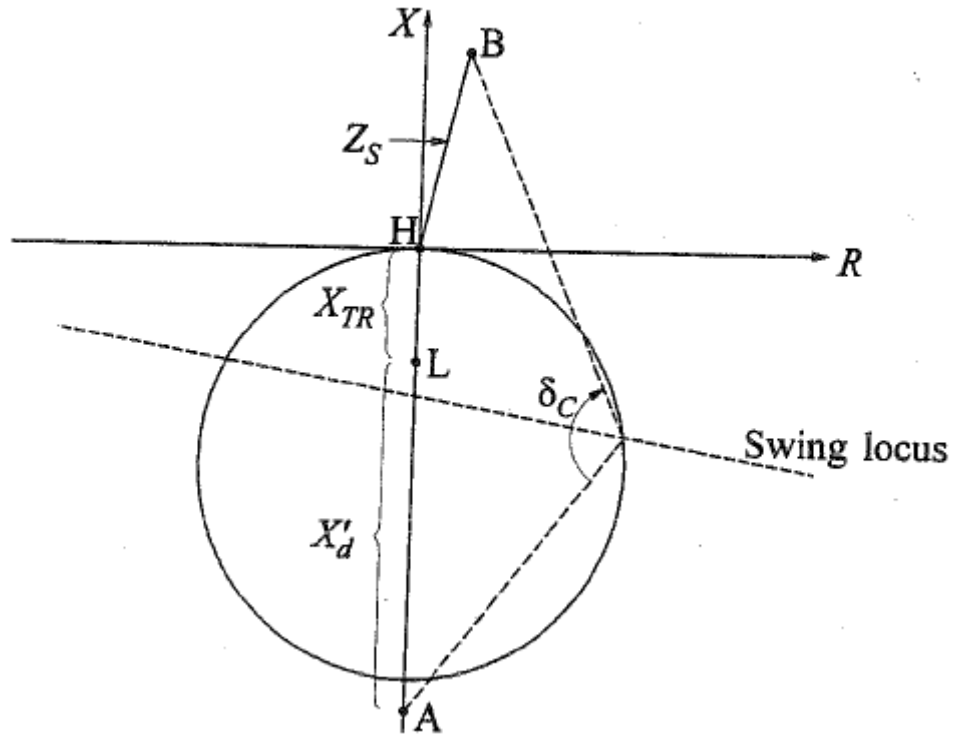
“The movement of the apparent impedance under out-of-step conditions is slow compared to its movement when a line fault occurs. Therefore, a transient swing condition can be detected by using two relays having vertical or circular characteristics on an R-X plane as shown... If the time required to cross the two characteristics (OOS2, OOS1) exceeds a specified value, the out-of-step function is initiated.”

The phrase “the out-of-step function is initiated” means that the functionality of the relay is changed such that it will not trip as a result of simply entering the trip zone used to detect faults but will trip if the swing moves too close to the electrical center.

As a result, the trip zone may need to be narrowed for OOS protection, as illustrated below [2].



It is interesting to note that it is possible for the electrical center may appear in the step-up transformer or in the synchronous generator itself. This can occur when the transmission system is very strong (low network impedance). In such a case, a special relay must be provided at the generator having a characteristic as shown below [2].



[1] C. Gross, "Power system analysis," second edition, Wiley, 1986.
 [2] P. Kundur, "Power system stability and control," McGraw-Hill, 1994.
 [3] E. Kimbark, "Power system stability, Vol. II, Power circuit breakers and protective relays," 1995, IEEE Press.