

# Protection 4

## 1.0 Introduction

Recall there are five basic classes of relays:

- Magnitude relays
- Directional relays
- Ratio (impedance) relays
- Differential relays
- Pilot relays

We study the impedance relay in these notes. Other names for impedance relays are “ratio relay” and “distance relay.” This material addresses section 13.3 and 13.8 in your text.

## 2.0 Impedance relays

Transmission systems such as the U.S. eastern, western, or Texas interconnections,

- are highly networked (meshed), and
- are constantly changing in terms of the source of fault currents, generators (due to units coming on-line and off-line), and to a lesser extent, in terms of circuit topology (due to maintenance and forced outages).

This feature makes protective relaying for transmission systems much more challenging than protective relaying for radial or “single-loop” systems that we have studied so far. The reasons for the additional difficulties are

- we cannot assume that the sources are in fixed locations as in a radial or single-loop system;
- we cannot be sure of the topology between sources and faults against which we are trying to protect.

Recall that it was exactly these two features of radial or single-loop systems which allowed us to identify bounds on minimum and maximum current levels and thus to utilize over-current relays. So we do not use overcurrent relays here.

Impedance relays have much better discriminatory abilities relative to over-current relays (magnitude or directional). By this, we mean that impedance relays are better able to discriminate (to distinguish) between conditions for which they should operate and conditions for which they should not.

To understand the fundamental advantage gained from an impedance relay, consider a 3-phase fault, and recall the effects:

- voltage drops and
- current drops.

Suppose  $\Delta V = 0.5(V_{normal})$  and  $\Delta I = 2(I_{normal})$ .

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

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

From this, we can see that:

$$Z_{fault} = \frac{1}{4} Z_{normal} \text{ but } I_{fault} = 2I_{normal}.$$

Therefore, proportionally, a larger change is seen in impedance than current, and so faults are easier to correctly detect when measuring impedance relative to measuring current.

Example:

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.

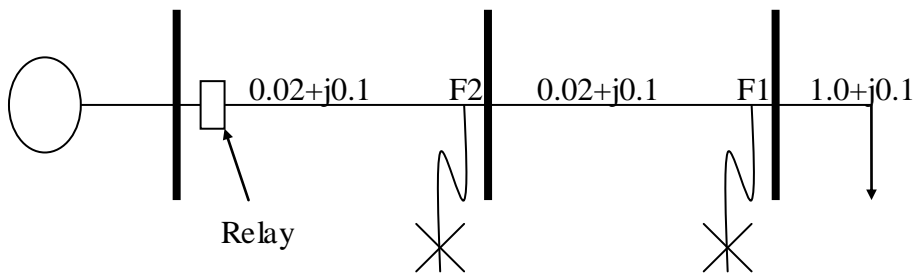


Fig. 1

Solution:

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

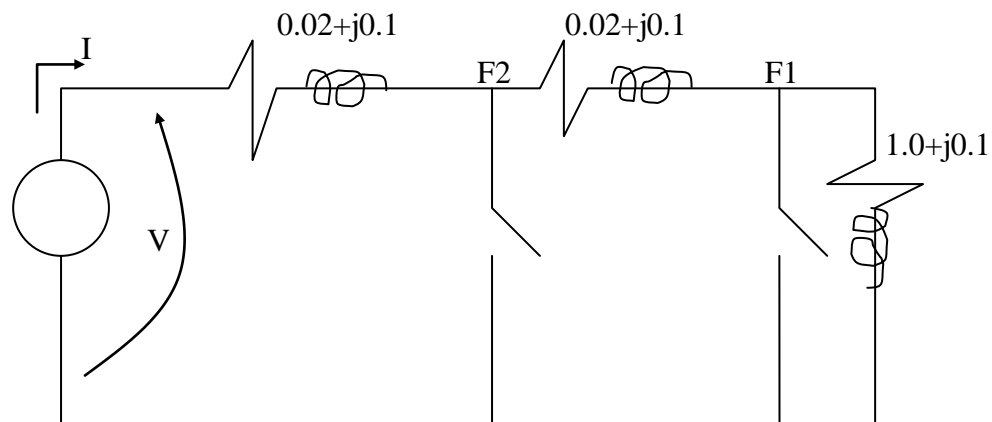


Fig. 2

The desired impedance is

$$Z = \frac{V}{I} \quad (1)$$

(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 the Z-plane:

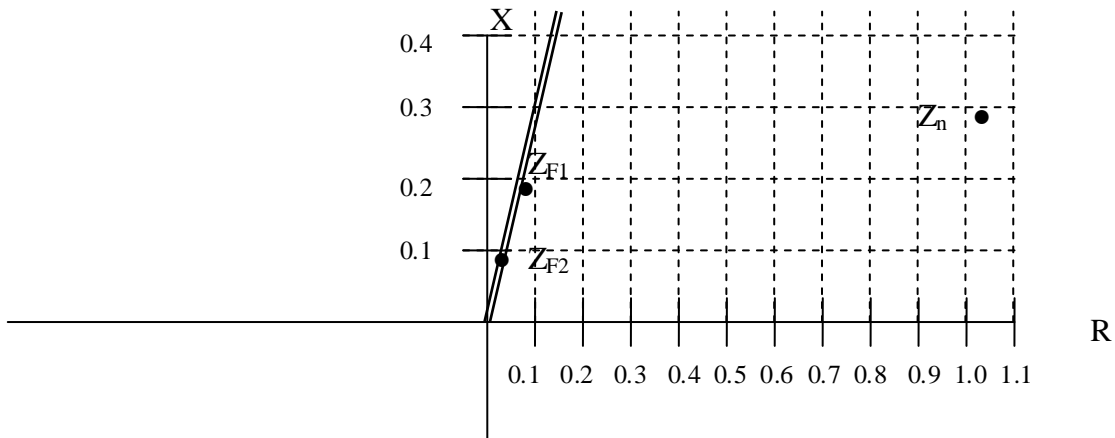


Fig. 3

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 quite significant. It implies that the relay can accurately judge the fault location based on the impedance it sees.

### 3.0 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.

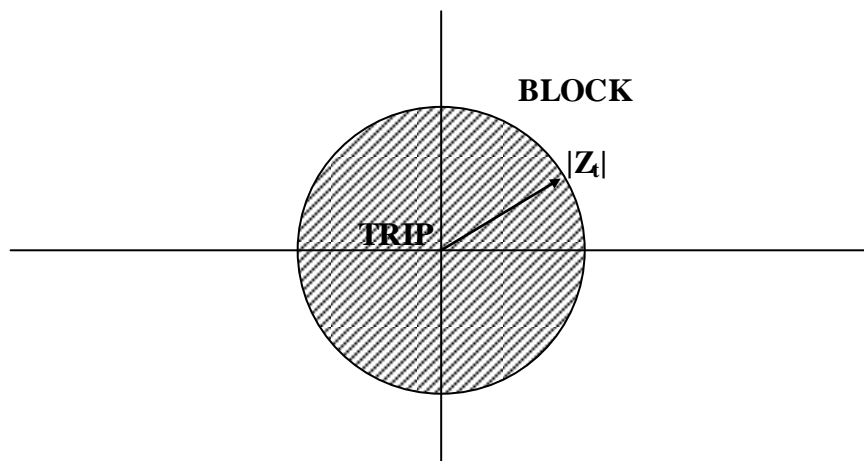


Fig. 4

We may also plot the locus of impedance values corresponding to the particular circuit we are protecting (the line impedance locus), as we move a fault 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.

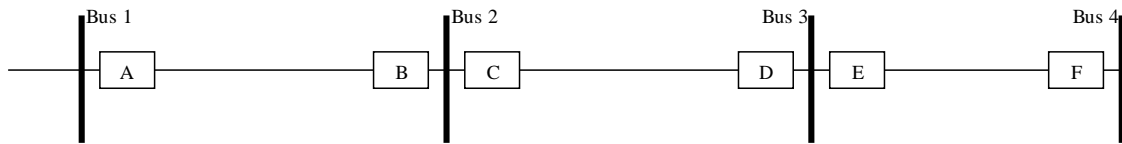


Fig. 5

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 is shown in Fig. 6.



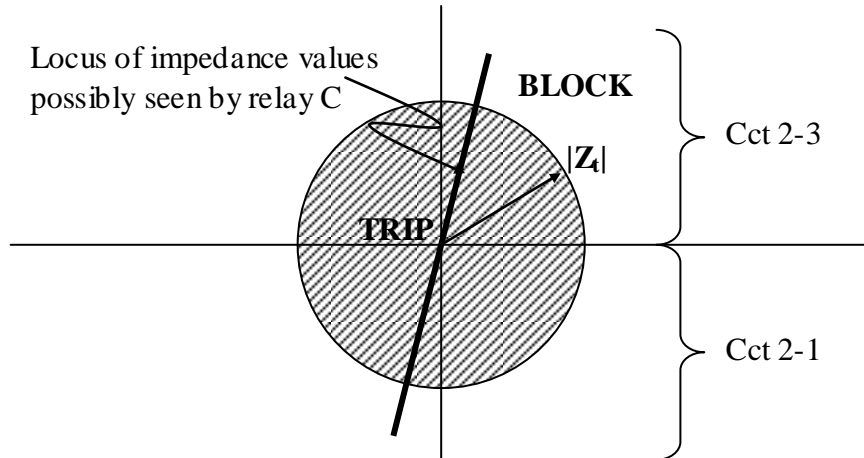


Fig. 6

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, where the directional relay is described in the previous notes called “Protection 3.” 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  $\theta$  is the angle of the  $I_{23}$  current phasor relative to the angle of the  $V_2$  voltage phasor.

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

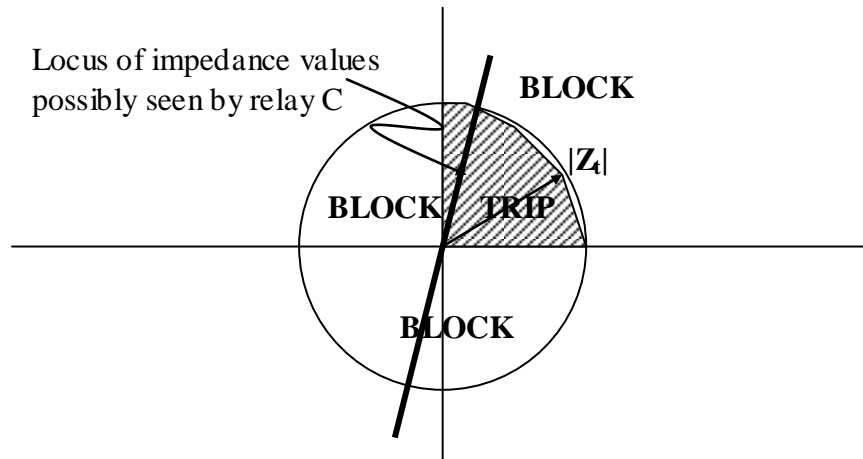


Fig. 7

Another approach to providing directionality in impedance relays is the Mho relay (13.4 in text). We will not have time to cover this in class.

### Zones of protection

The other thing to observe in Fig. 6 (and in Fig. 7) is that the line impedance locus extends beyond the trip zone indicated by the circle of radius  $|Z_t|$ . What is the significance of this?

This means that the relay C is set to protect only a portion of the cct. 2-3, as shown in Fig. 8.

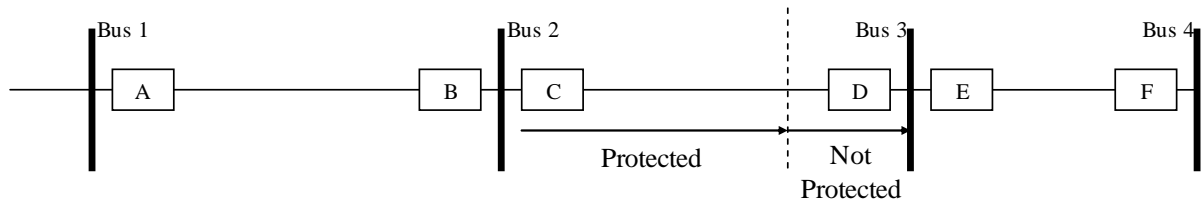


Fig. 8

It is common to set the relay to protect, within its primary zone, only about 80% of the circuit. Why would we want to design this relay to only protect a portion of the circuit?

The rationale (see Fig. 9) lies in the fact that a point on cct. 2-3, just to the left of bus 3 as denoted by the red circle, is electrically the same as a point on cct. 3-4, just to the right of bus 3, as denoted by the yellow circle.

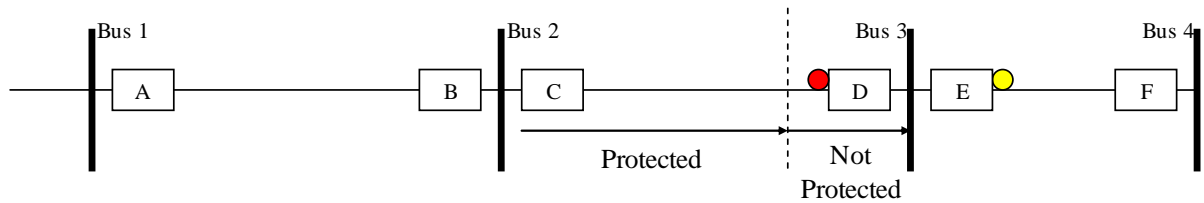


Fig. 9

If we set Relay C to protect 100% of cct. 2-3, so that it will trip for the red circle, then it will not be possible to ensure that Relay C will not trip for the yellow circle. If Relay C trips for the yellow circle, then bus 3 will be deenergized unnecessarily (Relay E should trip for the yellow circle).

This still leaves us with a problem, however. If Relay C does not trip for the red circle, what does?

This leads to the notions of zones, reach, and backup protection for impedance relays. These are very important and interesting notions. Let's investigate.

First, let's recall the term "zone." Impedance relays typically have 2 or 3 zones, called (appropriately) the relay's zone 1, zone 2, and zone 3.

The different zones are distinguished by the reach, or the impedance (distance) of the relay. Fig. 10 illustrates the three zones for Relay C.

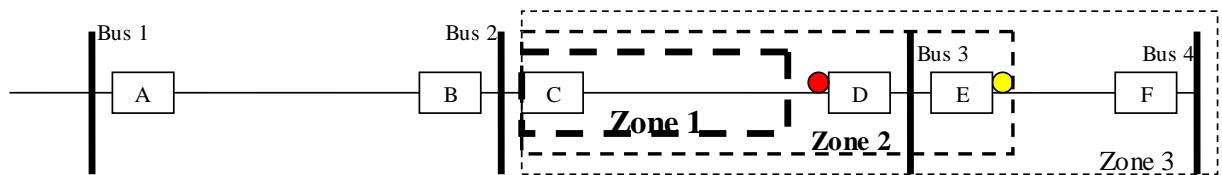


Fig. 10

The threshold settings for the three zones are denoted  $Z_{t1}$ ,  $Z_{t2}$ , and  $Z_{t3}$ , where  $Z_{t1} < Z_{t2} < Z_{t3}$ , as illustrated in the impedance characteristic of Fig. 11.

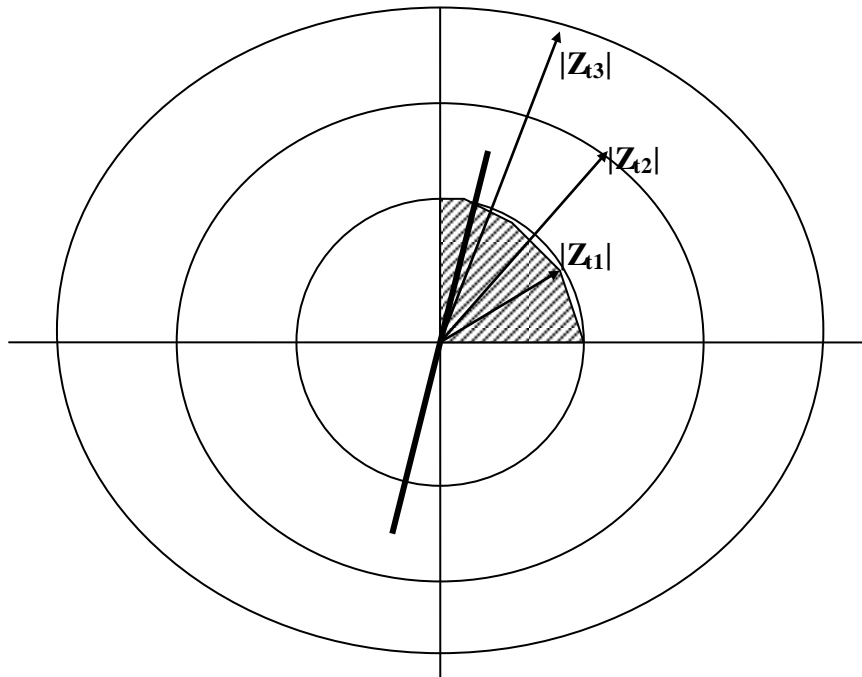


Fig. 11

With respect to these various zones, the impedance relay is set to operate as follows:

- As fast as possible for any fault within its zone 1, assume the operating time is  $T_1$ .
- With time  $T_2$  for faults within its zone 2
- With time  $T_3$  for faults within its zone 3 where  $T_1 < T_2 < T_3$ .

Figure 12 illustrates the relation between operating time for relay C and fault location.

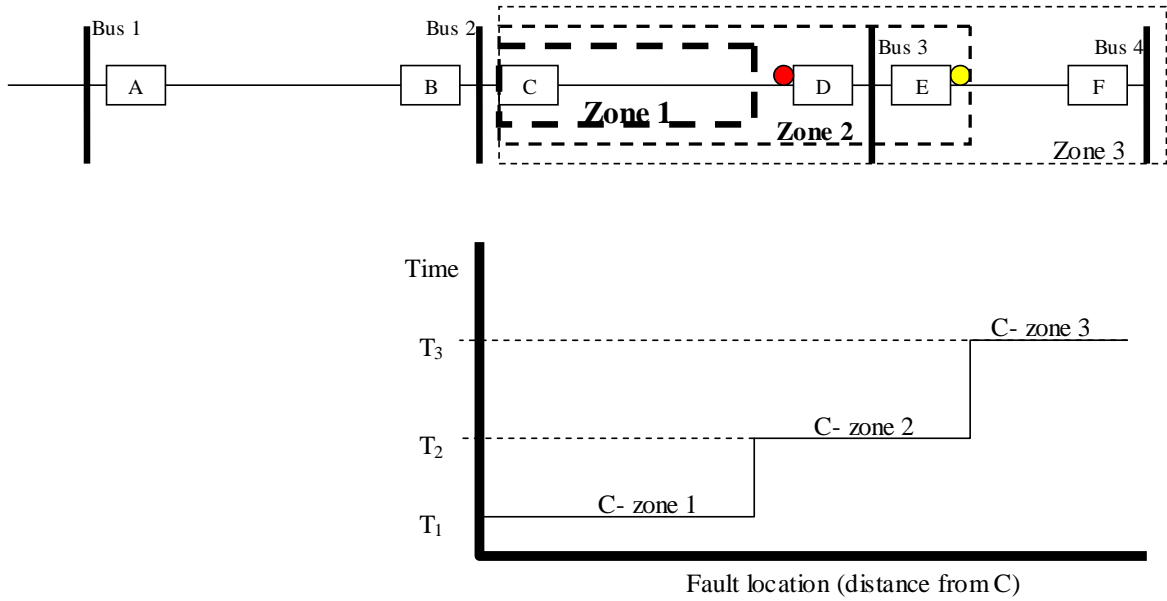


Fig. 12

Of course, Relays A, B, D, E, & F will also have similar characteristics. For example, I have superimposed a portion of relay E characteristic onto the time-location plot in Fig. 13.

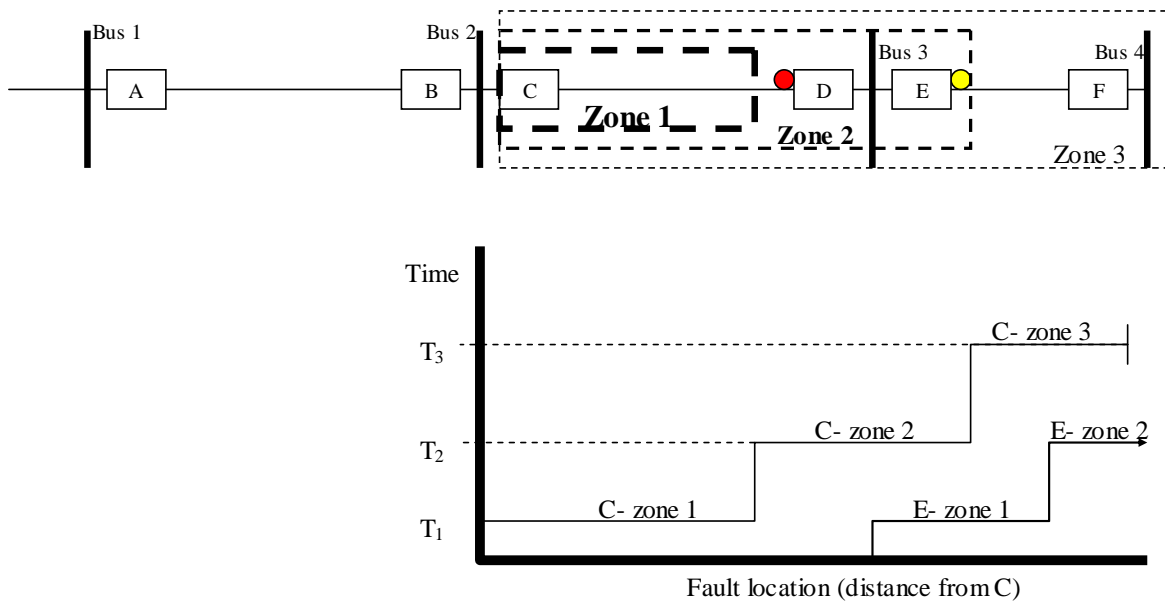


Fig. 14

From Fig. 14, we make the following observations:

- C-zone 2 overlaps with E-zone 1.
- C-zone 3 overlaps with E-zone 2.

What does this mean? This means that

- C-zone 2 serves as a backup for E-zone 1 and
- C-zone 3 serves as a backup for E-zone 2 (E-zone 2 will serve as a backup for some other relay's zone 1).

But note what is NOT happening:

- C-zone 1 and E-zone 1 do NOT overlap.
- C-zone 2 and E-zone 2 do NOT overlap.

What does this mean? This means that

- Relay C will NOT trip for faults in Relay E's primary zone if Relay E operates properly.
- Relay C will NOT trip for faults in Relay E's secondary zone if Relay E operates properly.



So we require that Zone k of Relay C not overlap with Zone k of Relay E, otherwise you may get Zone k operation of C for a desired Zone k operation of E.

The principle is a faster zone of protection must reach in distance beyond the reach of its backup.

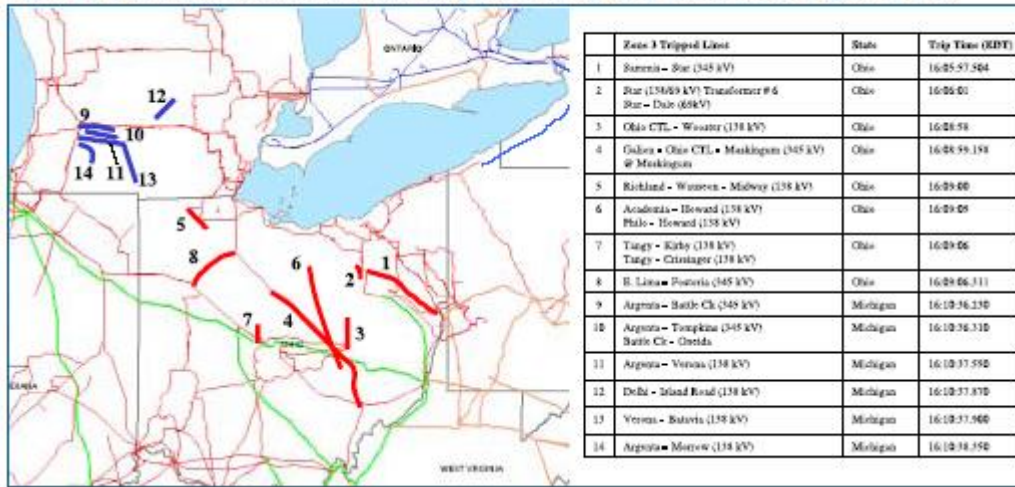
Final comment: Excerpted from “**Power System Outage Task Force Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations.**” See [http://energy.gov/sites/prod/files/oeprod/Documents andMedia/BlackoutFinal-Web.pdf](http://energy.gov/sites/prod/files/oeprod/Documents%20and%20Media/BlackoutFinal-Web.pdf)

“

Based on the investigation to date, the investigation team concludes that the cascade spread beyond Ohio and caused such a widespread blackout for three principal reasons. First, the loss of the Sammis-Star 345-kV line in Ohio, following the loss of other transmission lines and weak voltages within Ohio, triggered many subsequent line trips. Second, many of the key lines which tripped between 16:05:57 and 16:10:38 EDT operated on zone 3 impedance relays (or zone 2 relays set to operate like zone 3s) which responded to overloads rather than true faults on the grid.”

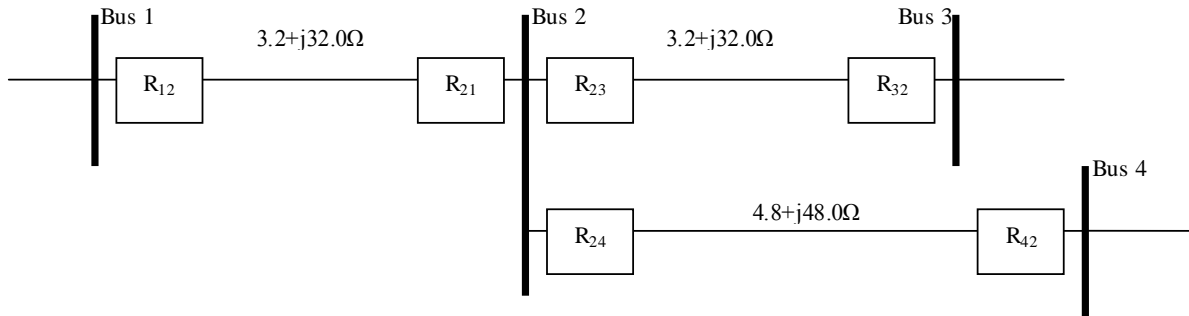
“**Phase 6.** After 16:10:36 EDT, the power surges resulting from the FE system failures caused lines in neighboring areas to see overloads that caused impedance relays to operate. The result was a wave of line trips through western Ohio that separated AEP from FE. Then the line trips progressed northward into Michigan separating western and eastern Michigan, causing a power flow reversal within Michigan toward Cleveland. Many of these line trips were from Zone 3 impedance relay actions that accelerated the speed of the line trips and reduced the potential time in which grid operators might have identified the growing problem and acted constructively to contain it.”

Figure 6.9. Map of Zone 3 (and Zone 2s Operating Like Zone 3s) Relay Operations on August 14, 2003



## Exam 2 Question

Consider the 138 kV transmission system.



Relays are impedance with directionality.

(a) Select the CT ratio so that maximum load current provides 5 amperes on the relay side. Choices are I:5 where I may be 50, 100, 150, 200, 250, 300, 400, 450, 500, 600, 800, 900, 1000, or 1200.

- (b) Select the VT ratio V:1 so that the rated line-to-neutral voltage provides 67 volts on the on the relay side.
- (c) If the primary (line) side of the relay sees an impedance of  $V_p/I_p=Z_{\text{line}}$ , determine an expression for the impedance seen on the relay side,  $Z_{\text{relay}}$ , as a function of  $Z_{\text{line}}$  and the CT and VT ratios.
- (d) Identify zone 1, 2, and 3 settings for R12, i.e., the threshold impedance values, on the relay side corresponding to 80% of line 1-2 (zone 1), 120% of line 1-2 (zone 2), 120% of the longest line beyond bus 2 (zone 3) which would be line 2-4 in this case.
- (e) Draw zone 1, 2, 3 circles on R-X diagram; plot the point corresponding to maximum cct.1-2 load of 50 MVA, 0.8 pf lag.