Protection 2

1.0 Introduction

There are five basic classes of protective relays:

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

We will study each of these.

But the simplest is the magnitude relay. We address it in these notes.

2.0 Magnitude relays

We saw in the last part of the previous notes “Protection 1” that redundancy (backup) of protective devices, even for a simple radial system, is complicated by the need to prevent backup protection from tripping when it is unnecessary to do so.

The way to address this issue is by providing time delay. The basic idea is that for a given fault current level, backup protection should be set to trip with a time delay relative to that of primary protection.

Three preliminary ideas need emphasis:

- Fault current magnitude is heavily influenced by the impedance between the fault point and the generation sources. Therefore, “close-in” faults have the higher fault currents.
- Minimum fault current for a given section of a power system is either a SLG[1] or LL fault at the electrically most distant point (point with greatest impedance from the source).
- The protection system implements three-pole switching independent of the fault type, i.e., circuit breakers on all three phases open for three-phase, LL, LLG, and SLG faults. This is also called “independent pole tripping.” So-

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[1] Here, by “fault current,” we mean the phase currents. Referring to Section 3.0 of the notes “UnsymmetricalFaultAnalysis2,” we observe that the phase currents are a function of the sequence currents, and the sequence currents depend on the sequence reactances and the connections of the sequence circuits for each particular fault type.

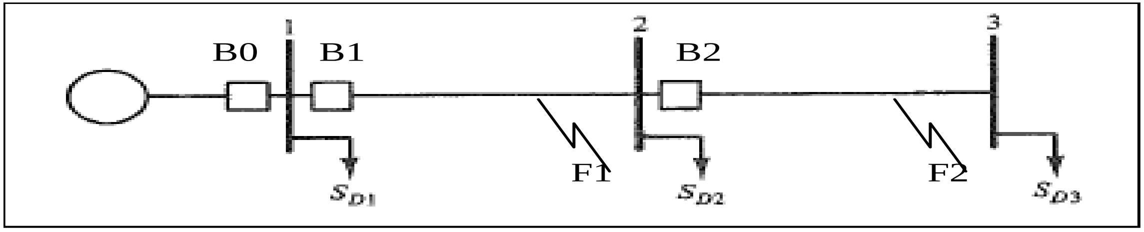
called single-pole switching is an alternative which is better for stability but has lower dependability than three-pole switching [1, p. 9-11]. The practice in the U.S. is to use three-pole switching, except in special cases; Europeans have taken the opposite approach, deploying single-pole switching in all EHV facilities since the 1950's [2].

Define the following:

- <u>Zone of protection</u>: for a relay, the portion of the power system for which the relay is designed to trip on occurrence of a fault.
- <u>Primary zone</u>: for a relay, the portion of the power system for which the relay is responsible to open first.
- <u>Primary relay</u>: for a zone, any relay that has responsibility to operate first on occurrence of a fault in that zone.
- <u>Backup relay</u>: for a zone, any relay that has responsibility to operate if the primary relay fails to operate.

- Relay operating time, T_P: This is the time required for the relay to operate for a fault in its primary zone.
- Coordination time, T_{CT}: time delay between operation of primary and backup relays. If the fault is cleared before expiration of the delay time, then the relay will not operate.
- Minimum fault current magnitude: $|I_f|$, the minimum fault current magnitude seen by the relay for any fault in the zone of protection.
- Relay pickup: $|I_p|$, the current magnitude for which the relay will operate.

Example: Consider coordinating relays R1, R2.



Setting R2 is easy. Compute the minimum fault current, $|I_{f23,min}|$, which is for a SLG or LL fault located at bus 3 (maximum impedance between source and fault). Then set relay pick-up $|I_{p2}|$ at that level (or lower), to operate as fast as possible.

So this scheme is:

$|I_f| > |I_p|$ ➔ Trip

$|I_f| < |I_p|$ ➔ Block

It is common to represent tripping characteristics on either a current or an impedance plane. Magnitude relays are often represented on a current plane, as shown below in Fig. 1.

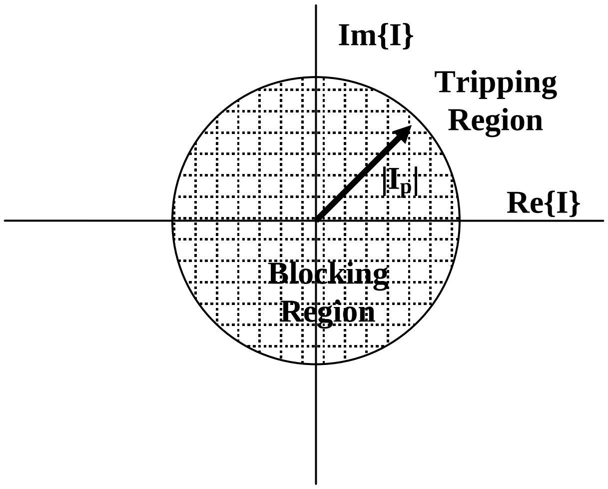


Fig. 1: Magnitude relay tripping characteristic

Let's assume $|I_{f23,min}|$=4 pu (computed based on fault analysis), and so $|I_{p2}|$=4 pu.

Now, let's consider approaches for setting R1.

Approach 1: Here, we use the same pickups for R1 and R2 ($|I_{p1}|=|I_{p2}|=4.0$).

- What is right with this? Both relays operate immediately for faults in their respective primary zones, i.e., R2 operates for faults on line 2-3, and R1 operates for faults on line 1-2.
- What is wrong with this? For all faults on line 2-3, R1 also operates immediately and unnecessarily removes line 1-2.

Approach 2: Here, we again use the same pickups for R1 and R2 ($|I_{p1}|=|I_{p2}|=4.0$) but now we introduce a time delay (coordination time) T_{CT} to the operation of R1.

- What is right with this? For faults on line 2-3, R1 will wait and so R2 will operate to clear them; the coordination time prevents R1 from operating for these faults.
- What is wrong with this? R1 will wait the same amount of time for faults on line 1-2! This is bad because line 1-2 is R1's primary zone of protection; therefore, for faults on line 1-2, we want R1 to operate as fast as possible.

Approach 3: Again, set the pickup for R2 at the minimum fault current for a fault on line 2-3, i.e., $|I_{p2}|=|I_{f23,min}|=4.0$. But now, instead of using the same value for the R1 pickup, let's use the minimum fault current for a fault on line 1-2, $|I_{f12,min}|$. This would be for a SLG or LL fault at bus 2. Since this fault is closer to the source than bus 3 (and so source-to-fault impedance is less), $|I_{f12,min}|$ will be larger than $|I_{f23,min}|$. Let's assume $|I_{f12,min}|=4.5$ pu. Therefore, $|I_{p1}|=|I_{f12,min}|=4.5$pu.

- What is right with this? Both relays operate immediately for faults in their respective primary zones, i.e., R2 operates for faults on line 2-3, and R1 operates for faults on line 1-2.
- What is wrong with this? For *some* faults on line 2-3, R1 also operates immediately and unnecessarily removes line 1-2. Why?
    - $|I_{f23,min}|=4.0$pu is the minimum fault current for faults on line 2-3, and so all faults on line 2-3 (except for the SLG or LL fault at bus 3) will have current exceeding 4.0pu. But might they exceed $|I_{p1}|=|I_{f12,min}|=4.5$pu?
    - $|I_{f12,min}|=4.5$ pu is the minimum fault current for faults on line 1-2, based on a SLG/LL

fault at bus 2. There is no guarantee that there might be a line 2-3 fault that results in a current exceeding 4.5 pu, and if there were, then R1 would operate for a line 2-3 fault. For example, a three-phase fault on line 2-3, very close to bus 2, could have current exceeding that of a bus 2 SLG/LL fault.

Figure 2 conceptually illustrates the situation.

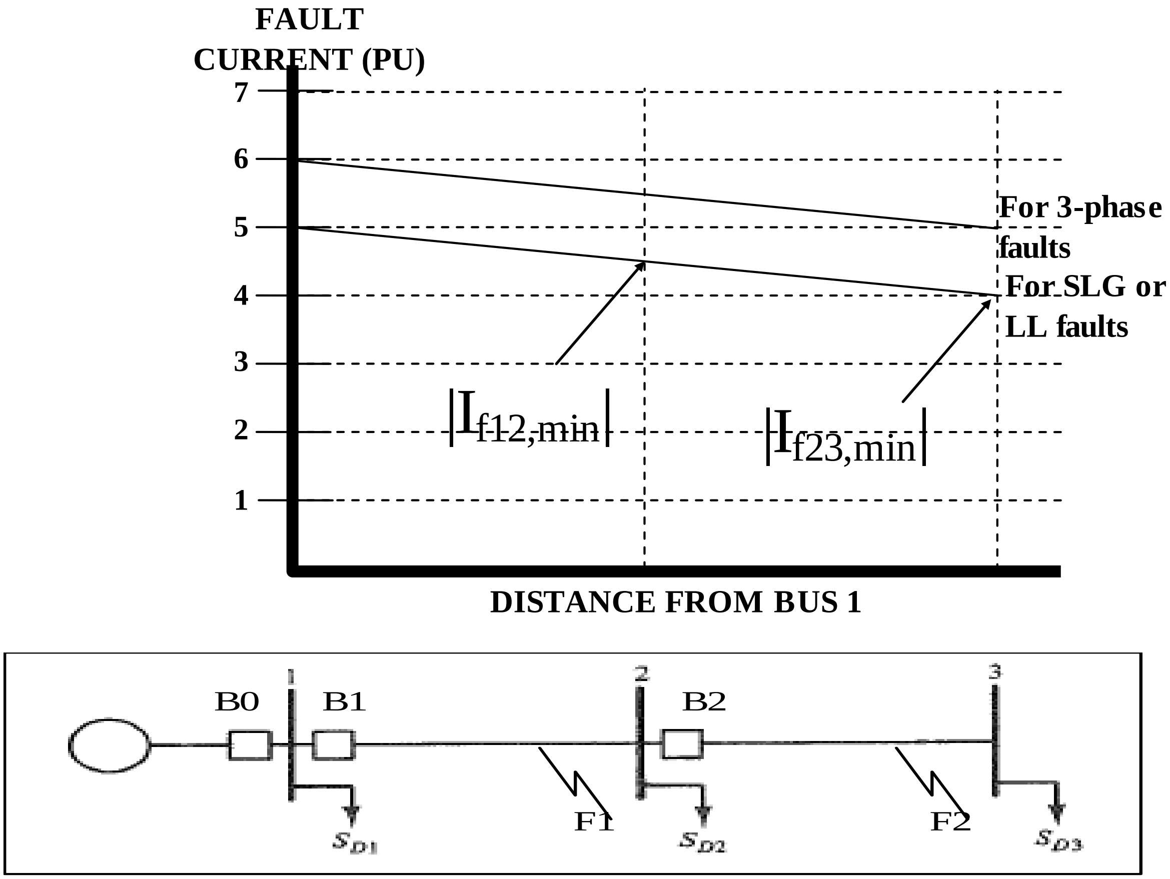


Fig. 2: Fault current magnitudes

Approach 4: Consider there are some faults for which the currents are so low that we know they must be faults on line 2-3, and there are some faults for which the currents are so high that we know they must be faults on line 1-2. Figure 3 illustrates these two sets of faults in the cross-hatched regions.

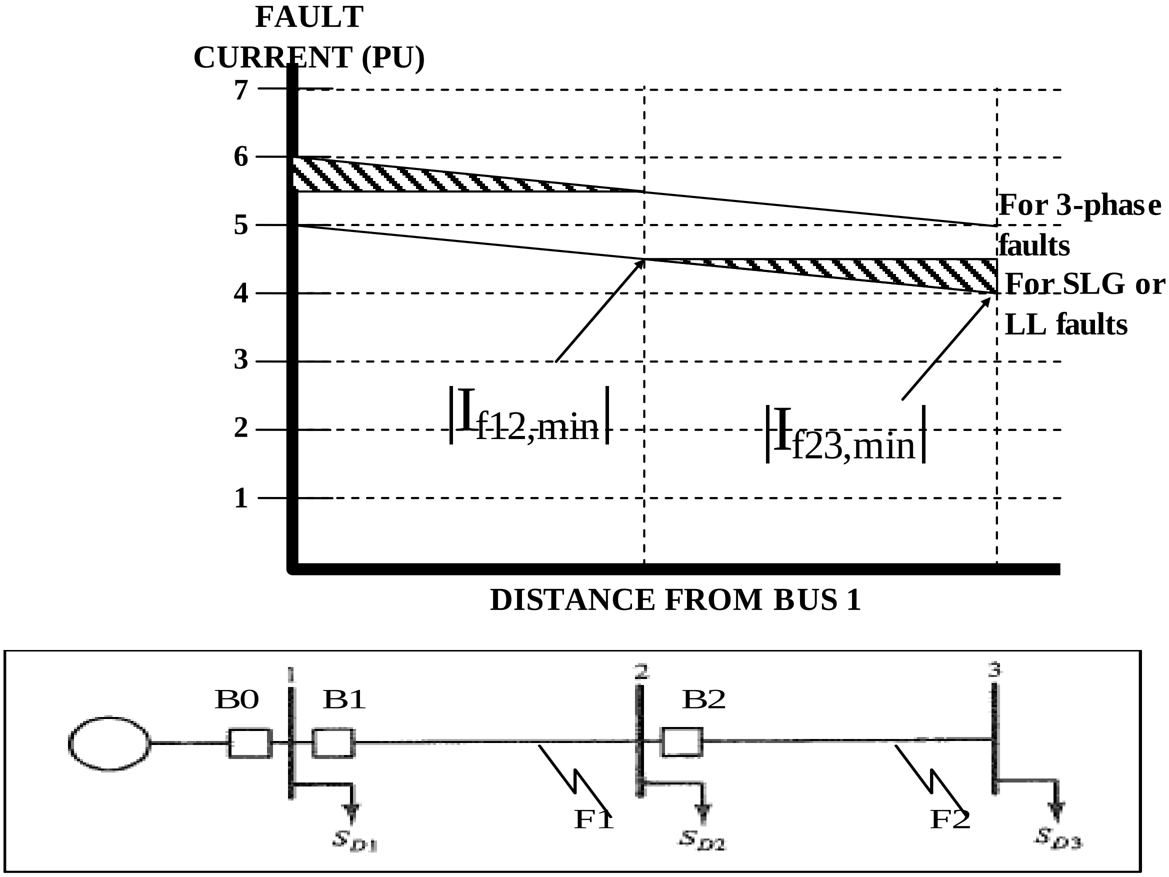


Fig. 3: Fault current magnitudes

The most important aspect of Fig. 3 is that there is a region of fault current, in this case between 4.5 pu and 5.5 pu, for which the fault could be on either line 1-2 or line 2-3. Thus, given that our relays only measure current, for a current in this range of 4.5-5.5pu, the relay can only know that there is a fault, but it cannot identify the line on which the fault occurs.

We address this uncertainty by using time delay. Our approach will be similar to Approach 2, where we set R1 with a pickup of $|I_{p1}|=|I_{f12,min}|=4.5$pu and a time delay. Now, however, we will improve over Approach 3 by making the time delay a function of current: the higher the current, the more likely the fault is on line 1-2, and the lower the time delay, and for currents above 5.5pu, there should be no time delay at all.

The time-delay function is illustrated by the family of curves shown in Fig. 13.3 of your text and in Fig. 4 below. We will say more about this, but for now, observe that each curve shows increasing time delay (abscissa) with decreasing current (ordinate).

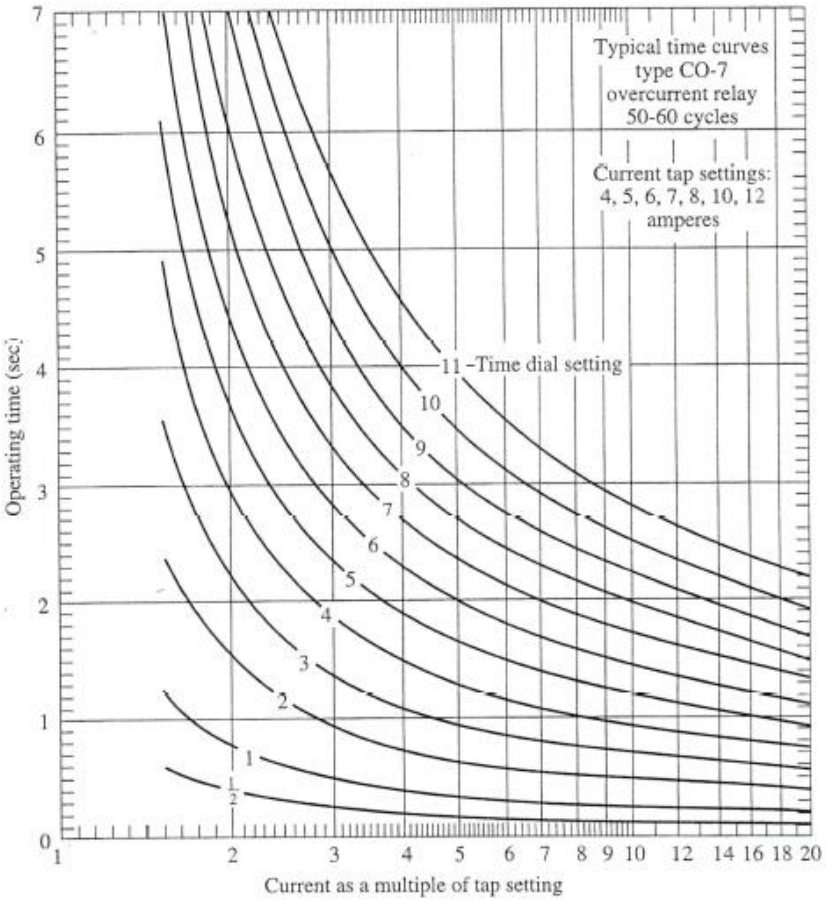


Figure 13.3 CO-7 time-delay overcurrent relay characteristics. (Courtesy of Westinghouse Electric Corporation.)

Fig. 4: CO-7 relay characteristic

- What is right with this? Three things:
  - It enables immediate clearing of all faults on line 2-3 by R2 while ensuring (with the delay) that R1 does not operate for a fault on line 2-3.
  - For low currents, it has very large delay while for high currents, it has very small

    delay, an appropriate approach because (i) the higher the current, the more severe the fault; (ii) the higher the current, the more likely it is located on line 1-2.

    - R1 provides an effective backup for R2, for faults having currents in excess of $I_{p2}=I_{f12,min}=4.5$pu.

- What is wrong with this? Just one thing: R2 has no backup for currents below 4.5pu.

Approach 5: Use exactly approach 4, except set the R1 pickup to be the same as the R2 pickup: $|I_{p2}|=|I_{f23,min}|=4.0$. The benefit to doing this is that then, R2 has backup for all faults and not just the ones about 4.5 pu. This is the approach we will use to set R1 in our problem.

Comments on relay characteristic

The time-overcurrent curve of Fig. 13.3 in your text and Fig. 4 above is for a particular kind of relay manufactured by Westinghouse called the CO-7 time-delay overcurrent relay. We provide some explanatory comments about this figure.

- The characteristic is said to be inverse-time, because time increases as current decreases.
- The current on the ordinate is given not in units of amperes or per-unit but rather as a function of a ratio $|I_f|/I_p|$. This is called "multiple of tap setting" on the ordinate of Fig. 13.3. You can interpret it as either of:
  - o Multiples of pickup on the high side of the CT
  - o Multiples of pickup on the low side of the CT
- The ratio of CT currents will be inverse to the turns ratio (as for any transformer), so

$$\frac{\boldsymbol{I}_{\text{Line}}}{\boldsymbol{I}_{\text{Relay}}} = \frac{\boldsymbol{N}}{\boldsymbol{5}}, \quad \boldsymbol{N} > \boldsymbol{5} \tag{1}$$

  where the "5" is the relay-side current rating, a US standard [1, p. 157]. There are limited, discrete choices available for N.

- Using I_p as the minimum current level on the line-side of the CT for which the relay will operate, we have from (1) that

$$\frac{I_p}{Tap} = \frac{N}{5}, \quad \Rightarrow TAP = \frac{5}{N} I_p \tag{2}$$

  where Tap is the pickup setting, in Amps on the relay side of the CT.

- There are relays manufactured by other companies having a similar characteristic, e.g., the GE IFC-53.

Homework #5: (Part A). Problems 13.1-13.5 in text, based on Example 13.1 in the text.

3.0 Example

This example is similar to example 13.1 in the book, but not at all identical (and perhaps simpler). Study one; then work the other.

Consider the following 13.8 kV system.

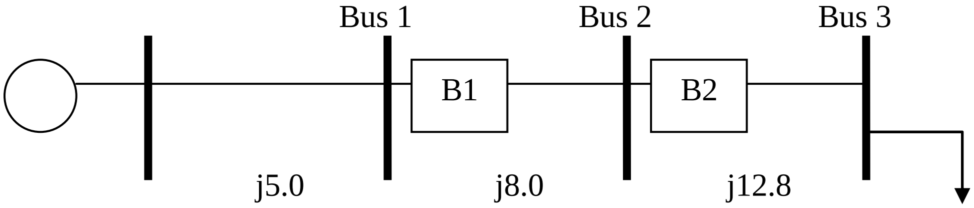


Fig. 5: Example system

Assume all sequence (pos, neg, zero) impedances are the same for each component and are given on the diagram. Find CT ratios, tap settings, and time dial settings (TDS) for B1 and B2. Use the GE IFC-53 relay, given in Fig. 6 below.

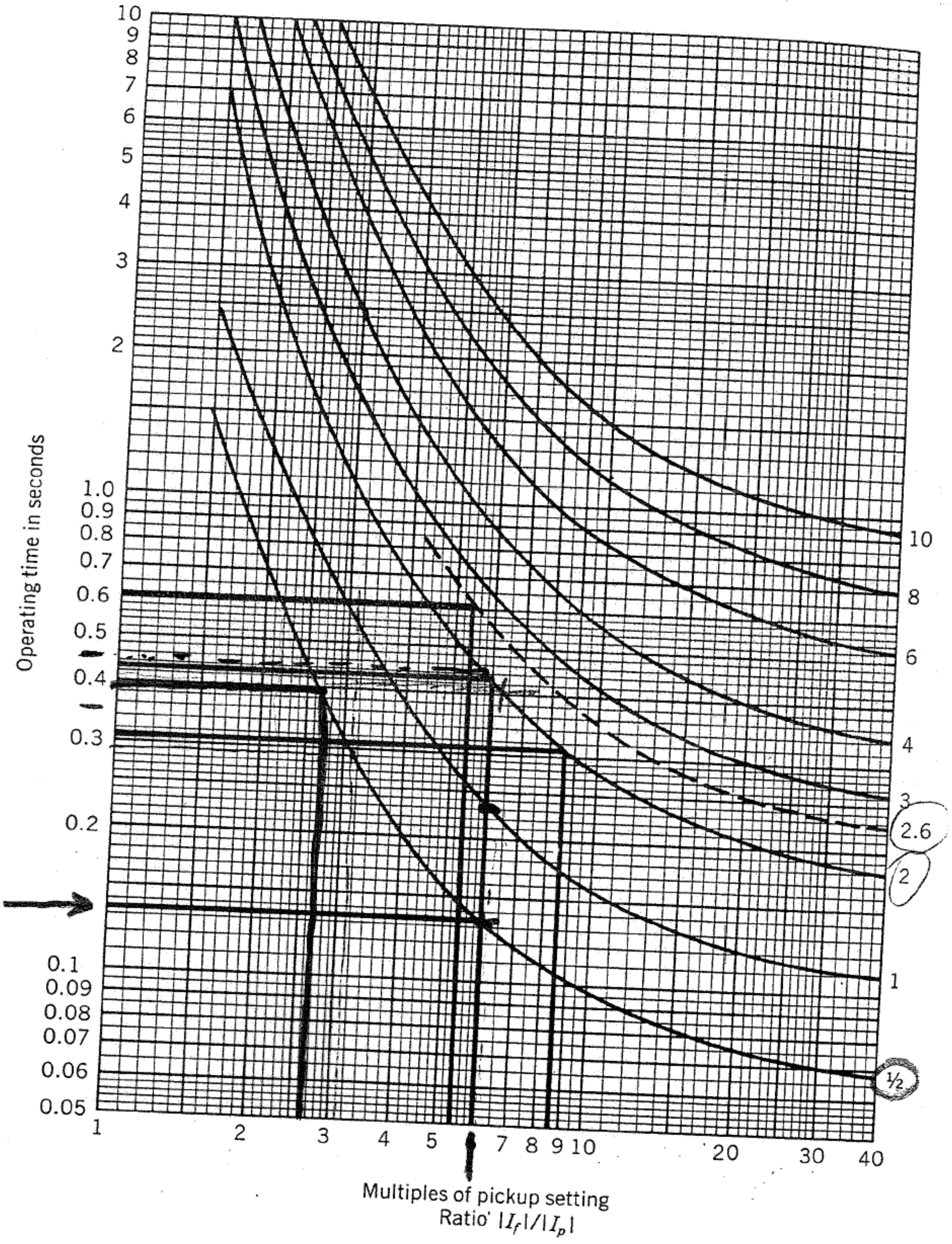


Fig. 6: GE IFC 53 relay characteristic

Possible CT ratios are:
50:5, 100:5, 150:5, 200:5, 250:5, 300:5, 400:5, 450:5, 500:5, 600:5, 800:5, 900:5, 1000:5, 1200:5.

Possible Taps (CT settings) are 4, 5, 6, 7, 8.

The coordination time is specified to be $T_{CT}=0.3$ sec, chosen to allow relay R2 to open breaker B2 accounting for relay operating time, breaker clearing time, and a safety margin [1, p. 397].

Let's first set R2.

We assume here that the LL fault gives the minimum fault current. Working in volts and amps, the LL fault is computed as follows.

First, get the LN voltage: V=13.8/sqrt(3)=7.97 kV.

The positive and negative sequence networks as seen from the bus 3 location are shown in Fig. 7.

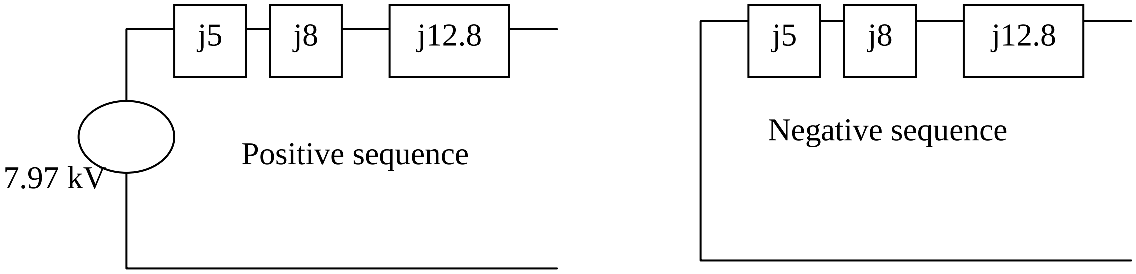


Fig. 7: Positive & negative sequence networks

The composite impedance in each of the two sequence circuits is j25.8 ohms. Therefore when we connect them together, as we should for the LL fault, we obtain:

$$I_a^+ = -I_a^- = \frac{7970}{j51.6} = -j154.4$$

And of course, $I_a^0 = 0$. Then we can get abc currents by multiplying by A, with the key calculation being for I_b, as follows

$$\begin{aligned} I_b &= \alpha^2 I_a^+ + \alpha I_a^- \\ &= 1\angle 240(-j154.4) + 1\angle 120(j154.4) \\ &= 267.4\angle 180 \end{aligned}$$

This is the minimum fault current. Call it $I_{f,\min}$. We now must recognize that there could be faults having fault impedance that result in even lower fault currents. To account for this, it is common to use a "safety" factor of 1/3 in identifying the desired pickup:

$$I_{f,\min}/3 = 267.4/3 = 89.1 \equiv I_{p,desired}$$

So now let's look at possible CT ratios:
50:5➔ $\text{Tap}_{\text{desired}}$=(5/50)(89.1)=8.91
100:5➔ $\text{Tap}_{\text{desired}}$=(5/100)(89.1)=4.45
150:5➔$\text{Tap}_{\text{desired}}$=(5/150)(89.1)=2.97
Noting that the highest available Tap is 8, if we choose the 50:5 CT, then we would have to choose 8, in which case we would get a pickup of 8(50/5)=80 Amperes. This may be lower than we like (too close to the load current).

Since the lowest Tap is 4, choosing the 150:5 CT results in a pickup of 4(150/5)=120. This may be too high (might miss some hi-impedance faults).

If we choose the 100:5 CT, we could pick a tap of 4, in which case we get a pickup of 4(100/5)=80, or we could pick a tap of 5, in which case we get a pickup of 5(100/5)=100.

The tap of 5 is more desirable, where we have a little less safety factor than 1/3, but we are more distant from the load currents.
So select the 100:5 CT, with a tap of $\text{Tap}_{\text{actual}}$=5.

In this case, the pickup is, as indicated above, $I_{p,actual}$=100A.

Now we need to select the time-dial setting (TDS). To do this, we need two things.

1. Specification on delay time – in this case, we want to operate as fast as possible, so there should be no intentional delay (pick TDS=1/2).
2. We check that the current for which operating time should be greatest – the minimum fault current, which is $I_{f,min}$=267.4A (see p.17). Thus, most other faults (which will have higher currents) will operate in less time. To identify this current on the time-overcurrent curve, we need to convert this current to
   - multiples of Tap (on the low side), or
   - multiples of pickup (on the high side).

   So we have $I_{f,min}/I_{p,actual}$=267.4/100=2.67.

   (Alternatively, we can convert $I_{f,min}$ to low side amps: 267.4*(5/100)=13.37A which has multiples of Tap as 13.37/5=2.67.)

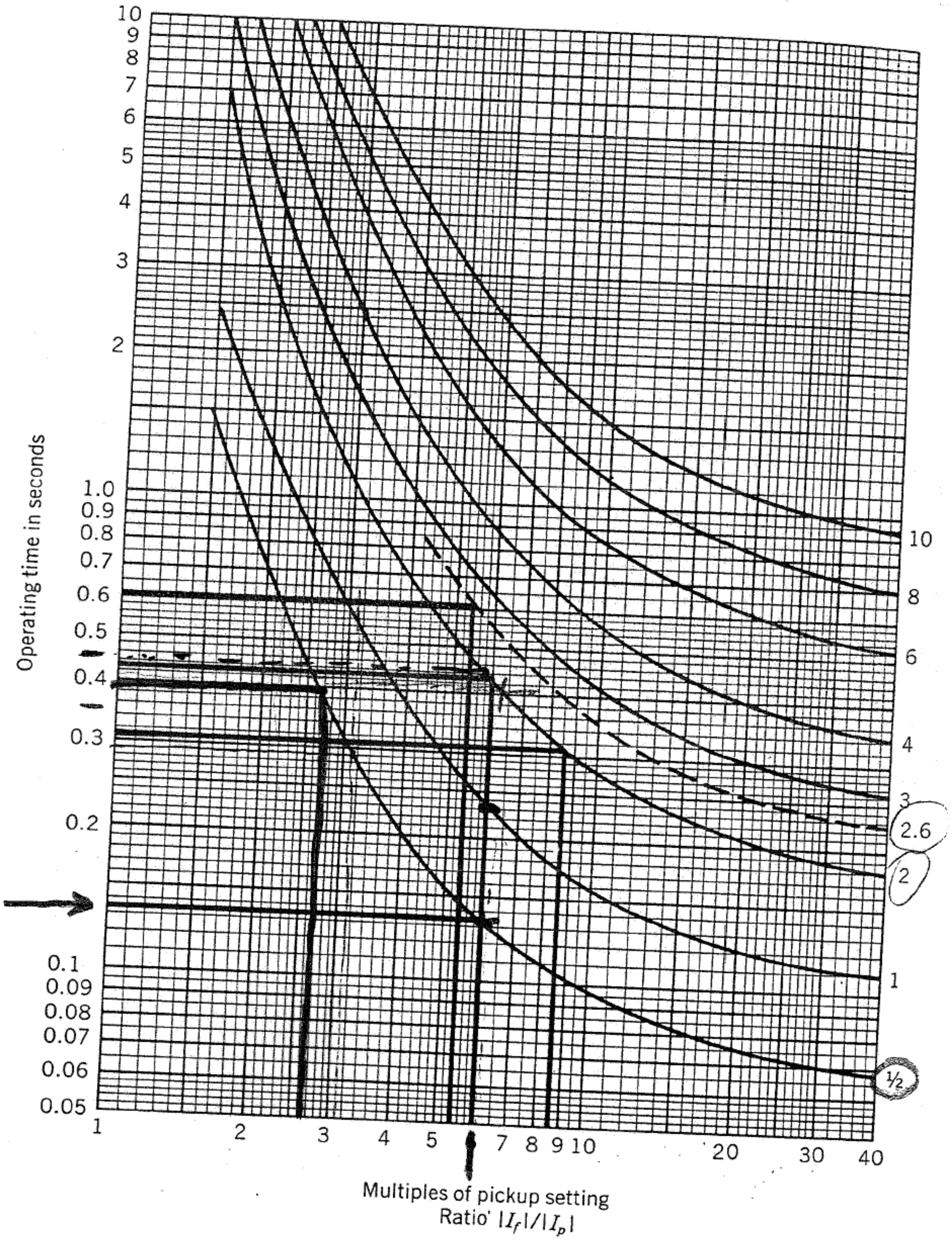
Reading off the time-overcurrent curve, if we pick a TDS of ½ (which results in the fastest possible clearing time), we see that 2.67 multiples of pickup results in a clearing time of 0.4 seconds. That is not very fast, but keep in mind here that most faults will have more current and will therefore clear faster.

The time of 0.4 seconds represents the slowest operating time among all faults in the protection zone for which there is no fault impedance.

Faults with lower fault currents than 267.4 A will open more slowly. For example,

- The time-overcurrent curve indicates a fault current of 1.5×pickup (150A in this case), using a TDS of ½, will require 1.5 sec to open.
- The time-overcurrent curve indicates a fault current of 1.0 times pickup (100A), using a TDS of ½, will require an infinite amount of time to open. This is the motivation for having the 1/3 margin built in: we would not want a faulted circuit to remain uncleared!

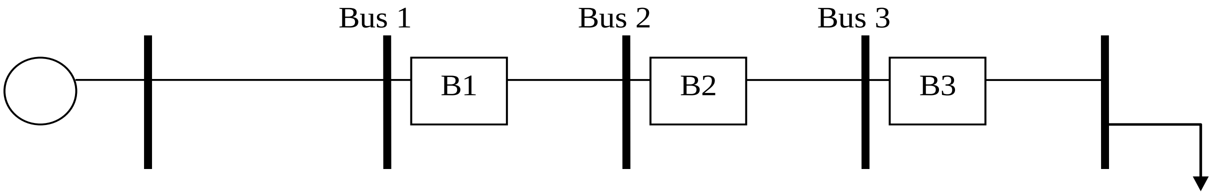
I have copied the time overcurrent curve below (and again on p. 26), even though it is also on page 15, to avoid having to flip back and forth.



Now set R1.
Here, we recall that R1 must serve as the backup for R2. It must operate for the smallest current in R2's zone, therefore the selection of CT ratio and Tap must be based on the line-line fault at the far end of line 2-3 (the R2 zone).

But this is what we used for setting R2. If we do the same here, the selection of CT ratio and Tap will be as for R1.
Therefore, once again, select the 100:5 CT, with a tap of $\text{Tap}_{\text{actual}}=5$, resulting in a pickup of $I_{p,\text{actual}}=100\text{A}$.

Aside: The fact that the CT ratio, Tap, & pickup for R1 is the same as that for R2 is due to the fact that R2 protects the last line of a radial system and therefore has no backup function (there is nothing "downstream" to backup). Consider there to be a 3rd section, as shown in Fig. 6 (similar to Example 13.1).



Then

- The R3 pickup would be set for minimum fault current in the R3 zone,
- The R2 pickup would be set for minimum fault current in the R3 zone, and
- The R1 pickup would be set for minimum fault current in the R2 zone.

Therefore R3 and R2 would have the same CT ratios and pickups, but R1 and R2 would not. So you get identical designs on CT ratio and pickups on two successive relays when one of them has no backup function (this will be the one at the end of the radial circuit).

So now set the relay TDS for R1. Here, we must ensure a coordination time of 0.3 secs. **This means that for any fault in the primary zone of R2, relay R1 should not open until <u>at least</u> T_{CT}=0.3 secs after relay R2 is supposed to open.**

This ensures the backup function, although present, will not interfere with the proper operation of R2.

Referring to the time-overcurrent curve, note that, for two relays and their corresponding selection of CT ratios and taps, and for a given current (translating to specific ratios on the abscissa), we can introduce a desired time delay between operation of the two relays by careful selection of time dial setting for each.

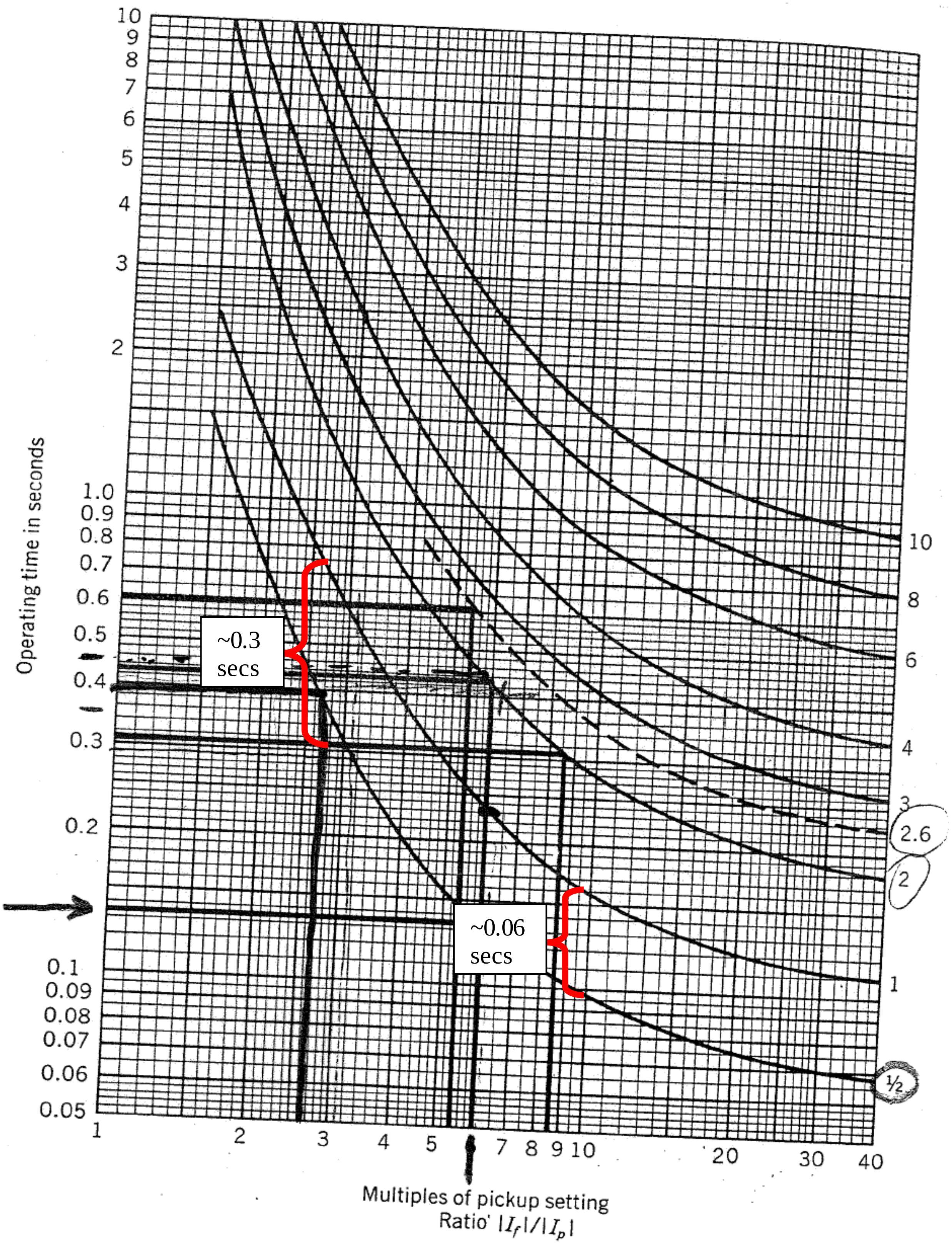
Question: What current should we choose to perform the coordination?

- Minimum fault current in the R2 zone?
- Maximum fault current in the R2 zone?
- Minimum fault current in the R1 zone?
- Maximum fault current in the R1 zone?

The choice should be for a current in the R2 zone because it is for such currents that we want the time delay (we want fast operation for currents in the R1 zone). So eliminate the bottom two options.

In deciding between the top two options, note

- Reference back to definition of coordination time on previous page indicates we need at least 0.3 seconds, so more is OK, less is not.
- Studying the time-overcurrent curve, we note that two curves (corresponding to different time-dial settings) are “closer” in vertical distance (along the ordinate) for larger currents than for small (they do not appear that way, visually, because of the ordinate is on a logarithmic scale). For example, consider the two TDS curves of ½ and 1, and see that the time difference in operation at 2.67 times pickup is about 0.3 seconds. But at 10 times pickup, the time difference in operation is about 0.06 seconds.


Operating time in seconds
10
9
8
7
6
5
4
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
1
2
3
4
5
7
8
9
10
20
30
40
Multiples of pickup setting
Ratio' $|I_f|/|I_p|$
10
8
6
4
3
2.6
2
1
½
~0.3 secs
~0.06 secs

Therefore, to ensure we get AT LEAST 0.3 sec time difference between the two relays (each relay having its own TDS and therefore its own time-overcurrent curve), we should perform the design for the maximum current (furthest to the right on the time-overcurrent curves). Then, we will be certain that the time delay exceeds the specified 0.3 seconds for any other fault.

It is generally the case that the maximum fault current is for a three-phase or a SLG fault. Assume that it is a three-phase fault. And to get maximum fault current, choose the "closest-in" location in the secondary zone of R1, which would be just to the right of R2.

Referring to Fig. 4, the Thevenin impedance for the positive sequence network will just be j5+j8=j13.

Computing the positive sequence fault current, we get

$$I_a^+ = \frac{7970}{j13.0} = -j613.1A = I_{f,\max}$$

This would have a ratio of $I_{f,max}/I_{p,actual}$=613.1/100=6.13 times the pickup.

From the time-overcurrent curves, we see that R2 (set at TDS of ½) will operate in about T_P=0.135 seconds. So we need R1 to operate in $T_B=T_P+T_{CT}$=0.135+0.3=0.435 seconds.

Because CT ratio and Tap are the same for R1, we can use the 6.13 times pickup for it as well. Move up from the T_P=0.135 point on the ordinate until we get to T_B=0.435, then move right until we get to the vertical line corresponding to 6.13 times pickup. The intersection corresponds to desired TDS curve, which has a value of 2.

Design Summary:

The final design to give coordination time of 0.3 seconds should appear as below:

	CT Ratio	Tap	TDS
R2	100:5	5	1/2
R1	100:5	5	2

4.0 Design Approach Summary

1. Coordination time is the time delay between operation of the primary relay and operation of the backup relay.
2. Tap is the pickup setting, in amperes, on the relay side of the CT; it has limited discrete choices.
3. Choosing taps and CTs (determines relay pickup)
   a. First determine the minimum fault current for which the relay should protect. If the relay has back-up responsibility, this will be for a fault outside the primary zone. Often (but not always), it is for a line-line fault.
   b. Employ a "safety margin."

$$I_{p,desired} = \frac{I_{f,\min}}{3}$$

c. Compute desired tap from

$$Tap_{desired} = I_{p,desired}\frac{5}{N}$$

for several different values of N. Choose a CT ratio that gives a $Tap_{desired}$ close to an available Tap, call it Tap_{actual}. Then recompute the pickup as

$$I_{p,actual} = \left(\frac{N}{5}\right)Tap_{actual}$$

and check to ensure it is close to $I_{p,desired}$.

4. Choosing TDS for back-up relays:
   a. Compute maximum fault current in backed-up zone, $I_{f,max}$.
   b. Identify operation time for primary relay, T_P
   c. $T_B=T_P+T_{CT}$
   d. Choose time dial setting to obtain T_B.

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[1] J. Lewis Blackburn, “Protective relaying: principles and applications,” Marcel Dekker, 1987.

[2] C. Taylor, W. Mittelstadt, T. Lee, J. Hardy, H. Glavitsch, G. Stranne, and J. Hurley, “Single-pole switching for stability and reliability,” IEEE Transactions on Power Systems, Vol. PWRS-1, No. 2, May 1986.