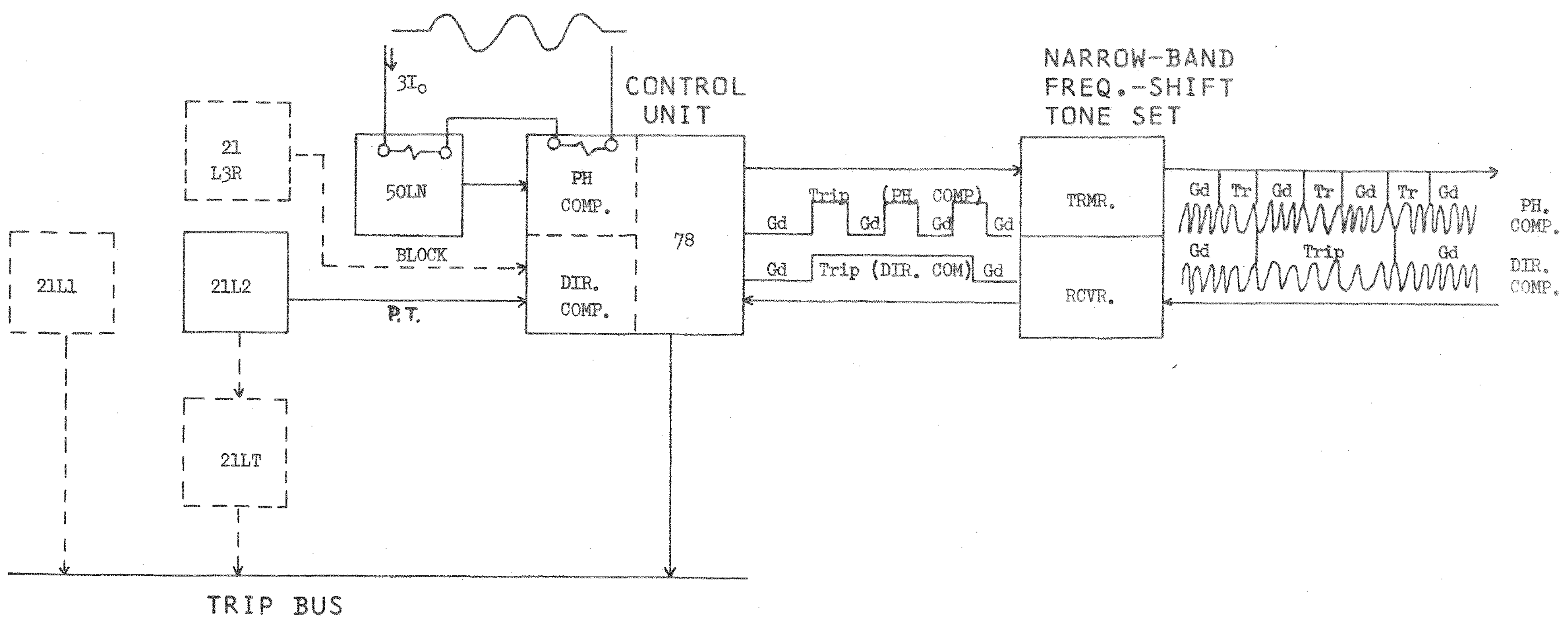
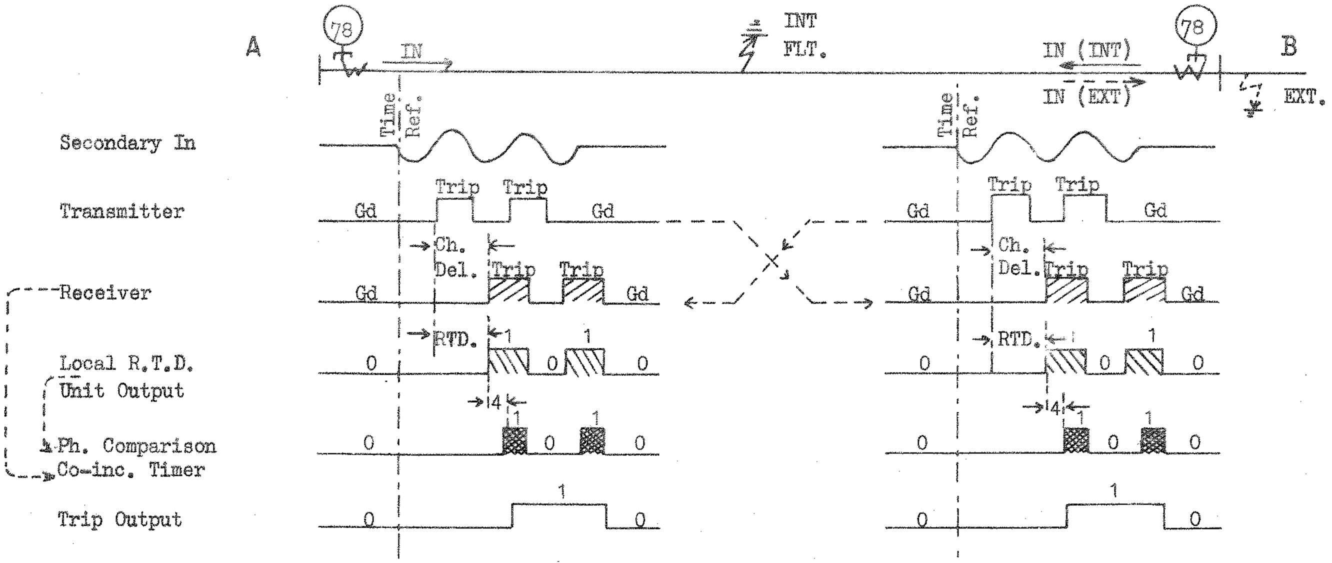
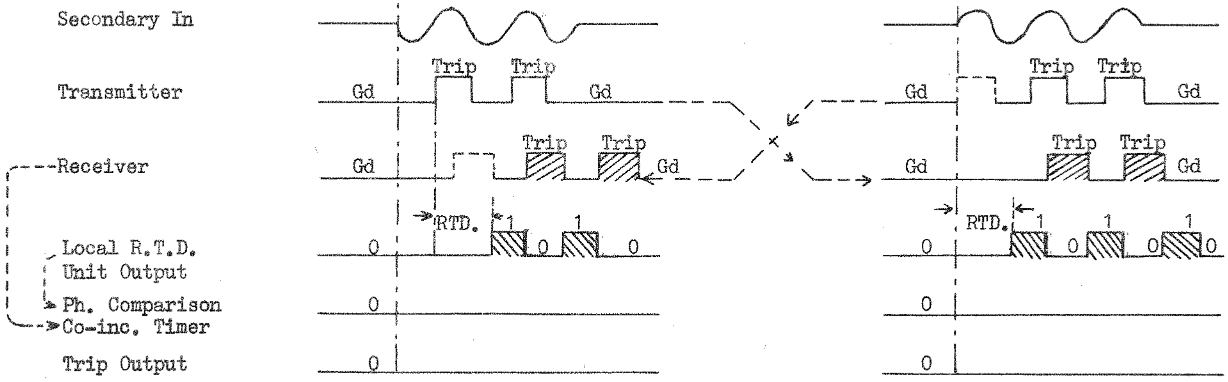


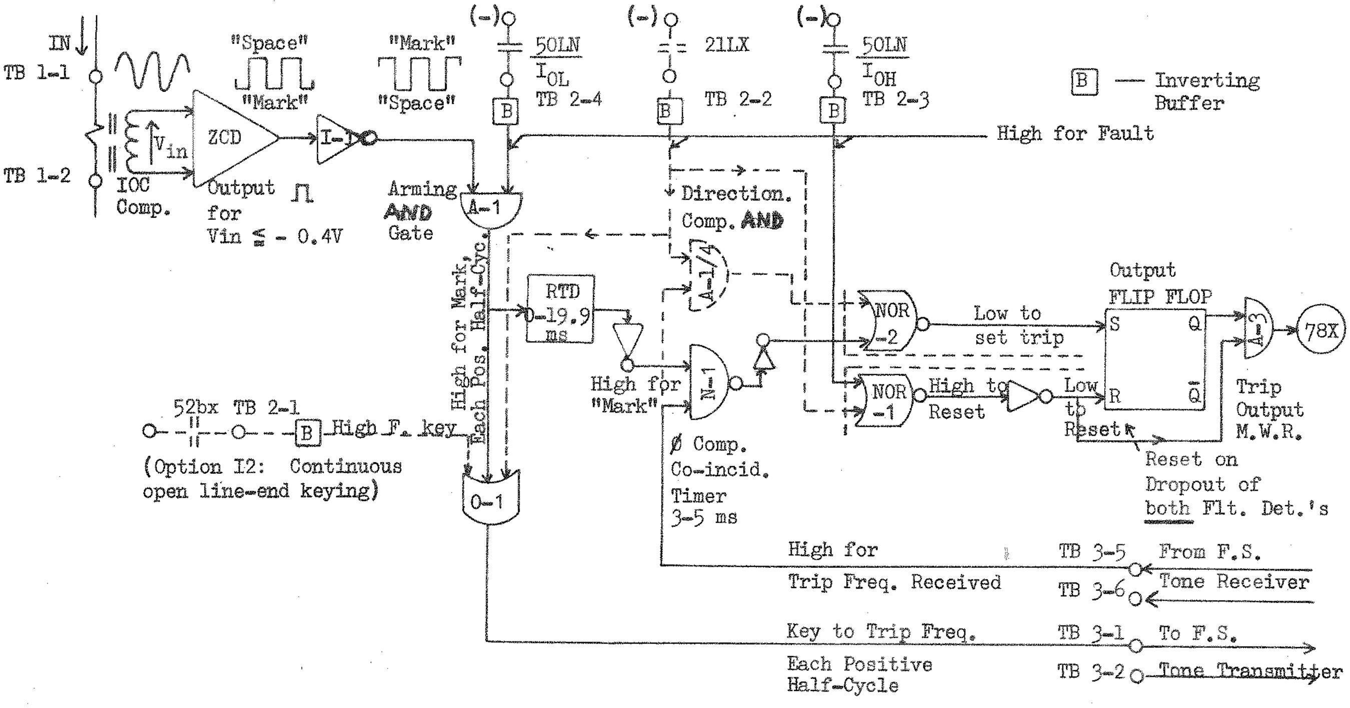
FIG. 1 - BASIC BLOCK DIAGRAM



A. INTERNAL FAULT

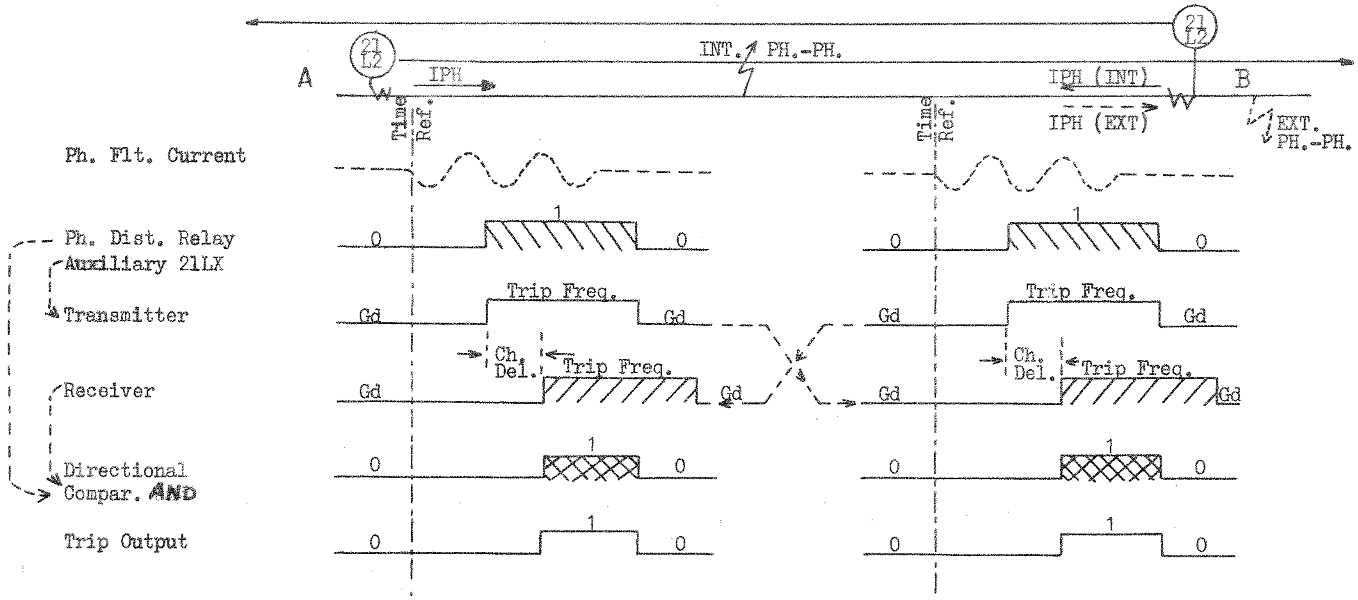


B. EXTERNAL FAULT

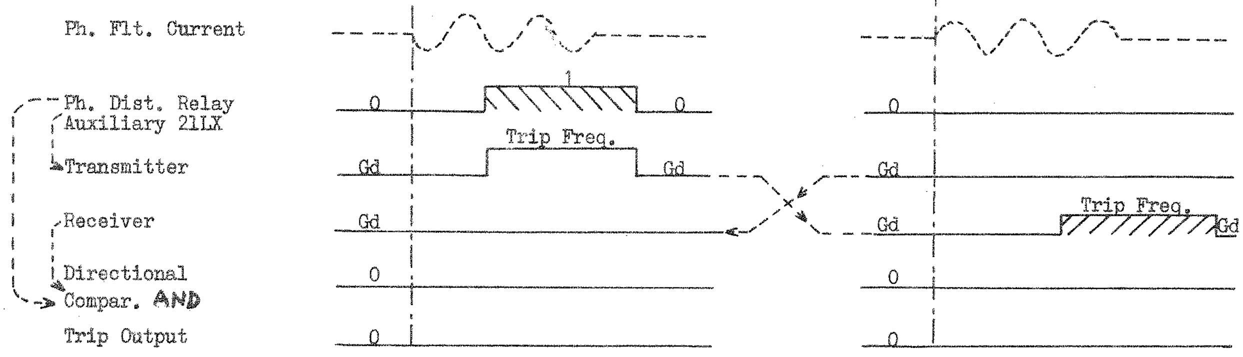


C. LOGIC SCHEMATIC

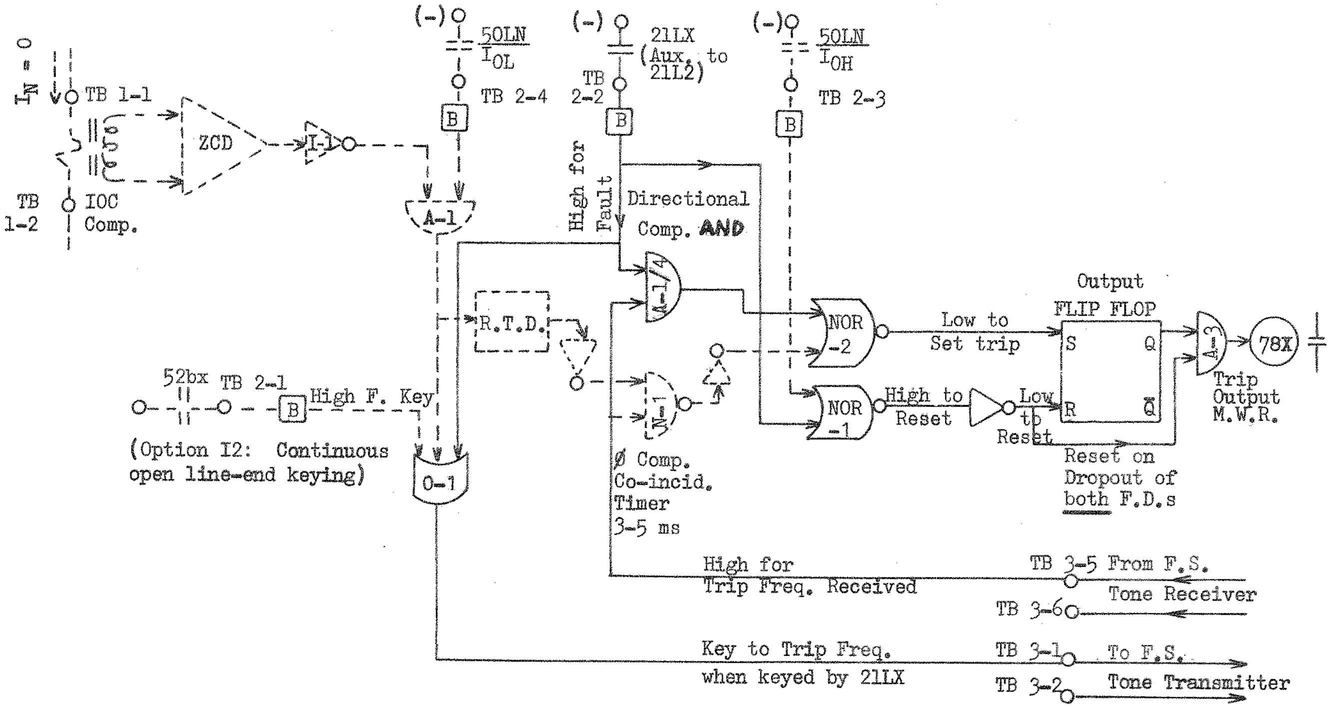
FIG. 2 - PHASE COMPARISON MODE FOR GROUND FAULTS



A. INTERNAL FAULT



B. EXTERNAL FAULT



C. LOGIC SCHEMATIC

FIG. 3 - DIRECTIONAL COMPARISON MODE FOR INTERPHASE FAULTS

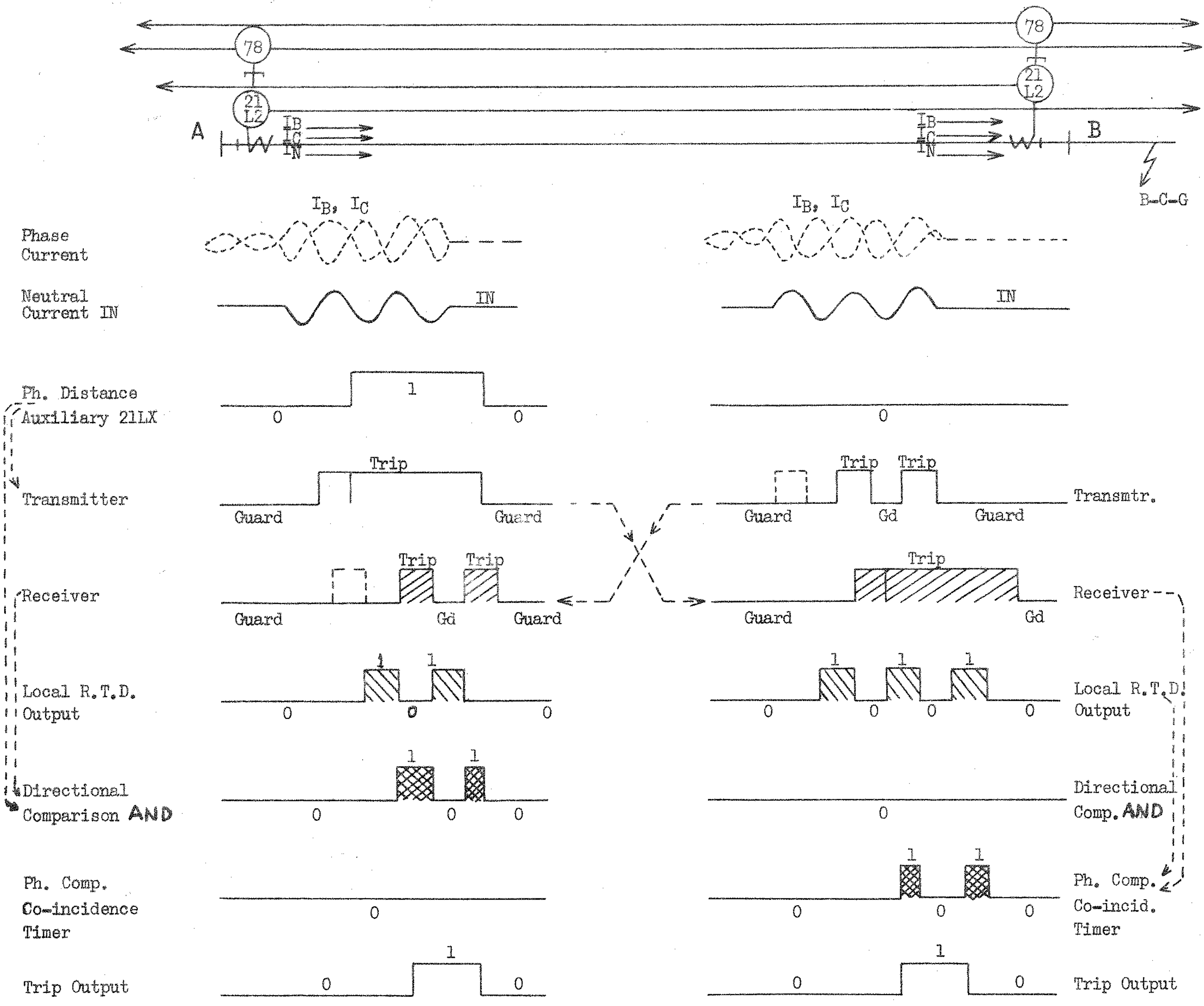


FIG. 4 - FALSE TRIP FOR EXTERNAL LLG FAULT SEEN BY PHASE DISTANCE AND GROUND RELAYS, IMPLEMENTING SIMULTANEOUS DIRECTIONAL COMPARISON AND PHASE COMPARISON LOGIC

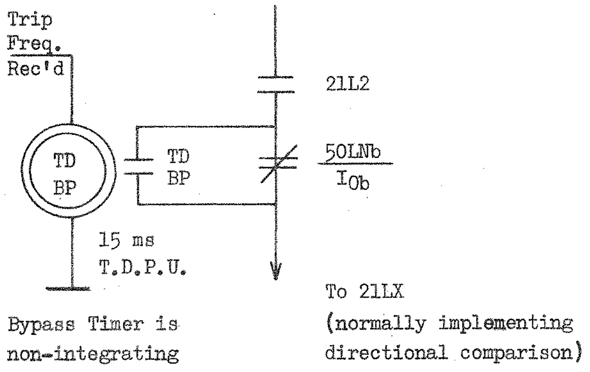
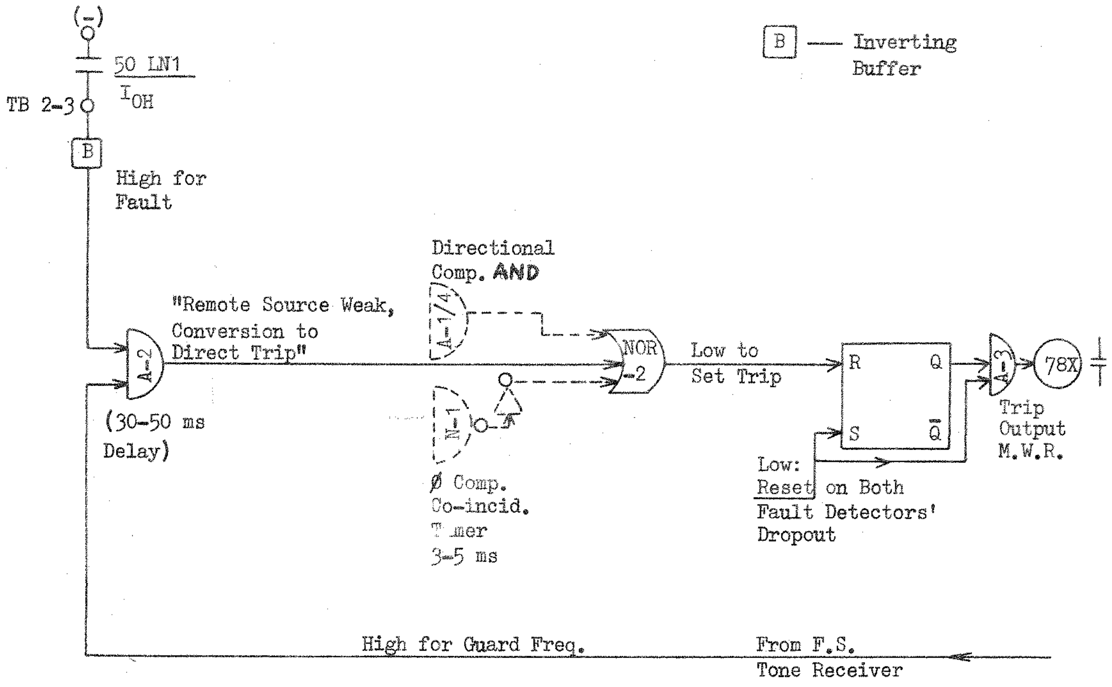


FIG. 5 - SOLUTION FOR ABOVE:
PHASE COMPARISON PREFERENCE FOR MIXED FAULTS SEEN BY DISTANCE RELAYS AND GROUND RELAYS



IF THE LOCAL $I_{OH}$ ELEMENT HAS OPERATED, BUT STEADY GUARD FREQUENCY CONTINUES TO BE RECEIVED FROM THE REMOTE TERMINAL, THIS IS DEEMED TO BE AN INTERNAL GROUND FAULT WITHOUT INFEED FROM THE REMOTE TERMINAL. AFTER 30 TO 50 MS DELAY, LOCAL DIRECT TRIP IS IMPLEMENTED.

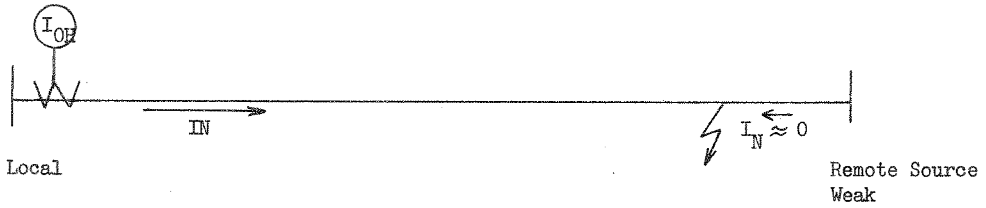
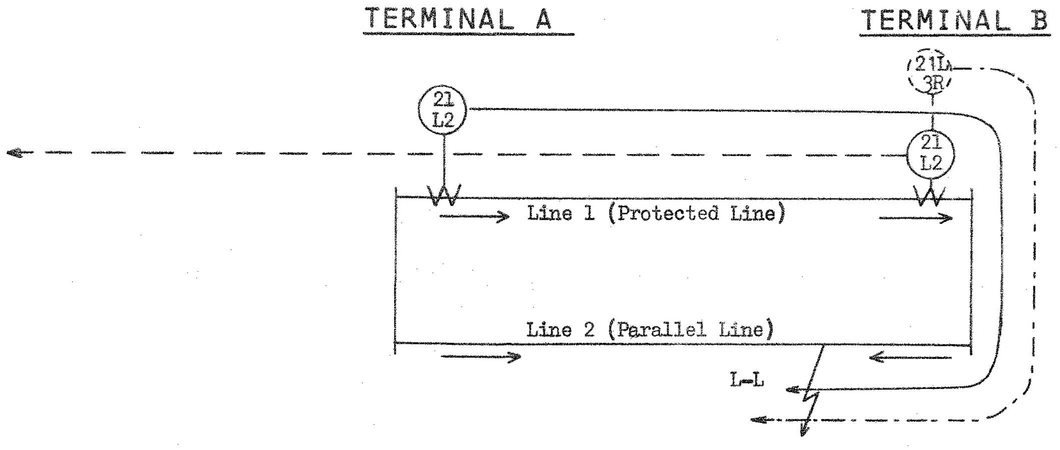
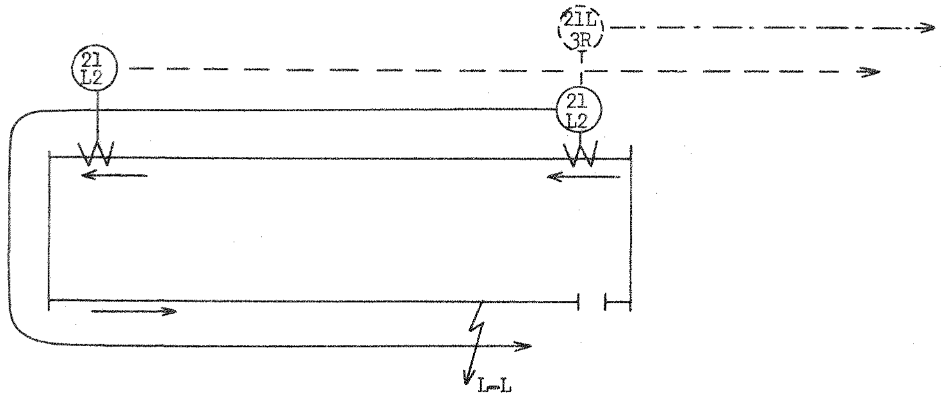


FIG. 6 "REMOTE SOURCE WEAK" FEATURE FOR INTERNAL GROUND FAULTS



(I) INCIDENT FAULT



(II) AFTER CLEARING OF PARALLEL LINE AT B

FIG. 7 - CURRENT REVERSAL ON SEQUENTIALLY
CLEARED INTERPHASE FAULTS

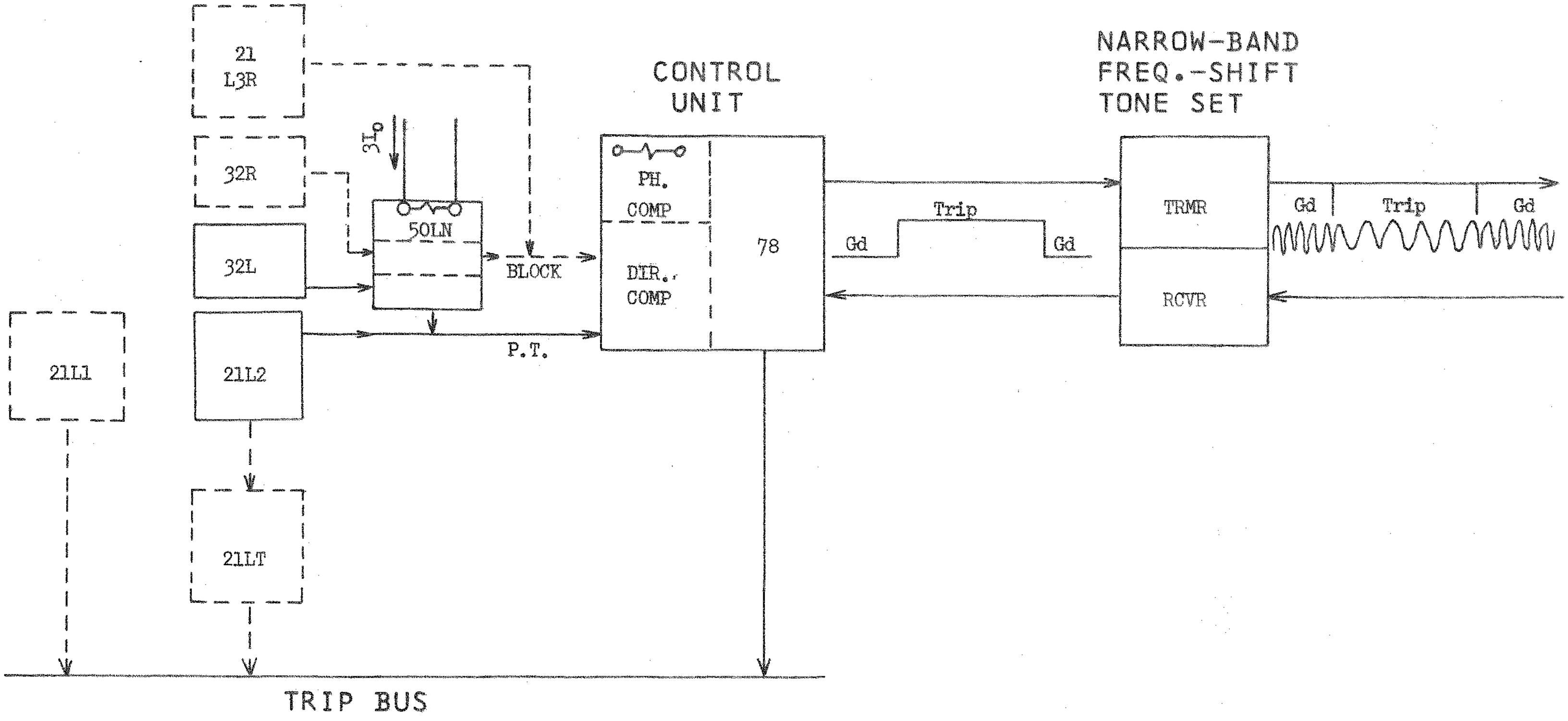


FIG. 8 - BLOCK DIAGRAM FOR ALL - DIRECTIONAL COMPARISON MODE

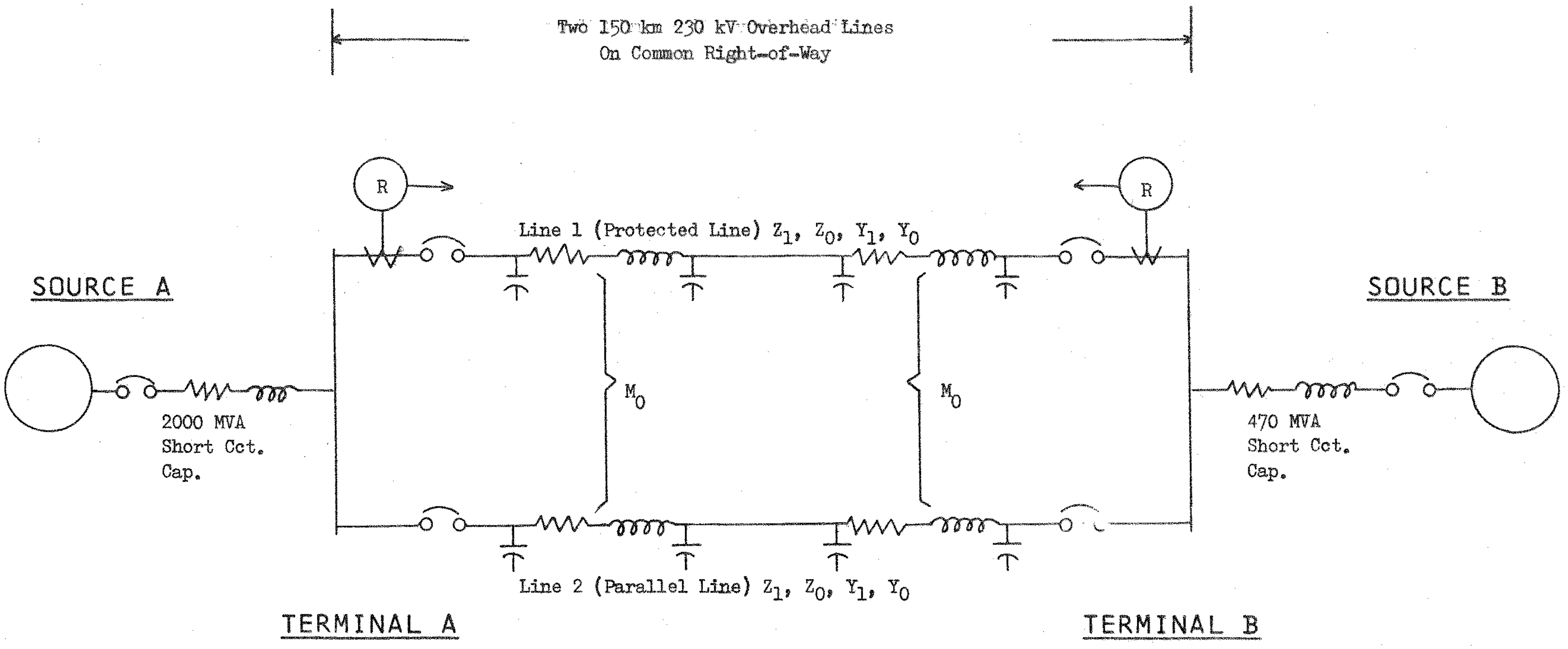


FIG. 9 - MODEL POWER SYSTEM SETUP
(480 - VOLT MODEL EQUIVALENT TO ABOVE SYSTEM)

# PART I - System Description, Selection Process for Relaying Scheme, and General Relaying Logic

## System Configuration

### A. 115 Kv System

The 115 Kv system which we are concerned with serves most of the load in the downtown Spokane area. Before about 1970 nearly all of the substations serving this area were fed from radial taps off 115 Kv lines. A 13 Kv tie line system was relied on to provide backup for outages of the 115 Kv source.

With increased loads the tie line system no longer was able to provide this backup.

Figure #1 shows this system prior to 1970.

It was decided that at least two 115 Kv lines were required at each of these substations. The tie line system would be phased out or converted to distribution feeders and reliability of service would come from the 115 Kv system.

Figure #2 shows this system as it exists today and also the additions planned through 1979.

The lines with directional comparison relaying vary in length from approximately 1/2 mile on an all underground circuit to just under three miles for an all overhead circuit. The first combination circuit is about .6 mile long with 60% overhead and 40% underground.

### B. Substation Configurations

Figure #3 is a One Line Diagram of our College & Walnut Substation. This configuration is typical for most of the substations in this area that are served by only two 115 Kv lines. The 13 Kv bus tie ACB is operated normally open wherever possible. Transformer faults require the tripping of both 115 Kv OCB's. The M.O.A.S. is then opened and the 115 Kv OCB's automatically reclose to pickup the load on the good transformer.

## System Configurations (Cont.)

### C. 115 Kv Underground Cable

So far to date all the 115 Kv cable that we have used has been low pressure oil.

Figure #4 is a cross section of this cable. Specifications for the lead sheath required that it be able to carry 10,000 amps for 1.0 second without any damage. Only the 115 Kv circuits which come into our Post Street Substation have utilized underground cable.

For comparison purposes most of the overhead 115 Kv lines use 556.5 MCM aluminum conductor.

## Choice of Relaying Scheme

### A. System Requirements and Performance Criteria

The following general criteria was originally established for the pilot relaying scheme on these lines:

1. Security

Many of the substations serve some of our most important system loads. Therefore prevention of unnecessary outages due to incorrect relay operation was of prime importance.

2. Reliability and Fault Clearing Time

On the majority of our 115 Kv lines clearing time is seldom a problem. But because of the fact that we could have three or four substations all in series off the same line, our backup relaying times stacked up and became very slow. Therefore, it was desirable to have the pilot relaying scheme operate for all faults on its protected line (5-6 cycle clearing time normally), even with one breaker open. This would greatly aid coordination problems.

On the underground cable circuits the pilot scheme is significantly important for limiting damage to the cable. In addition, 5-6 cycle clearing time is desirable from the aspect of safety.

## Choice of Relaying Scheme (Cont.)

### A. System Requirements and Performance Criteria (Cont.)

2. (Continued)

Obviously the backup relaying on the underground cable circuits would have to satisfy the 10,000 amp - 1.0 second requirement for the cable sheath.

3. Flexibility and Standardization

Since we might have to construct a three-terminal line it is advantageous to have a pilot relaying system which can be applied (with minor modification) to three-terminal line protection.

To simplify construction and testing, some emphasis was placed on selecting a scheme flexible enough to be used on all or most of these 115 Kv lines.

### B. Pilot Relay Schemes Which Were Considered

It is not practical to discuss all the relaying systems that were considered. But it is felt that at least a brief listing and discussion of schemes, which are commonly applied to lines as these, would be helpful.

1. A-C Pilot Wire System, Using Leased Telephone Circuit

In theory this system might appear to be the most logical choice to protect short 115 Kv lines. But this scheme was not chosen for the following reasons:

a. The telephone company prefers not to lease circuits for this type of system any more. It has not been the policy of our company to construct our own telephone circuits.

b. Security against false trips is nearly impossible to achieve. Anyone who has applied this type of protection is familiar with the difficult problem of protecting the telephone circuit against all the electrical and human hazards which can result in false operation.

Choice of Relaying Scheme (Cont.)

B. Pilot Relay Schemes Which Were Considered (Cont.)

1. (Continued)

b. (Continued)
Even with fault detecting relays to supervise the pilot wire tripping this scheme was not considered secure enough to be used.

c. Phase distance and directional ground relays would still be required for backup. In addition, phase and ground instantaneous directional overcurrent fault detectors would be required to increase the security so the cost is not significantly less than other schemes considered.

2. Permissive Overreaching Transfer Trip Using F.S. Audio Tones Over Leased Telephone Circuit, VHF Radio, or Microwave (960 MC).

VHF radio is seldom applied for a relaying channel, although certain limited applications could be acceptable. The frequency spectrum is rather limited and in our application several different frequencies would be required. Also, because many of the substations are located in downtown Spokane, our Communications Department recommended that we not use VHF radio because of possible interference problems.

Using the leased telephone circuit for the P.O.T.T. scheme we have more security than with the pilot wire. But we still had the problems of protecting the leased circuits and working with the telephone company to maintain their reliability. In addition, because the tone channel might squelch on ground faults, there was concern over the tripping dependability of this scheme. Coordination for ground faults was the problem of greatest concern and this was the weakest area for the P.O.T.T. scheme using leased telephone lines.

Choice of Relaying Scheme (Cont.)

B. Pilot Relay Schemes Which Were Considered (Cont.)

2. (Continued)

Therefore, if the P.O.T.T. scheme were to be used, the communication system should be on microwave (obviously, there is nothing unusual about this conclusion, since microwave is generally considered to be the most desirable and most reliable communication method for transfer trip relaying).

The P.O.T.T. scheme via microwave would provide excellent protection for the overhead or underground 115 Kv lines. It has the flexibility for use on all the lines considered, even three-terminal lines if necessary. The big problem with this scheme though, was in providing the line of site communication path between all the various stations. This difficulty resulted in this scheme being economically unattractive for many of the lines. In addition, there is the uncertainty of installing a microwave system within a city, where building construction could block a microwave path and necessitate major changes or additions. Reluctantly we dropped this scheme from consideration.

3. Phase Comparison or Directional Comparison Using Powerline Carrier

   a. An on-off carrier system was preferred over a frequency shift carrier system for the following reasons:

      (1). Because the lines are very short and within the city a continuous carrier signal was not desired. Channel monitoring wasn't felt necessary. The on-off carrier would be checked at least once a week.

B. Pilot Relay Schemes Which Were Considered (Cont.)

3. (Continued)

a. (Continued)

(2). With the system previously described, it is very possible to have an internal line fault with contribution from one terminal only. Therefore, pilot tripping should occur upon relay operation at one end of the line only. The on-off carrier provided this feature.

b. An electro-mechanical directional comparison scheme was chosen to function with the on-off carrier for the following reasons:

(1). The additional cost of solid state relaying schemes could not be economically justified. The faster operating times of these systems was of no significant advantage.

(2). The directional comparison scheme is more flexible than phase comparison. Three-terminal lines could be handled easier if necessary. Variations in fault current magnitudes (phase faults in particular) would have little effect on the directional comparison scheme. The complete independence of phase and ground fault settings on the directional comparison scheme is an advantage on some lines.

Choice of Relaying Scheme (Cont.)

B. Pilot Relay Schemes Which Were Considered (Cont.)

3. (Continued)

b. (Continued)

(3). For external phase faults the carrier trip relay (distance relay), associated with the directional comparison scheme, would pickup much less often than the overcurrent fault detector which permits phase comparison tripping. Therefore, in this carrier blocking scheme the directional comparison should be more secure.

(4). Since distance and directional ground overcurrent relays were required for backup in both cases the directional comparison scheme was slightly less expensive.

(5). The phase comparison would have been solid state with E-M backup, while the directional comparison could be all E-M. Since our company has more experience with E-M pilot systems (the majority of which are directional comparison) some engineering design time and relay testing time could be saved by use of the directional comparison system.

## Description of the Directional Comparison Scheme

### A. Component Description

Referring again to Figure #3, the relaying equipment on the line to Post Street will be described. As was mentioned earlier this line is a combination circuit utilizing both overhead and underground construction.

The scheme is a standard K-DAR directional comparison using TC carrier. The protective relays are basically standard E-M types (only the carrier equipment, some timing relays, and the reclosing relays are static devices). Primary protection is obviously provided by the carrier scheme, with a distance relay (for multi-phase faults) and a directional ground overcurrent relay (for ground faults) providing the carrier stop and trip functions. A distance relay provides carrier starting for phase faults and the non-directional overcurrent unit in the 85 relay provides carrier starting for ground faults.

Backup for internal line faults is provided by the 21B distance relay and the 67N directional ground overcurrent relay (time unit only).

The relaying equipment is the same at the Post Street terminal except for the addition of a non-directional instantaneous and time overcurrent ground relay which is operated by current in any of the cable sheaths. Since the cable sheath is grounded only at the Post Street end this relay will detect faults in the underground cable portion of the College & Walnut-Post Street line.

Because the lines are short and have low losses, signal reflections are of prime concern on the carrier system. The discontinuity at the cable-overhead junction is, of course, responsible for these reflections and they are attenuated very little by the short lines. For the idealized case of a combined overhead-underground line, it is desirable to have a carrier frequency with a wave length corresponding to half the cable length looking into the overhead and a carrier frequency with a wave length corresponding to one eighth or three eighths of the overhead length looking into the cable.

Description of the Directional Comparison Scheme (Cont.)

A. Component Description (Cont.)

Frequencies corresponding to one fourth the length should be avoided on both the overhead and underground and in addition, because our overhead line is short, a frequency corresponding to half its length should also be avoided on it.

Our line was too short to rely only on calculations to determine the carrier frequency. Therefore we made carrier frequency vs. attenuation tests from each direction and then selected the frequency with the lowest attenuation. By making these tests it was felt that a carrier bypass was not required at the junction.

Carrier frequencies for the all underground and all overhead lines were determined by calculation.

The carrier equipment utilized a narrow receiver band width because of its higher attenuation rating (50 db channel rating vs. 40 db for the standard carrier equipment). This carrier set is specifically designed for lines with high attenuation.

In addition, the coupling capacitors are Hi-C (.006 ufd) to help reduce the coupling loss. This is particularly important on the cable due to its low characteristic impedance. With Zc = 37 ohms for the cable the Hi-C coupling capacitor has a resistive coupling loss of about 1.75 db compared to about 4.0 db for a standard .002 ufd coupling capacitor.

B. Relay Logic and Control Schematics

Figure #5 shows the relaying schematic for the Post Street terminal of the line to College & Walnut.

It is our general philosophy to have automatic reclosing whenever the breaker is tripped by carrier or by the 86T-1 or 86T-2 relays. The reclose time is in the range of 1-3 seconds.

Transformer faults at Post Street result in the operation of one of the 86T relays.

B. Relay Logic and Control Schematics (Cont.)

These relays trip both 115 Kv OCB's and open the faulted transformer motor operated air switch so the OCB's can automatically reclose. This is why 86T-1 or 86T-2 tripping is via the selective reclosing auxiliary relay. Obviously a carrier blocking signal must be sent to the remote terminals of both lines into Post Street to prevent a carrier trip on a transformer fault. The zener diode prevents carrier squelching for tripping other than by the carrier relays.

Overcurrent fault detectors are used to supervise all distance relay tripping (carrier or time delay backup). This is necessary to prevent undesired tripping when one line is out and another is temporarily faulted (such as Metro-Sunset open and a temporary fault on the College & Walnut-Westside line).

The 50/51N relay will operate for any fault in the underground cable. It will immediately trip the 115 Kv OCB and also pickup device 79B. 79B has one cycle pickup time and 7-10 cycle dropout, so it will de-energize the power supply of the reclosing relay and automatically place it in the lockout state. Thus no reclosing will occur at the Post Street terminal for a cable fault.

Current reversals will occur on this line (as well as on several other lines in the Spokane area) for the clearing of certain external line-to-ground faults. A discussion on the use of the E-M KA-4 relay instead of the solid state SKA (or SKAU-3) will explain why it was used.

The additional cost of the SKA relay and the fact that its use can occasionally result in slower carrier tripping for internal line faults, are two deterrents to its use. The slight delay in carrier tripping is a result of the transient blocking circuit. In particular, when E-M carrier trip relays are used with the SKA relay, they must operate at both line terminals within about 22 ms after carrier is started at either terminal or the transient blocking circuit will time out, resulting in a 25 ms delay at one or both terminals before carrier tripping can occur.

Description of the Directional Comparison Scheme (Cont.)

B. Relay Logic and Control Schematics (Cont.)

The Ios unit of the SKA operates very fast to start carrier on ground faults, for example, and the carrier ground trip relay can certainly on occasion take longer than 22 ms to operate (ground faults that are lower than about 4 times the pickup of the instantaneous unit are typical examples).

Although there are a number of differences between the SKA and KA-4 relays, probably the major one is this transient blocking circuit, which is specifically designed to prevent undesired tripping on the clearing of external faults. Therefore, to justify use of the SKA, one must justify the need for this transient blocking circuit. And indeed there are occasions when this is required. But our company's experience shows it to be very rare when the KA-4 will not suffice.

Figure #6 shows the two lines from Sunset to Westside with ground fault current contributions for a fault just outside OCB A-410 at Westside. 3Io flows are shown before and after A-410 trips (which we will assume occurs before A-198 at Sunset). Obviously a current reversal occurs on the College & Walnut-Post Street line when A-410 trips.

Prior to A-410 tripping, the directional and instantaneous units of the 67NC relay have operated at Post Street and carrier has been stopped. As soon as A-410 trips, two things must occur to prevent a false trip at either College & Walnut or Post Street:

a. The directional contact of the 67NC relay at Post Street must open to permit the sending of carrier to College & Walnut before the carrier trip circuit can make up at College & Walnut.

b. The carrier trip circuit must open at Post Street before carrier is squelched at College & Walnut.

Therefore, with 1828 amps ground current from College & Walnut to Post Street (right after A-410 trips) the directional contact of the 67NC relay at Post Street opens in a maximum of 4 ms.

### B. Relay Logic and Control Schematics (Cont.)

The CSG contact opens in about 2 ms, so carrier is retransmitted in about 6 ms to College & Walnut. Assuming 400 amps pickup at College & Walnut on the 67NC instantaneous unit, 36 volts polarizing voltage and 1828 amps operating current; the directional (back) contact of 67NC opens in about 3 ms to permit the instantaneous unit to pick up. The instantaneous operates in about 21 ms for the total time of 24 ms. The directional unit (normally open) contact closes in about 19 ms, and this is the time to energize the CSG coil. The RRG trip contact would (with no RRH current) make up in about 31 ms (19 ms for directional unit plus 5 ms for CSG unit plus 7 ms for RRT unit). Since the 67NC instantaneous unit operate time is less than the RRG time, the 31 ms is the determining time to make the carrier trip circuit.

Analyzing "a" first, the carrier trip circuit would make up at College & Walnut in 31 ms but carrier will be retransmitted from Post Street in 6 ms. Using carrier propagation time plus channel delay of 6 ms, the coordination time at College & Walnut is 31 -6 -6 = 19 ms.

Analyzing "b", the carrier is squelched at College & Walnut in 24 ms and the Post Street carrier trip circuit will open in 4 ms, so the coordination time is 24 -4 = 20 ms.

This example shows that the KA-4 relay does suffice and in nearly all cases this is true. Occasionally, when coordination time is very short, the pickup time of the CSG can be increased to improve this time. For internal faults where the RRG contact closes before the instantaneous unit contact, this CSG time increase won't delay the total trip time. For all other internal faults the additional 2-3 ms (CSG time increase) delay in tripping is considered acceptable.

This is a theoretical evaluation. Practically speaking it takes very good relay testing maintenance for these times to hold true.

The rest of the control schematic, including the carrier control circuit, is fairly standard and straight forward.

## PART II - Relay Settings and Application Problems

### A. Ground Relays

Basically there is nothing unique about the ground relay settings on these short lines. The 67N relays on the College & Walnut to Post Street line obviously can't utilize instantaneous units. The time overcurrent settings are made in the conventional manner. The carrier start unit of the 85 relays are set at the minimum value of .5 amps (100 amps primary) at both terminals. The 67NC relay is set at 2 amps (400 amps primary) at both terminals.

The 50/51N relay at Post Street is set for a 40 amp pick up on the time unit. Since this relay does block reclosing the instantaneous unit is set slightly lower than the 67NC relay, to insure that for any cable fault reclosing does not occur at Post Street. This instantaneous setting is 320 amps primary.

### B. Distance Relays

The application of distance relays on these short lines does present some unusual problems. In particular there are five items related to the distance relay settings and operations which will be discussed. These items are:

1. 30 unit operation of KD-11 carrier start relay
2. Arc resistance
3. Reach for SLG faults
4. Response to low energy level faults
5. Coordination problems with a circuit switcher protecting a transformer bank tapped off a short line.

#### 1. 30 Unit Operation of KD-11 Carrier Start Relay

Figure #7 shows the various line impedances, in primary ohms, from Westside to Sunset. This figure illustrates the "shortness" of the lines into Post Street. As an example, the College & Walnut-Post Street line has impedances of $Z1 = .08 + j.33 = .34 \angle 76.4^{\circ}$ and $Zo = .23 + j1.61 = 1.63 \angle 82^{\circ}$ primary ohms.

B. Distance Relays (Cont.)

1. 3Ø Unit Operation of KD-11 Carrier Start Relay (Cont.)

The Zo value does not take into account the cable sheath because it is grounded only at Post Street. (With a 1000/5 C.T. ratio and 1000/1 P.T. ratio, we have a 5/1 multiplier for secondary to primary ohms on this line.)

Figure #8 shows typical Zone 2 and Zone 3 carrier relay settings on a medium or long line.

Figures #9 and #10 show the distance relay settings for the 3Ø and Ø-Ø units of the Zone 2 and Zone 3 carrier relays at College & Walnut and Post Street.

Even though the Zone 3 carrier start relay is offset only .12 secondary ohms = .6 primary ohms, this is nearly twice the line Z1! Therefore, we have the rather unusual situation that for essentially all 3Ø faults and possibly some Ø-Ø faults involving AØ (but probably no 2Ø-ground faults because of the system parameters, i.e., $Zos > \frac{1}{2} Zc$) the 3Ø unit will operate to start carrier. This is very similar to what occurs for any internal line fault involving ground. Also, since some of the Zone 3 relays are used for backup, their time delay must take into account this "forward reach".

2. Arc Resistance

Arc resistance is an item often mentioned in short line relaying applications. The longest distance between phase conductors on these 115 Kv lines is about 9.5 feet. For phase faults the arc is generally short initially, but if carrier were out of service, some elongation of the arc will occur within the 20 or 40 cycle Zone 2 timer settings. There are several empirical equations which are used to calculate arc resistance but perhaps the AIEE equation, from Reference 7, is as valid as any:

## B. Distance Relays (Cont.)

### 2. Arc Resistance (Cont.)

$$R_{arc} = \frac{8750\ L}{(I)^{1.4}}$$

For a radial line fault then:

$L$ = length of arc in feet
$I$ = fault current in primary amps
$R_{arc}$ = Ø-N ohms of arc resistance

Using $L = 10$ feet and $I = 2500$ amps minimum (under outage conditions), $R_{arc} = 1.53$ ohms. With $L = 13$ feet, $R_{arc} = 1.99$ ohms. Therefore, it was considered desirable for the Zone 2 relays to accommodate at least 1.5 ohms arc resistance, and 2 ohms if possible, for faults right at the origin. Looking at the phase-phase units in Fig. #10 we see that this is easily accomplished. Because the source impedance is many times the line impedance, the phase-phase units provide excellent coverage on these short lines.

In order for the 3Ø unit to provide adequate arc resistance coverage, the maximum torque angle was adjusted to 45°. This resulted in the 3Ø characteristic being more similar to the Ø-Ø characteristic, without sacrificing any protection at the line angle.

I have heard relay engineers mention that they don't feel arc resistance is much of a problem since their fault oscillograms indicate current magnitudes very close to calculated values. This is really not a valid argument, even for short lines, because the fault angle is substantially affected even though the fault magnitude is not.

As an example for a 3Ø line end fault at Post Street the total $Z1 = .0844 \angle 77.6^\circ$ per unit $= 11.16 \angle 77.6^\circ$ primary ohms. $I3Ø = 5950$ amps. Even with 3 ohms arc resistance ($z1 = 5.4 + j10.9 = 12.16 \angle 63.6^\circ$) $I3Ø$ still $= 5460$ amps or only about 8% less. But to the College & Walnut breaker $Z1 = 3.08 + j.33 = 3.1 \angle 6.1^\circ$. To the breaker at Westside $Z1$ only changes from $6.92 \angle 75.8^\circ$ to $8.19 \angle 55^\circ$.

B. Distance Relays (Cont.)

2. Arc Resistance (Cont.)

Thus for lines that are 3-4 primary ohms or longer it is easy to see why arc resistance is seldom a problem. But for lines requiring distance relay settings around 3 ohms primary or less arc resistance appears to be an important consideration.

Based on the Zone 2 settings at College & Walnut the 30 unit can accommodate about 2.44 primary ohms of arc resistance (for a fault just past the breaker and the 0-0 unit can handle about 4.5 ohms primary. If the 30 unit had used a 60° MTA with the same reach at the line angle it would have accommodated only about 1.53 ohms primary.

3. Reach for SLG Faults

Because the lines into Post Street utilize underground cable, it would be advantageous if the carrier distance relays had the ability to detect SLG faults. For cable faults, tower footing resistance doesn't have to be considered and arc resistance should be quite low. Therefore, it might seem logical to expect the Zone 2 carrier distance relays to operate for SLG faults, especially when they are set roughly 8-10 times the positive sequence line impedance.

It is well known that distance relays have limited response to SLG faults. Equations have been developed for both conventional mho type and compensator type distance relays, describing their response.

It has been stated that, as a general rule of thumb, the K-DAR 0-0 unit should be set three times the positive sequence impedance of the protected line to assure coverage for SLG faults.

This statement is valid for medium to long transmission lines under most system conditions. But because the response of the 0-0 unit is highly dependent on the source impedances (as is the 30 unit or any conventional mho relay), particularly the zero sequence source impedance, this statement certainly doesn't apply to the system being discussed here.

## B. Distance Relays (Cont.)

### 3. Reach for SLG Faults (Cont.)

Equation 22 of Reference 3 specifically describes the minimum impedance setting on the Ø-Ø unit in order for it to operate on all SLG faults in the protected line. This equation is as follows:

$$Z'_{app} = Z'_{IL} + j100 \left( \frac{1}{I'_g} - \frac{.67}{I'_{3\phi}} \right) + \left( \frac{66\ Kv}{R_c I'_g} + 1.5\ R_{TF} \right) \frac{R_c}{R_v}$$

where:

$Z'_{app}$ = secondary ohms seen by Ø-Ø unit for a line end fault (at the remote end of the line) with the remote breaker open.

$Z'_{IL}$ = positive sequence impedance of protected line in secondary ohms.

$I'_g$ and $I'_{3\phi}$ = SLG and 3Ø fault current magnitudes respectively, in secondary amperes, for a line end fault with the remote breaker open.

Kv = Primary line - line kilovolts

$R_c$ = Current transformer ratio

$R_v$ = Potential transformer or device ratio

$R_{TF}$ = Equivalent tower footing resistance in primary ohms.

This equation was developed making several simplifying assumptions, all of which are very reasonable for our system.

The term " $\frac{66\ Kv}{R_c I'_g}$ " represents 1.5 times the ground fault arc resistance ($R_{arc} = \frac{44\ Kv}{I_g}$ , all primary values, for this equation).

## B. Distance Relays (Cont.)

### 3. Reach for SLG Faults (Cont.)

Now $I'_{3\phi} = \dfrac{V'_{L-N}}{Z'_1}$ and $I'_g = \dfrac{3V'_{L-N}}{Z'_1+Z'_2+Z'_o}$

where:

$V'_{L-N}$ = secondary line-neutral voltage $= \dfrac{115}{\sqrt{3}} = 66.4$ volts

$Z'_1$, $Z'_2$, and $Z'_o$ = total positive sequence, total negative sequence, and total zero sequence impedance respectively, in secondary ohms, for line end fault with the remote breaker open.

If we ignore tower footing resistance and ground fault arc resistance, and taking the impedances as vector quantities, with $Z'_1 = Z'_2$, we have:

$$Z'_{app} = Z'_{IL} + 100 \left( \frac{1}{\dfrac{3V'_{L-N}}{2Z'_1+Z'_o}} - \frac{2}{\dfrac{3V'_{L-N}}{Z'_1}} \right)$$

$$= Z'_{IL} + 100 \left( \frac{2Z'_1+Z'_o}{3V'_{L-N}} - \frac{2Z'_1}{3V'_{L-N}} \right)$$

$$= Z'_{IL} + 100 \; \frac{Z'_o}{3V'_{L-N}}$$

Since $V'_{L-N} = 66.4$ volts then:

$Z'_{app} = Z'_{IL} + \dfrac{Z'_o}{2}$ or in primary ohms $Z_{app} = Z_{IL} + \dfrac{Z_o}{2}$

where $Z_o = Z_{oL} + Z_{os}$ (Zero sequence impedance of protected line and Zero sequence source impedance, respectively)

B. Distance Relays (Cont.)

3. Reach for SLG Faults (Cont.)

Now for a long line $Z_o \simeq Z_{oL}$. And for typical lines $Z_{oL} \simeq 3Z_{IL}$.

Therefore $Z_{app} \simeq Z_{IL} + \frac{3}{2} Z_{IL}$ OR $Z_{app} = 2.5\ Z_{IL}$ (3)

Thus by setting the 0-0 unit three times the positive sequence impedance of the protected line it should operate for most ground faults (it is assumed that $I_{fault} \gg I_{load}$, so the reach of the 0-0 unit is not appreciably affected (shortened) by load current).

But for our system, considering the College & Walnut-Post Street line and a fault on the line side of the College & Walnut breaker, with the breaker open, $Z_{IL}$ and $Z_{OL}$ are both very small.

So: $Z_{app} \simeq \frac{Z_{os}}{2}$ (4)

This says, basically, that the compensator setting on the 0-0 unit must be set greater than 50% of the Zero sequence source impedance (under the radial fault condition) in order to detect SLG faults on this short line.

In this case $Z_{os}$ at Post Street = 27 $\angle 79^o$. Thus the 0-0 unit on the Zone 2 carrier relay at Post Street would have to be set greater than 13.5 $\angle 79^o$ primary ohms to detect SLG faults on the line to college & Walnut. This amounts to about 40 times the positive sequence impedance of the line!

## B. Distance Relays (Cont.)

### 3. Reach for SLG Faults (Cont.)

So far only the Ø-Ø unit has been discussed. The reason for this, of course, is that the Ø-Ø unit is much more sensitive in detecting SLG faults than the 3Ø unit. The 3Ø unit will not operate for AØ-ground faults, but it does have limited response for BØ and CØ-ground faults.

Rewriting equation 141 from Reference 1, and using the same notation as we did for the Ø-Ø unit, we have:

$$Z_{app} = 3.33\ Z_{IL} + .67\ Z_{os} \tag{5}$$

This equation was developed with the additional assumption of $Z_{oL} = 3Z_{IL}$. We could rewrite this equation to include $Z_{oL}$ but it really isn't necessary, since it shows that if $Z_{IL} \ll Z_{os}$ (likewise $Z_{oL} \ll Z_{os}$) then

$$Z_{app} \cong .67\ Z_{os} \tag{6}$$

Thus the 3Ø unit would have to be set approximately one-third longer than the Ø-Ø unit to detect BØ-ground or CØ-ground faults on the protected line. In our case the 3Ø unit of the Zone 2 carrier relay at Post Street would have to be set greater than $18\ \underline{/79^\circ}$ primary ohms or if a $60^\circ$ MTA were used, greater than $19\ \underline{/60^\circ}$ primary ohms.

B. Distance Relays (Cont.)

3. Reach for SLG Faults (Cont.)

As a matter of interest conventional mho distance relays would have to be set greater than:

$$Z_{app} = Z_{IL} + \frac{jZ_1}{\sqrt{3}} + \frac{(1-a^2)\,Z_0}{3}$$ (using same notation as before)

in order to detect SLG faults in the protected line.

This means the Zone 2 carrier relay at Post Street (if it were a conventional mho type) would have to be set greater than:

$$Z_{app} = \frac{j(8.97\ \angle 76.9)}{\sqrt{3}} + \sqrt{3}\ \angle 30^\circ\ \frac{(27\ \angle 79^\circ)}{3}$$

$$= 5.18\ \angle 166.9^\circ + 15.59\ \angle 109^\circ$$

$$= -5.04 + j1.17 - 5.08 + j14.74$$

$$= -10.12 + j15.91$$

$$= 18.86\ \angle 122.5^\circ$$

This would be the impedance seen by the "A-B" relay. The "C-A" relay would see $-5.18\ \angle 166.9^\circ + 15.59\ \angle 49^\circ$ or the same 18.86 ohms but at a $34.78^\circ$ angle. If a $60^\circ$ MTA were used then the required setting would be greater than $20.9\ \angle 60^\circ$ primary ohms. If a $45^\circ$ MTA were used the setting would be greater than $19.2\ \angle 45^\circ$ primary ohms. This is roughly equivalent to the $3\phi$ unit of the compensator relay.

B. Distance Relays (Cont.)

### 4. Response to Low Energy Level Faults

In this discussion "low voltage level faults" might really be more explicit than "low energy level faults". For typical transmission lines having both a Zone 1 and a Zone 2 distance relay, the dynamic response of the Zone 1 relay is normally relied on to clear close-in faults where the relay voltage approaches zero volts. In the case of the compensator distance relay, Ø-Ø faults are covered quite well, even on a static basis, because the Ø-Ø unit utilizes potential from the sound phase to develop operating torque. But for a 3Ø fault which produces very low voltage, the "memory action" of the 3Ø unit must be relied on, since this unit's static response shows that it will not operate for this type of fault.

In addition, whenever the voltage available at the relay for a theoretical zero voltage fault at the reach or balance point location is low, the distance relay can underreach. The most common case is for a distance relay protecting a very short line, with a fairly large source impedance. This is, of course, just what we have.

Therefore, there are two concerns on these short lines. The first problem being that, because we don't have Zone 1 relays, if carrier is out of service, then the static response of the distance units should provide operation by time backup. The second problem is that of underreaching due to low relay voltages.

Since the Metro-Post Street line is all underground cable, it is extremely remote to have a fault not involving ground (such as might occur between the OCB and cable potheads). But on the College & Walnut-Post Street line it is much more likely.

B. Distance Relays (Cont.)

4. Response to Low Energy Level Faults (Cont.)

Based on the settings at College & Walnut or Post Street, Reference 6 states that the $3\phi$ unit will operate with .75 volts line-line and 3.7 amps. Even if we completely ignore the line impedance, and taking the minimum radial fault current of about 2500 amps primary, only .15 primary ohms arc resistance will create .75 volts secondary line-line. Therefore, it would be extremely unlikely that a $3\phi$ line fault could occur that wouldn't operate the $3\phi$ unit. The operating time could be very long for this type of fault though.

Appendix No. 1 of Reference 5 provides equations to evaluate the range of operation for both the $3\phi$ and $\phi$-$\phi$ units. Equation 3 of this appendix is stated as follows:

$$V_{3\phi} = \frac{1.5TI_{3\phi} \pm \sqrt{(1.5TI_{3\phi})^2 - 3.46\ P_{3\phi}\ \frac{1 \pm M}{s}}}{1.732\ \frac{1 \pm M}{s}}$$

where:

T, S, M = Compensator tap setting, main winding auto-transformer tap setting, and tertiary winding auto-transformer tap setting, respectively on the $3\phi$ unit.

$I_{3\phi}$ = Secondary $3\phi$ fault current

$P_{3\phi}$ = Minimum positive operating value = 2.3 volts squared for short range $3\phi$ unit.

$V_{3\phi}$ = Secondary line-line volts where $3\phi$ unit will operate.

This equation is nothing more than the simple solution of a quadratic equation with the form:

$$V_{3\phi} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

B. Distance Relays (Cont.)

4. Response to Low Energy Level Faults (Cont.)

Therefore, $V_{3\phi}$ has two solutions and these define the limits between which the 3Ø unit will operate without memory action. The low value defines the minimum (static) operating voltage for a close-in or "zero volt fault". The upper value defines the operating voltage for a zero volt fault at the relay balance point and is used to calculate the amount of underreach.

For the 3Ø unit of the Zone 2 relay at College & Walnut, assuming the fault angle is equal to the MTA,

$$S = 1$$

$$T = .92$$

$$M = + .09$$

$$I_{3\phi} = \frac{2500}{200} = 12.5 \text{ amps secondary}$$

$$P_{3\phi} = 2.3 \text{ volts squared}$$

substituting these values into equation (3) and solving we get

$$V_{3\phi} = \frac{1.5 \times .92 \times 12.5 \pm \sqrt{(-1.5 \times .92 \times 12.5)^2 - 3.46 \times 2.3 \times 1.09}}{1.732 \times 1.09}$$

$$V_{3\phi} = \frac{17.25 \pm \sqrt{297.56 - 8.67}}{1.89}$$

$$V_{3\phi} = \frac{17.25 \pm 17}{1.89}$$

$$V_{3\phi} = .13 \text{ and } 18.12 \text{ volts secondary}$$

This means the 3Ø unit will operate <u>without memory action</u> for secondary Ø-Ø voltages between .13 and 18.12 volts with 12.5 amps at the maximum torque angle. In terms of impedance this is:

$$Z = \frac{18.12}{\sqrt{3} \times 12.5} = .837 \text{ ohms and } \frac{.13}{\sqrt{3} \times 12.5} = .006 \text{ ohms.}$$

B. Distance Relays (Cont.)

4. Response to Low Energy Level Faults (Cont.)

This represents line coverage between $\frac{.006}{.844}$ = .71% to $\frac{.837}{.844}$ = 99.17%. So it would take a 30 fault that produced less than 690 volts primary 0-0, before the 30 unit wouldn't operate on a static basis.

The 0-0 unit can be analyzed in a similar manner using equation (8) of Appendix 5. This equation has only one solution since the 0-0 unit operates for all 0-0 faults from zero volts out to the solution value. For the College & Walnut 0-0 unit the $V_{0-0}$ = 12.91 volts secondary. This corresponds to .5963 secondary ohms or 99.38% reach.

Thus the compensator distance relay operates accurately over an extremely wide voltage range. This independence of voltage is a necessary characteristic, particularly for the system being discussed.

5. Coordination Problems With a Circuit Switcher Protecting a Transformer Bank Off a Short Line

This is not a problem directly related to the carrier relaying scheme, but since we may eventually put carrier relaying on the College & Walnut-Westside line, and because this problem seems to be occuring more frequently, it was felt worth pointing out.

The application of circuit switchers for protecting 115/13 Kv transformer banks is very common in our company. In most locations a 30 instantaneous overcurrent relay is used to block tripping for faults above the circuit switcher rating. The circuit switcher interrupting rating at Fort Wright is 6000 amps maximum, and this is the primary pickup value set on the 30 instantaneous blocking relay.

B. Distance Relays (Cont.)

5. Coordination Problems With a Circuit Switcher Protecting a Transformer Bank Off a Short Line (Cont.)

For faults above the circuit switcher rating one or more of the remote breakers must clear in order to reduce the fault duty below the dropout of the 30 blocking relay. This value is about 90% of pickup or 5400 amps primary. Therefore, under the normal case of both line breakers being closed, the distance and ground relays must operate for a transformer fault of 5400 amps. In our system we actually prefer them to operate down to 80% or 4800 amps. This provides a 10% margin below the 30 instantaneous unit dropout.

Ground faults in the transformer are no problem but phase faults can be difficult to protect. In our case the Zone 2 relay at Westside required a primary ohm setting of slightly over 18 ohms in order to see a 4800 amp fault at Fort Wright, with infeed from College & Walnut. A Zone 3 relay could have been used at Westside, but it was decided to wait until the Post Street-Second & Scott 115 Kv line is built, since a Zone 3 relay will definitely be required then.

This, of course, is only one of the relaying problems when a tapped load is connected to a short line. But it does show how this connection can result in longer settings than might be desirable, or the addition of a Zone 3 relay where it would otherwise not be required.

## Conclusion

This paper has described the selection and application of a relaying scheme for a portion of the 115 Kv transmission system in the Spokane area. The relaying system utilized was a conventional directional comparison carrier blocking system. As a result of some rather unusual system conditions (i.e., very short 115 Kv lines), some of the application problems and relay settings were rather unique. Certain items, such as arc resistance, were discussed which, even though they are familiar to most relay engineers, are seldom considered when making relay settings.

This entire system has recently been placed in operation. We are planning on making some staged fault tests on the College & Walnut-Post Street line provided approval is obtained from our systems operation people. These faults will be used to verify the operation of the carrier relaying scheme.

Marshall K. Brammer

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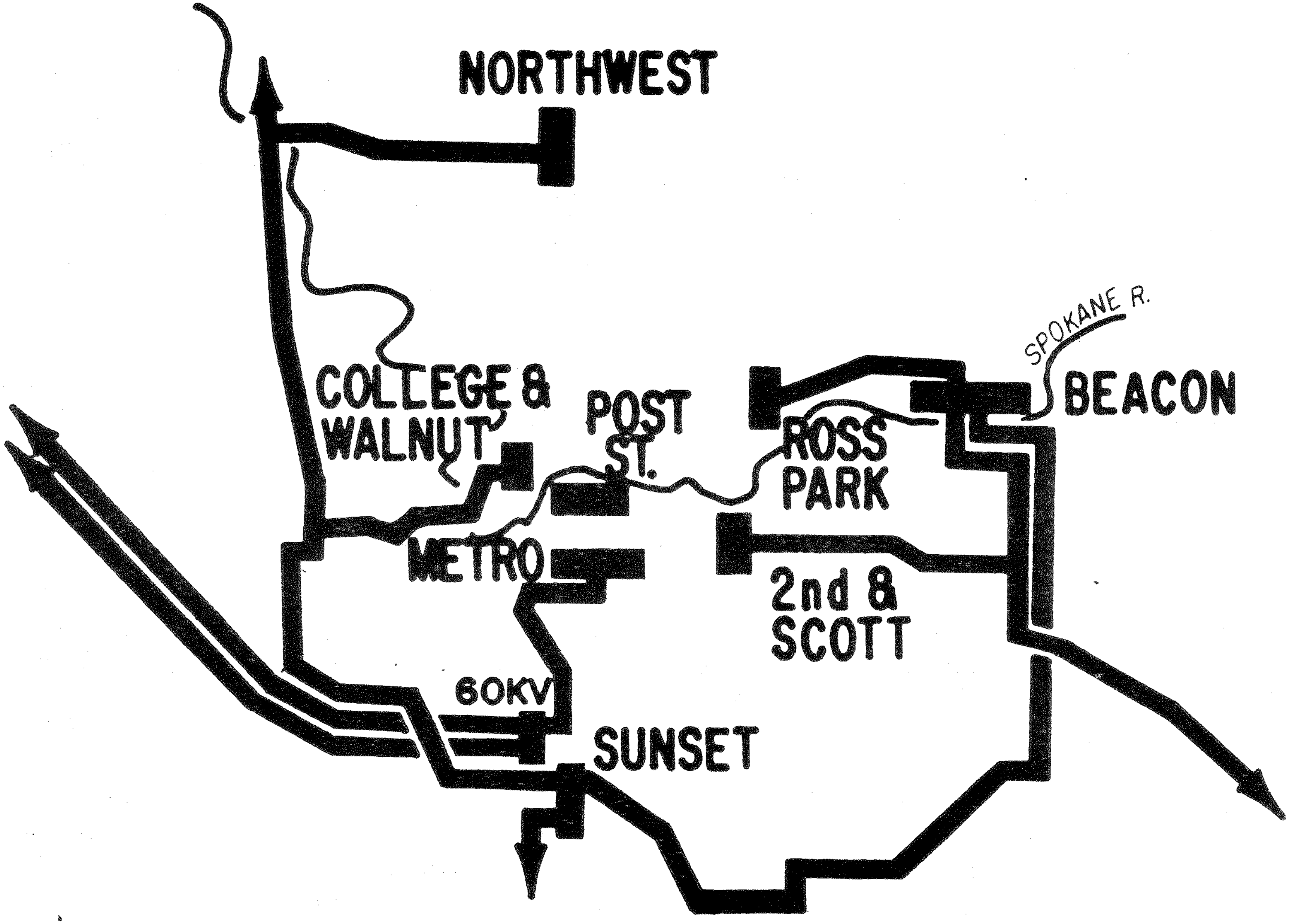

FIGURE 1-BEFORE 1970

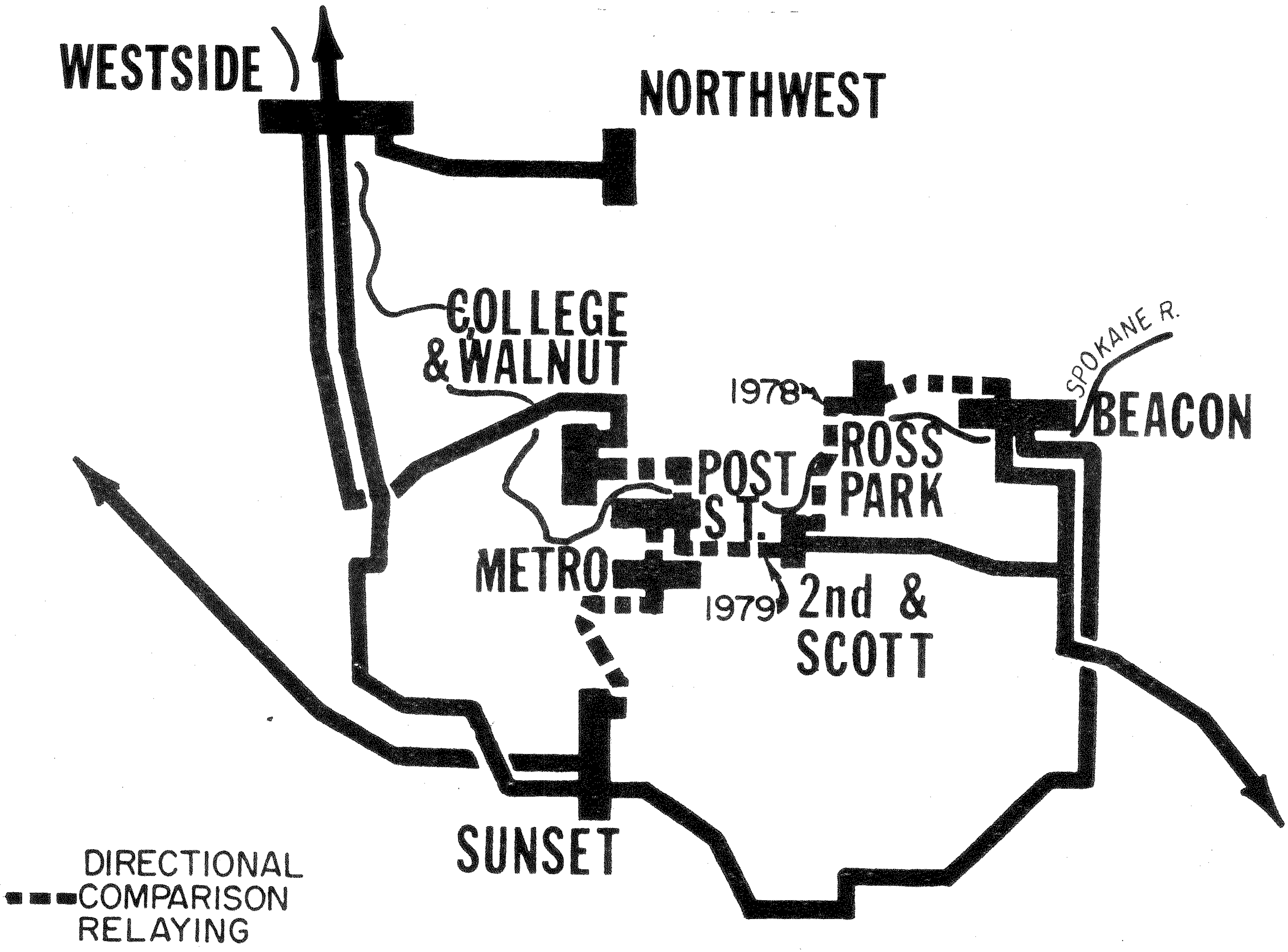

FIGURE 2 – PRESENT

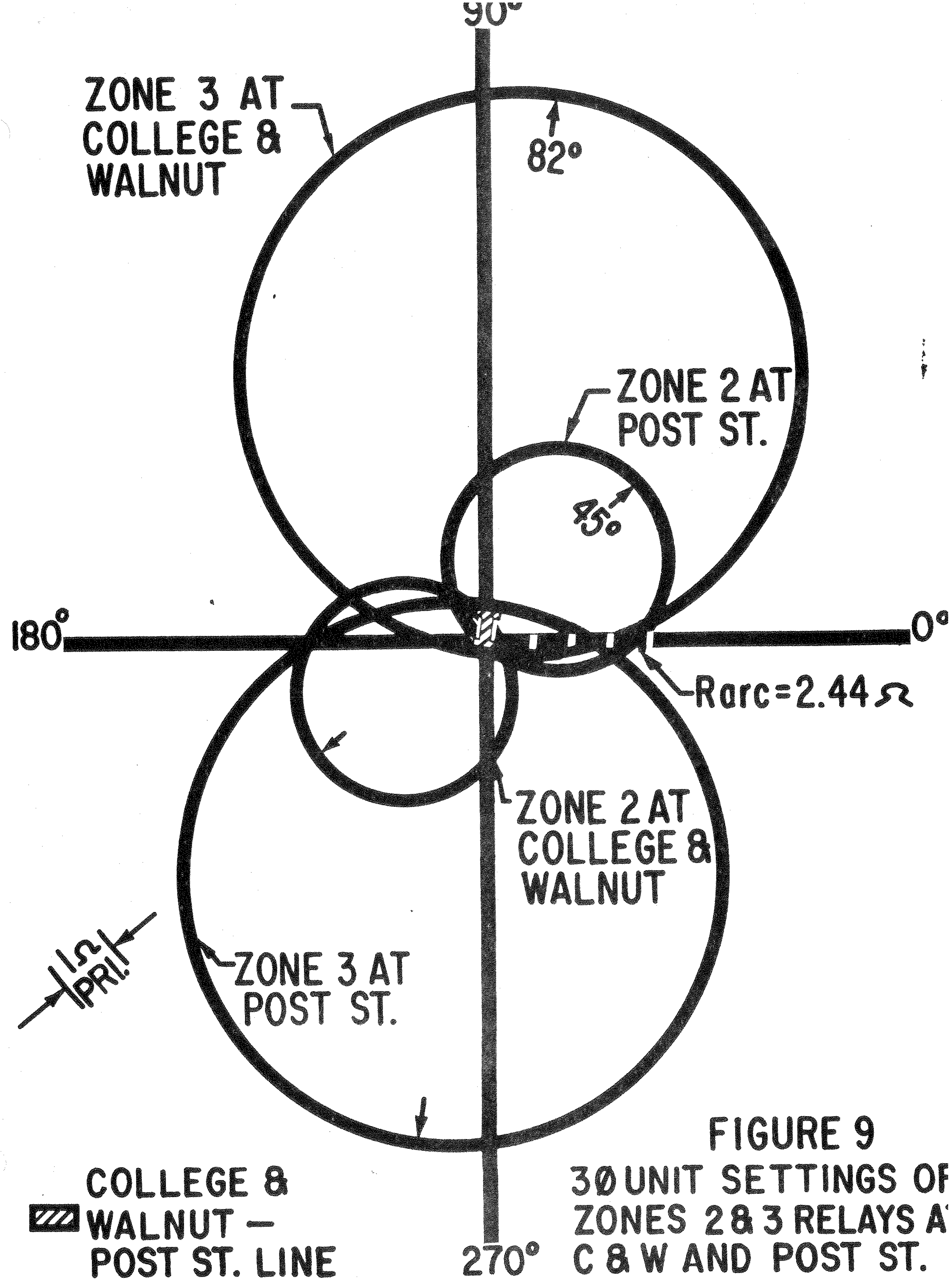

FIGURE 9
3Ø UNIT SETTINGS OF
ZONES 2 & 3 RELAYS A
C & W AND POST ST.

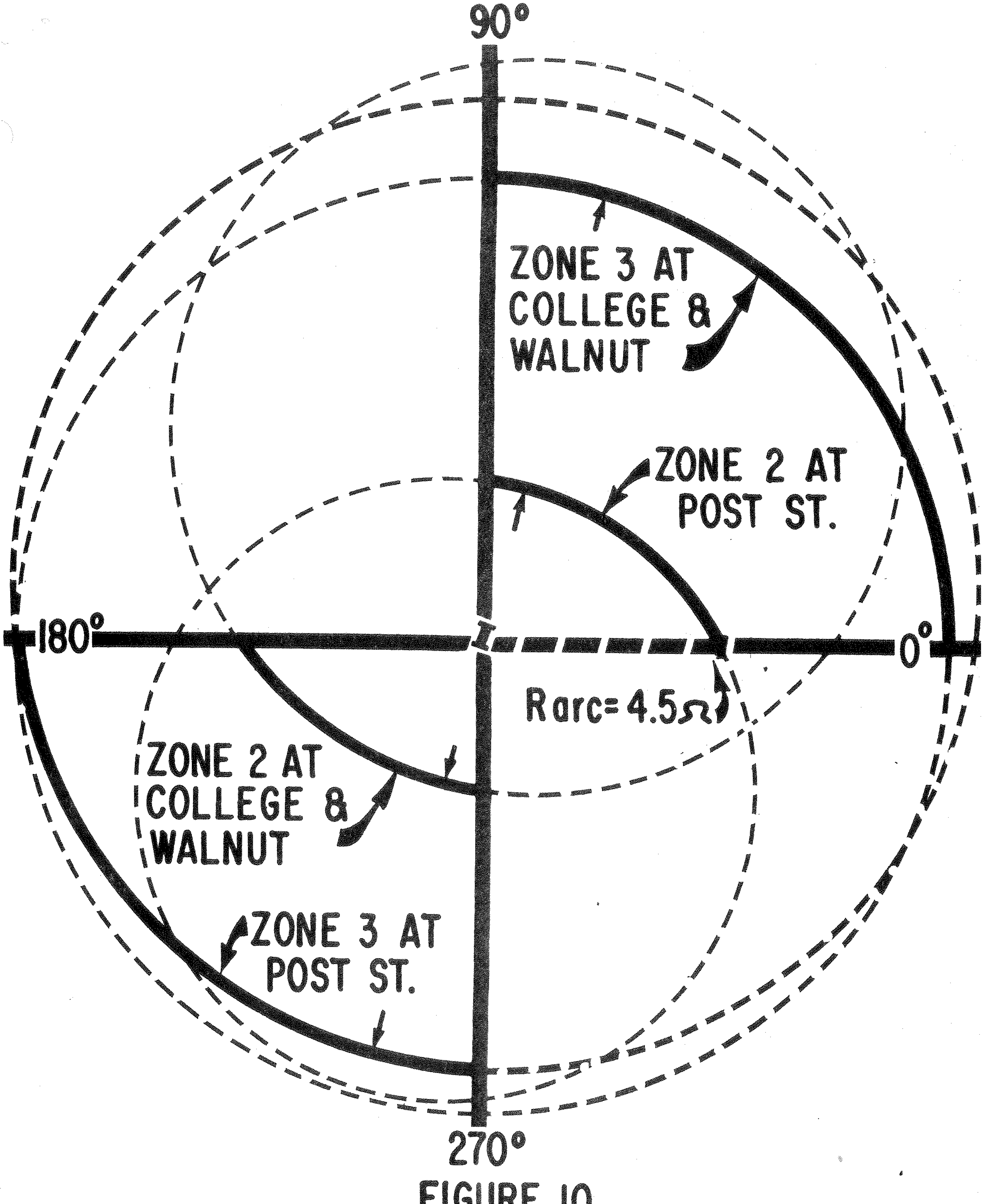

FIGURE 10

0-0 UNIT SETTINGS OF ZONES 2 & 3
RELAYS AT C & W - POST ST. LINE