FIELD TESTING OF POLARIZED MHO DISTANCE RELAYS
UNDER UNBALANCED FAULT CONDITIONS

BY

W. O. Kennedy P. Eng.

Saskatchewan Power Corporation
Regina, Saskatchewan

PRESENTED BY

J. A. Jodice

Doble Engineering Company
Watertown, Massachusetts

Summary

Recent advances in the development of test equipment and programmable calculators now make it possible to field test polarized mho distance relays and obtain the expanding characteristic of the relay which results from unbalanced fault conditions. This paper describes the test method and test equipment required to obtain these curves. Field tests on two relays have shown good correlation with manufacturer's published figures. A discussion on non circular mho characteristics is also included.

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Introduction

Traditionally, distance relay manufacturers have recommended that utilities wishing to test polarized mho distance relays with unbalanced voltages test only at the relay set point. Those utilities wishing to do polar curves of relay characteristics were advised to use reduced and balanced test voltages and vary the current in magnitude and angle. The result is a mho characteristic passing through the origin with the center of the circle on the replica impedance at half its value. Fixed unbalanced voltages will give a circular mho characteristic but this characteristic may be non circular in shape and the center may not lie on the replica impedance of the relay.

This paper describes a test method now in use by the Saskatchewan Power Corporation which uses "off the shelf" test equipment to obtain the expanding characteristic of a polarized mho distance relay under unbalanced fault conditions. Test results using a Doble F3C test set are given for two NEI Reyrolle relays; THS and THR. These results show good agreement with the predicted characteristics given by the relay manufacturer.

Polarized Mho Relay Theory

In 1965 Wedepohl[1] published his paper on the expanding nature of the polarized mho relay characteristic. A two input distance relay under unbalanced fault conditions has the following equations:

$$S_1 = I_f Z_n - V_f \qquad 1$$

$$S_2 = V_f + K_1 I_f Z_n + K_2 V_p \qquad 2$$

Where:

I_f is the fault current with angle ϕ

Z_n is the relay replica impedance θ

V_f is the fault voltage with angle γ

K_1 is the offset constant with a value from 0 to 1

K_2 is the polarizing constant with a value from 0 to 1 and may have an angle β

V_p is the polarizing voltage and has an angle δ

For a circular polarized characteristic with $K_1 = 0$ and K_2 with some value other than 0, the two points on the circumference which form the diameter of the characteristic are:

for S_1; $\quad Z_n$ 3

and for S_2; $\quad -\dfrac{K_2}{K_2 + 1} \; Z_s$ 4

While these values, see Figure 1, define a circular characteristic which does not pass through the origin, field testing to obtain this characteristic is impossible unless there is a discreet set of voltages and currents for each fault impedance value.

Other Characteristics

It is well known that a circular characteristic can be obtained by using fixed unbalanced voltages and varying the current in magnitude and angle. Not so well known is that depending upon the source impedance angle, this characteristic may lie on either side of the replica impedance.

Variable currents are preferred over voltages since only one quantity has to be varied. Also, modern electronic relays have the ability to carry 10-20 amps of secondary current continuously. In addition, the test set used can, with two current sources in the parallel mode, deliver currents to two decimal places with 1% accuracy up to 30 amps.

Equations 1 and 2 with $K_1 = 0$ may be rewritten as follows:

$$S_1 = I_f \underline{/\phi} \; Z_n \underline{/\theta} - V_f \underline{/\gamma} \qquad 5$$

$$S_2 = V_f \underline{/\gamma} + K_2 \underline{/\beta} \; V_p \underline{/\delta} \qquad 6$$

Appendix 1 gives a solution for these equations which yields

$$Z_f = Z_n \, (A \sin \phi + B \cos \phi) \; \underline{/\gamma - \phi} \qquad 7$$

This is the equation of a circle having one point of the circumference on the origin; in other words, a mho characteristic. The radius is:

$\frac{Zn}{2}$ in magnitude and has an angle equal to the abs $(\tan^{-1} \frac{B}{A})$.

Where the center of the circle lies is dependant on the angle of source impedance. Figures 2 and 3 show the effect of varying the angle of source impedance from 75° to 90°.

Figure 2 shows that part of the mho characteristic lies inside the polarized mho characteristic and part outside. Figure 3 shows the mho characteristic completely inside the polarized mho characteristic. Observed test results show that where the two characteristics are in close proximity to each other, the polarized mho characteristic "grabs" and non circular characteristics result.

For persons wishing to test polarized mho relays using this method, the above will allow them to accurately predict where the characteristic will lie but will not allow them to obtain the expanding characteristic of the polarized mho distance relay.

Programmable Calculator

As stated earlier, separate voltages and currents are required for each fault impedance. The calculations involved are repetitive by nature and lend themselves to being programmed. The TI 59 programmable calculator was chosen because both the Northern and Southern Test Crews were already equipped and using them for other work.

Separate programs were written for the phase and ground elements and each program is divided into three parts.

The first section identifies the program, sets the angle of Z_f to -30° and through a series of prompts requests the line and source impedances together with their angles and for the ground relay element the zero to positive sequence impedance ratios and the relay Ko factor.

The second section of the program calculates the S_1 and S_2 relay vectors, the fault impedance Z_f, and prints the value of Z_f.

The third section calculates the voltages and currents associated with Z_f and prints their values.

The flow charts for both programs are shown in Figures 3 and 4 and Figure 5 shows sample printouts for both the phase and ground programs.

The programs are stored on four magnetic cards, two for each relay element. Each program calculates 17 test points from -30° to 130° in 10° steps. The running time for the phase program is 4 minutes 15 seconds and for the ground 8 minutes 30 seconds. The actual testing time takes 20 minutes per relay element which leads to the acceptance of the long calculation time.

The calculator is limited in the number of program steps available and a choice between program size and memory allowance was required. The prompts require a lot of memory at the expense of program size. A number of decisions were made prior to the actual programming.

1. The prompts were required since the programs are not used regularly.

2. The programs were to be non interactive.

3. The system was radial in nature and unloaded prior to the fault.

4. All prefault voltages and currents were symmetrical.

5. The effects of shunt capacitance were ignored.

6. The ratio of Zo/Z_1 is a pure number.

The program's limiting values of -30° and 130° were chosen as follows.

1. Relays with quadrilateral characteristics lie in the -20° to 120° region.

2. The phase sequence of the voltages changes for a fault vector in the -30° region.

3. Resistance grounded systems will shift the characteristic in the -R direction.

4. Although it is quite simple to change the test limits, relay testing time increases proportionally.

5. It was desired to keep the testing time to 8 hours including equipment set up time for an 18 element relay.

<u>Test Set</u>

In order to use the values of the program to test a relay, a test set which has the ability to vary both the magnitude and phase angle of the test quantities independent of each other was required. As before we wanted to make use of test equipment already in use by the test crews; in this case, a Doble[2] F3C test set was chosen.

For phase faults, we used the TEE connection as shown in Figure 7a. The angle of the fault voltage is held constant at 0° and the angle of the TEE is allowed to rotate. The magnitude of the TEE voltage is held constant at 100 volts. Similarly, the angle of the fault current is fixed with respect to the angle of the fault voltage for a given fault impedance. This greatly simplifies field calculations of the fault impedance.

For ground faults, see Figure 7b. The angle of the fault voltage is held constant at 0° and all other quantities rotate with respect to it.

Test Results

Before commencing actual testing, the transmission lines were surveyed with the following results.

1. The majority of lines are 160 km in length with SIR's ranging in value from 0.25 to 2.5.

2. Some short lines 10 km in length exist with SIR's of 4 to 10.

3. The Zo/Z1 of the lines lie between 2.5 and 3.

4. The Zo/Z1 of the sources lie between 0.5 and 0.9.

5. The line angles lie between 60° and 80°.

6. The source angles lie between 80° and 90°.

When deciding on what test parameters to use it became apparent that low SIR's were to be avoided since test currents greater than 20 amps were required. These values are above most electronic relay continuous current ratings. Although tests were conducted on lines at lower SIR values by reducing the test quantities the test results were unacceptable with the conclusion that testing at higher SIR values is now recommended.

During the initial field testing phase, it was decided to have a number of the System Test Technicians perform the actual tests using their judgement of when relay operation occurred. The results of two of these tests are shown in Figures 8, 9, 10, and 11. The test relays were Reyrolle[3] THS and THR both of which have circular characteristics and are moderately cross (leading phase) polarized distance relays for both the phase and ground elements.

Test results for the phase elements were better than for the ground relay. The THS relay, Figure 8, has a "pimple" approximately 20° leading the set point angle. This "pimple" has been observed using other test methods. For this test case, the voltages form a negatively rotating set below 0° and the test results in the 0 to -30° region are ignored. Otherwise, a maximum 5% discrepancy for the particular fault impedance value is noted.

The THR phase relay, Figure 10, gave the same maximum discrepancy of 5%, although 1% was regularly observed. Above the relay replica impedance angle, the test set followed the relay S_3 characteristic which is perpendicular to this angle. This is an example of "grabbing" which occurs with the other test method described earlier in this paper. The "grabbing" has been observed to be arbitrary by nature when using the new test method.

Test results for the ground elements gave good results with the relay underreaching by a maximum of 8% of the particular fault impedance value below the replica impedance angle and by the same amount above for both the THS and THR relays; see Figures 9 and 11. Better correlation was observed for the THR below the relay angle.

Since these test results are more accurate than other test methods previously used by the test personnel, all Reyrolle relays will, in future, be tested using this method.

Teaching Tool

The test method has increased the knowledge and understanding of polarized mho relay theory and application by the System Test Technicians. The ability of the Technicians to field test these relays over a range of SIR's and observe the expanding nature of the relay characteristic is expected to aid in the trouble shooting of future protection problems.

Future Developments

Future developments include:

1. The possible modification of the programs to make them interactive to try and reduce any inherent discrepancies.

2. The inclusion of a "divisor" to hold the test currents to under 20 amps, allowing an even greater flexibility in the testing of relays.

3. A rearrangement of the test voltages to obtain voltages to 1 decimal place.

In addition, test programs are now being developed for other polarized mho distance relays used on the SPC system so that all relays will be tested using this method.

Conclusions

This paper has demonstrated that by using "off the shelf" test equipment, a regime for testing polarized mho distance relays with circular characteristics is possible. Maximum discrepancies of 5% and 8% for the phase and ground elements respectively are to be expected, although these discrepancies tend to be smaller with the newer generations of electronic relays.

The test method is based on the availability of the relay equations in the S_1, S_2, ..., S_n format from the manufacturer. The very nature of the design of distance relays makes it impossible, given the size of the calculator, to write a general test program for all relays.

Manufacturer's test sets tend to be specialized to that particular manufacturer's relay design(s) and are considered unsuitable for our test purposes.

This test method will be used and modified taking advantage of the advances in "off the shelf" test equipment which will allow us the capability of testing all relays using one piece of equipment.

Acknowledgements

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The permission of Doble Engineering Company and NEI Canada Ltd. to quote their equipment in this paper is also acknowledged.

References

1 Wedepohl, L. M. Polarized Mho Relay
Proc. IEE Vol. 112 No. 3 March 1965

2 Instruction Manual F3C Test Set
Doble Engineering Company, Watertown, Mass.

3 THS and THR Instruction Manuals
Reyrolle Protection Ltd., Hebburn, England

Appendix

One of the boundary conditions of a phase comparitor is:

$$\underline{/S_1} - \underline{/S_2} = 90° \qquad \text{A1}$$

Taking the tangent of both sides yields

$$\tan \underline{/S_1} \cdot \tan \underline{/S_2} = -1 \qquad \text{A2}$$

Equations 5 and 6 can be written in the following form:

$$S_1 = IZ_n \cos(\phi + \theta) + j\, IZ_n \sin(\phi + \theta)$$

$$-V \cos\gamma - j\, V_f \sin\gamma \qquad \text{A3}$$

$$S_2 = V_f \cos\gamma + j\, V_f \sin\gamma$$

$$+ K_2V_p \cos(\beta + \delta) + jK_2V_p \sin(\beta + \delta) \qquad \text{A4}$$

which yields

$$\tan \underline{/S_1} \doteq \frac{I\, Z_n \sin(\phi + \theta) - V_f \sin\gamma}{I\, Z_n \cos(\phi + \theta) - V_f \cos\gamma} \qquad \text{A5}$$

$$\tan \underline{/S_2} = \frac{V_f \sin\gamma + K_2V_p \sin(\beta + \gamma)}{V_f \cos\gamma + K_2V_p \cos(\beta + \gamma)} \qquad \text{A6}$$

Substituting into A2 and rearranging to extract the variable "I" yields

$$I = \frac{V_f}{Z_n (A \sin\phi + B \cos\phi)} \underline{/\phi} \qquad \text{A7}$$

where

$$A = \frac{V_f \sin(\gamma - \theta) + K_2V_p \sin(\beta + \delta - \theta)}{V_f + K_2V_p \cos(\beta + \delta - \gamma)} \qquad \text{A7a}$$

$$B = \frac{V_f \cos(\gamma - \theta) + K_2V_p \cos(\beta + \delta - \theta)}{V_f + K_2V_p \cos(\beta + \delta - \gamma)} \qquad \text{A7b}$$

Now

$$Z_f = \frac{V_f \angle\gamma}{I} \qquad \text{A8}$$

and substitution yields:

$$Z_f = Z_n (A \sin\phi + B \cos\phi) \angle\gamma - \phi \qquad \text{A9}$$

which is the equation of a circle having one point of the circumference on the origin.

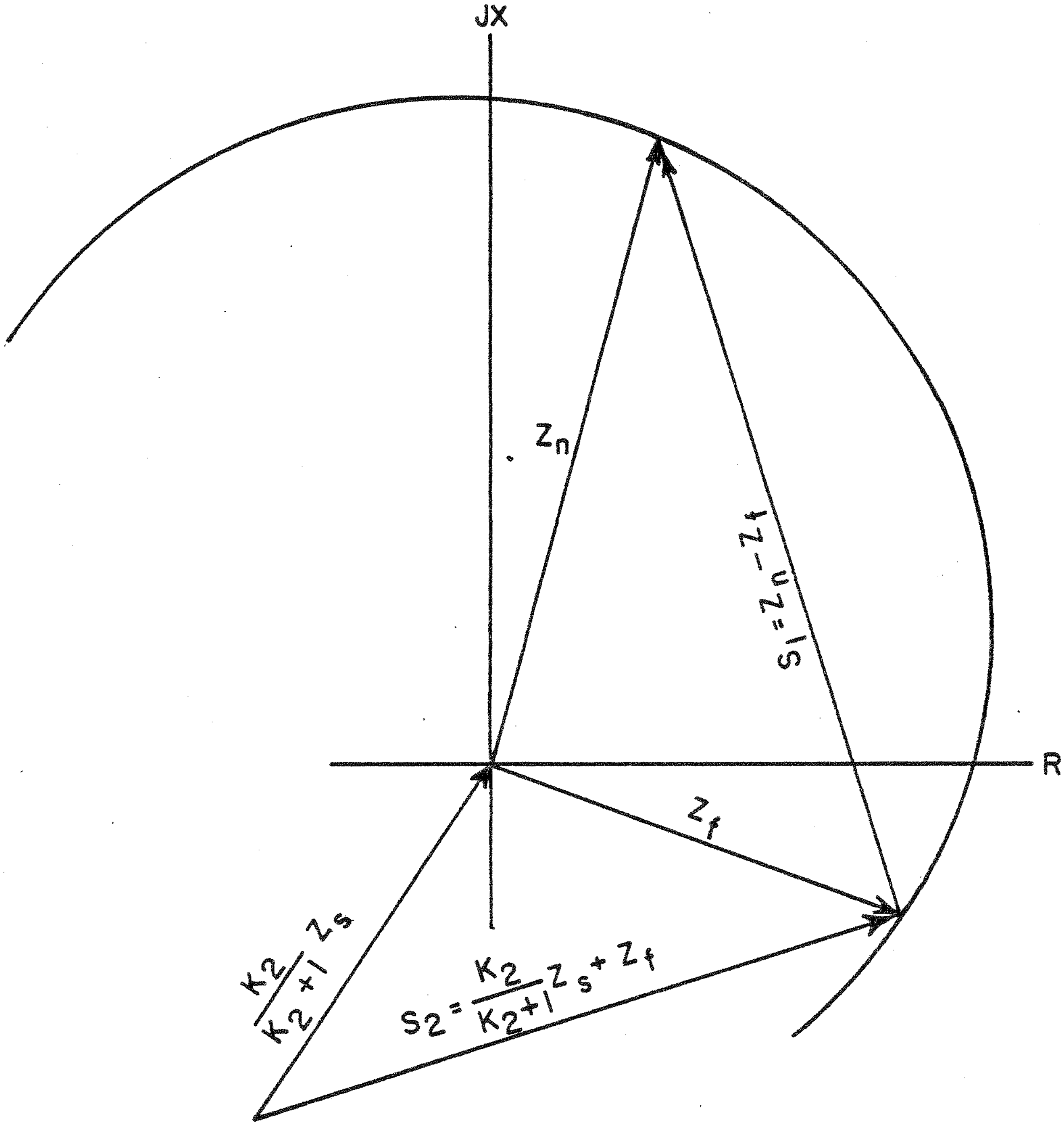


FIGURE I

PHASOR DIAGRAM FOR POLARISED MHO RELAY

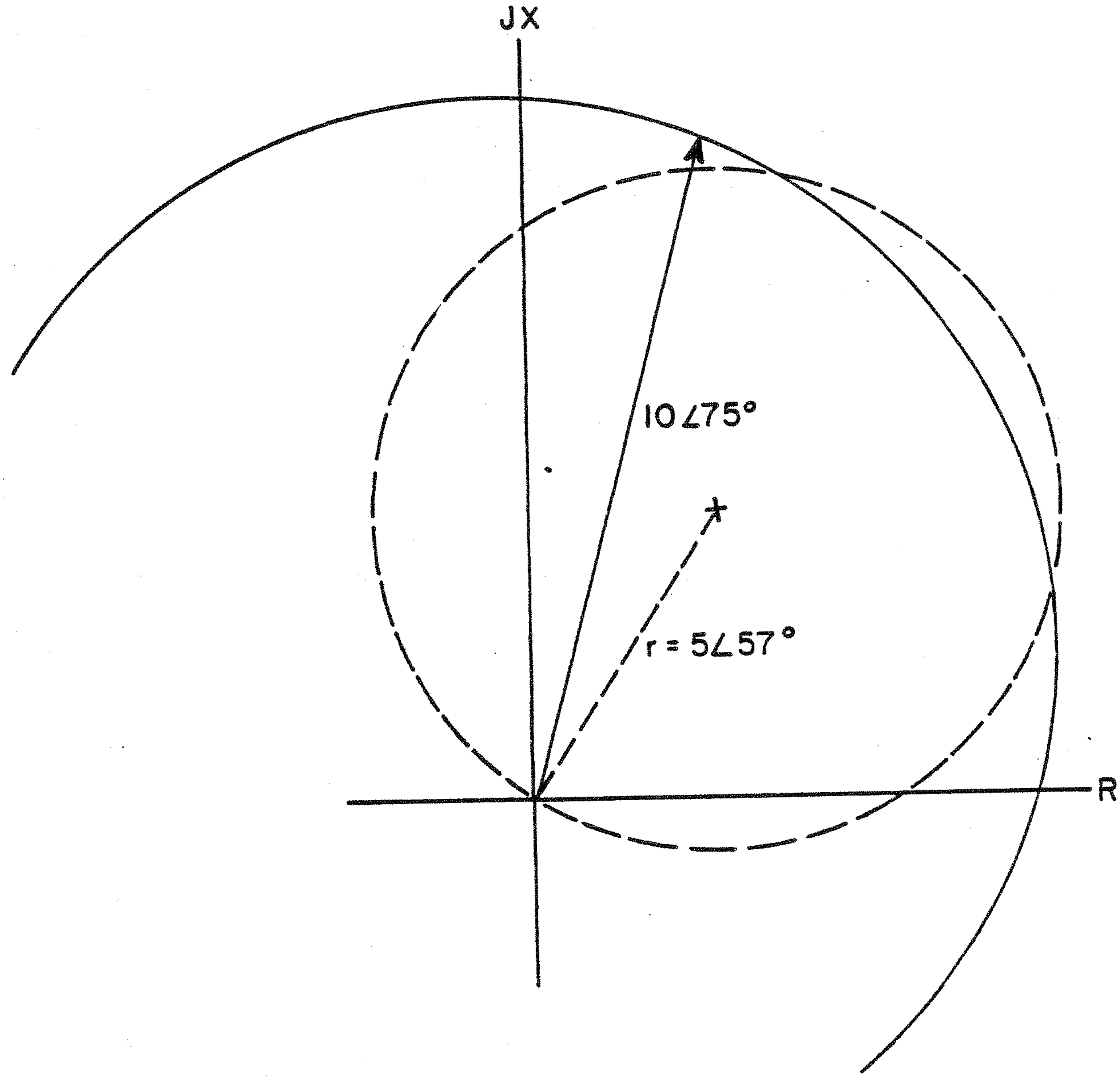


FIGURE 2

COMPARISON OF POLARISED MHO AND MHO CHARACTERISTIC FOR

$Z_n = 10\angle 75°$

$Z_s = 30\angle 75°$

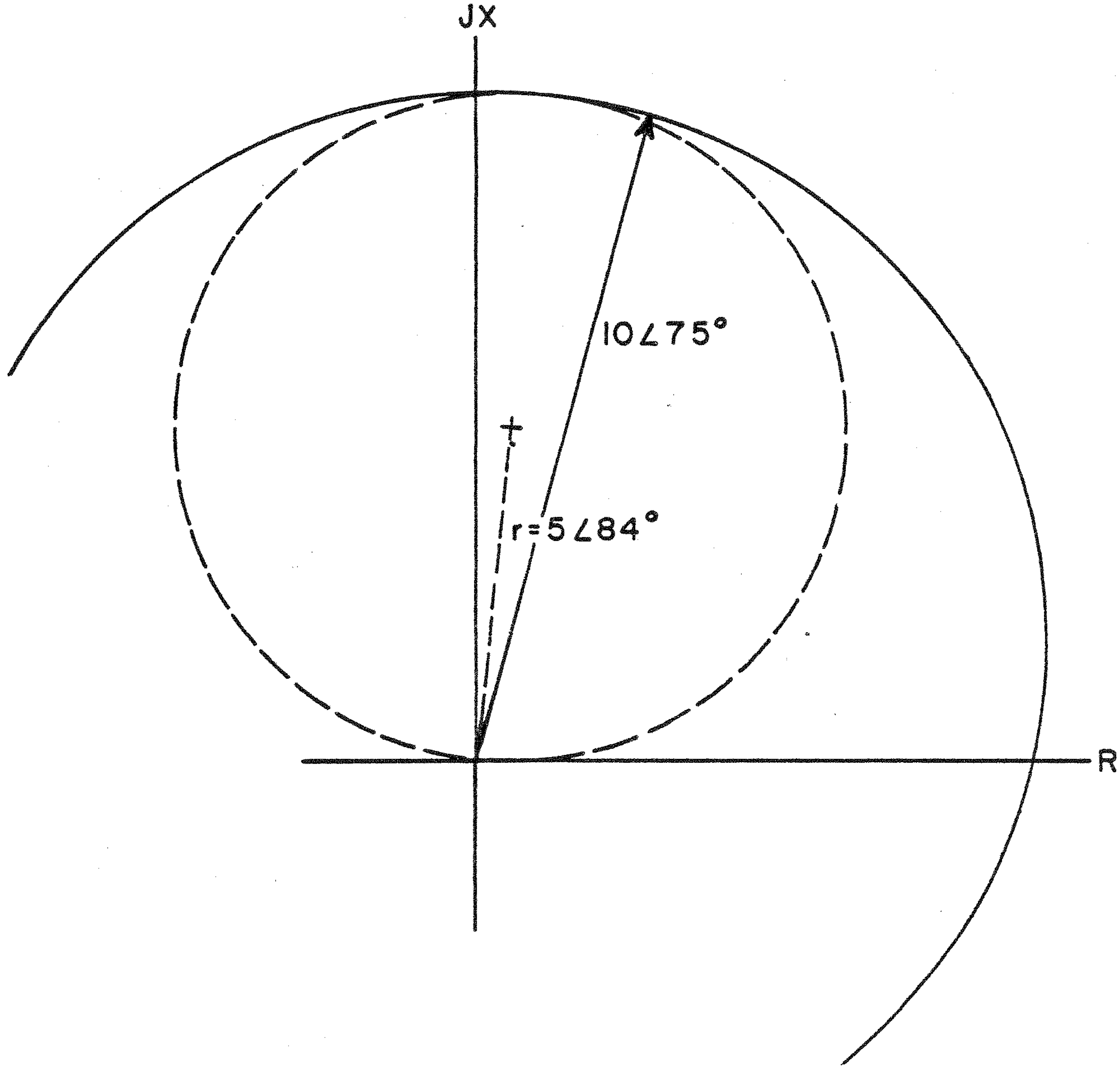


FIGURE 3

COMPARISON OF POLARISED MHO AND MHO CHARACTERISTICS FOR

$Z_n = 10\angle 75°$

$Z_s = 30\angle 90°$

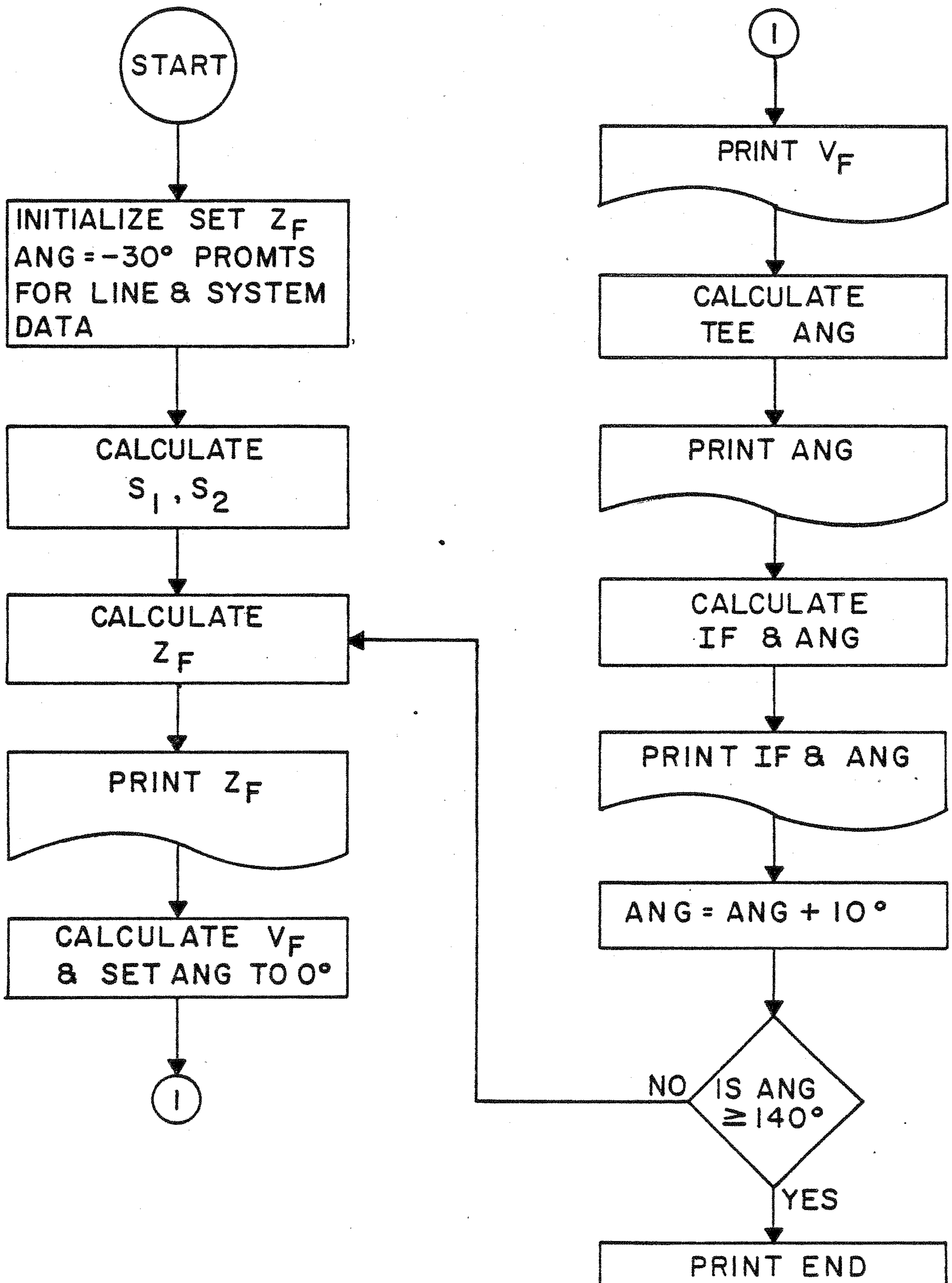


FIGURE 4
FLOW CHART
PHASE CALCULATIONS

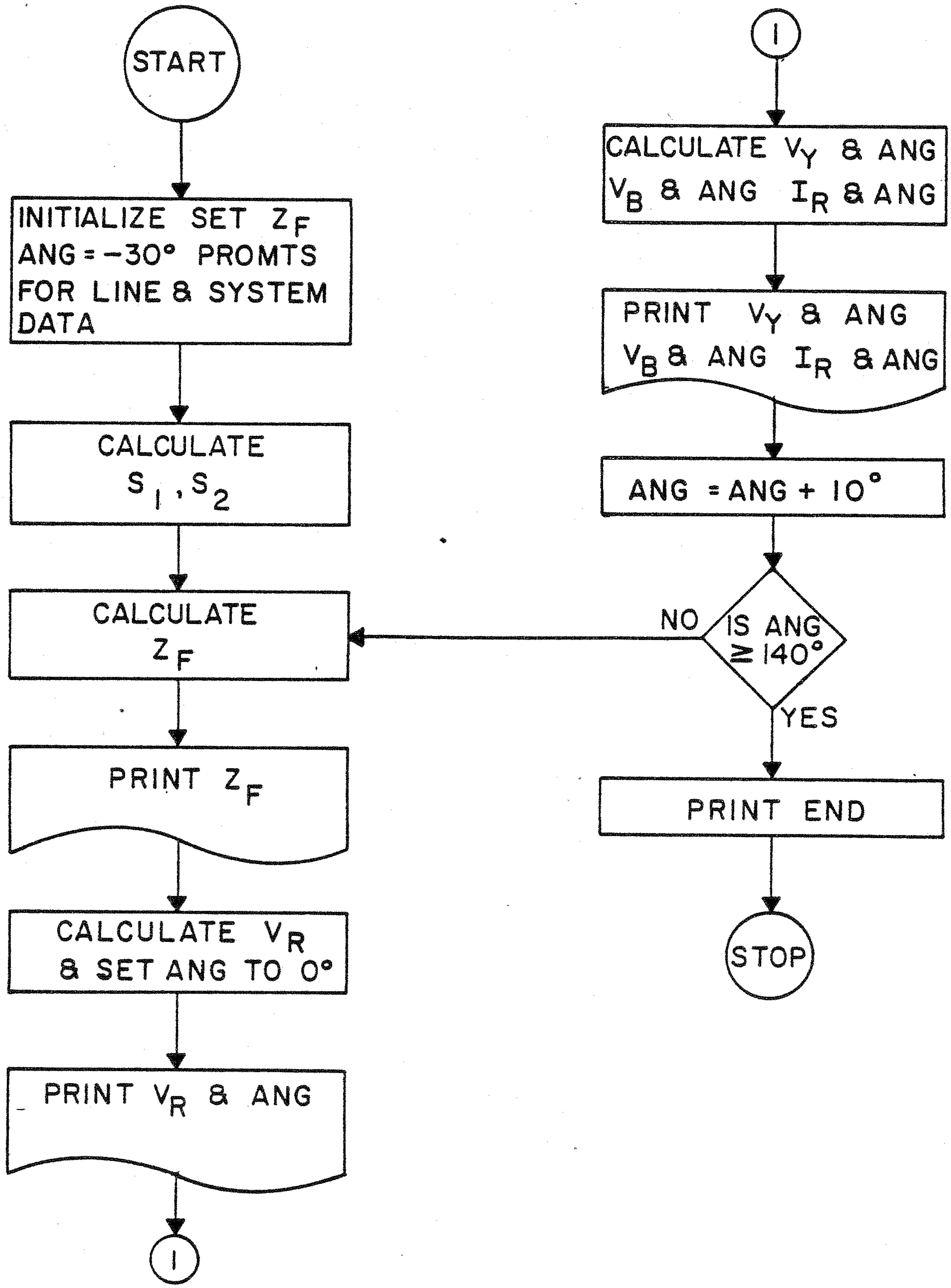


FIGURE 5
FLOW CHART
GROUND CALCULATIONS

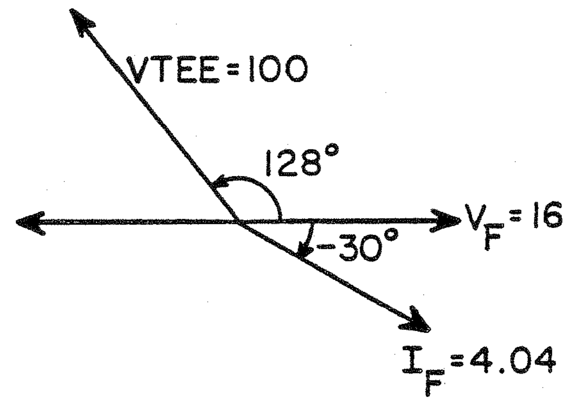
```
    THS / THR
PHASE CALCULATION

MARK 3

ENTER REACH  Z
       4.56
ENTER REACH ANG
        75.
ENTER SOURCE Z
       11.4
ENTER SOURCE ANG
        80.

SET VTEE= 100 V

       2.79       ZF
        15.       VF
       186.       AN
       5.34       IF
        30.       AN

       2.94       ZF
        15.       VF
       175.       AN
       5.10       IF
        20.       AN
```

```
     THS / THR
GROUND CALCULATIONS

ENTER REACH  Z
       0.45
ENTER REACH ANG
        60.
ENTER SOURCE Z
         5.
ENTER SOURCE ANG
        90.
ENTER ZL0÷ZL1
         3.
ENTER ZS0÷ZS1
        0.9
ENTER K0
      0.667

        0.67       ZF
         17.       VR
          0.       AN
         65.       VY
        349.       AN
         66.       VB
        225.       AN
       15.14       IR
         30.       AN
```

FIGURE 6

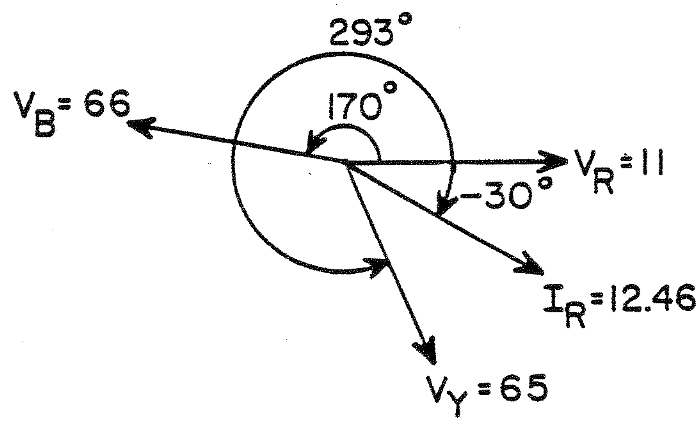
SAMPLE PRINT OUTS

3.91	ZF
16.	VF
128.	AN
4.04	IF
-30.	AN



(a) PHASE FAULT

0.53	ZF
11.	VR
0.	AN
65.	VY
293.	AN
66.	VB
170.	AN
12.46	IR
-30.	AN



(b) GROUND FAULT

FIGURE 7

TEST VECTORS

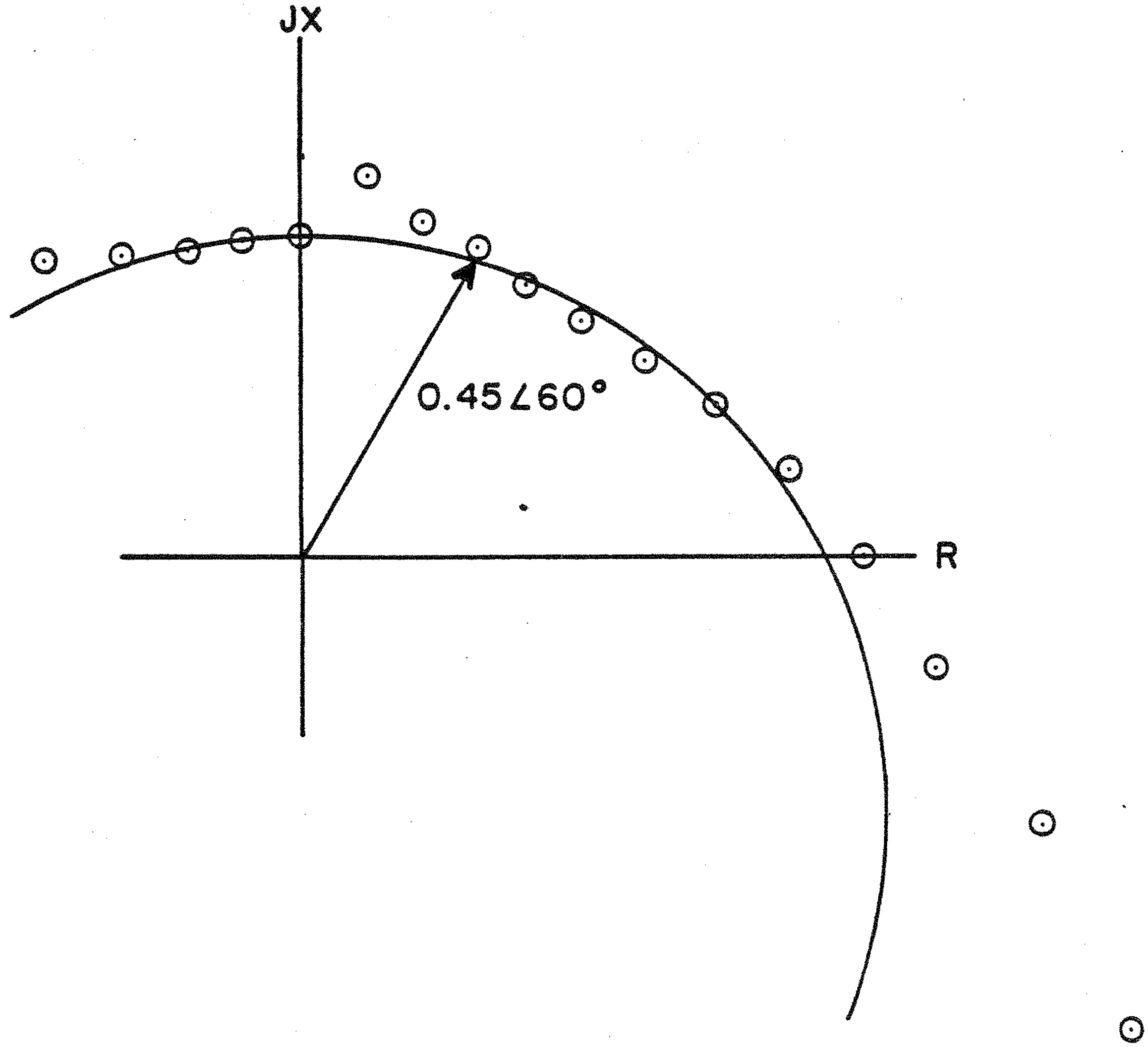


FIGURE 8

THS PHASE RELAY

$Z_n = 0.45\angle 60°$

$Z_s = 5\angle 90°$

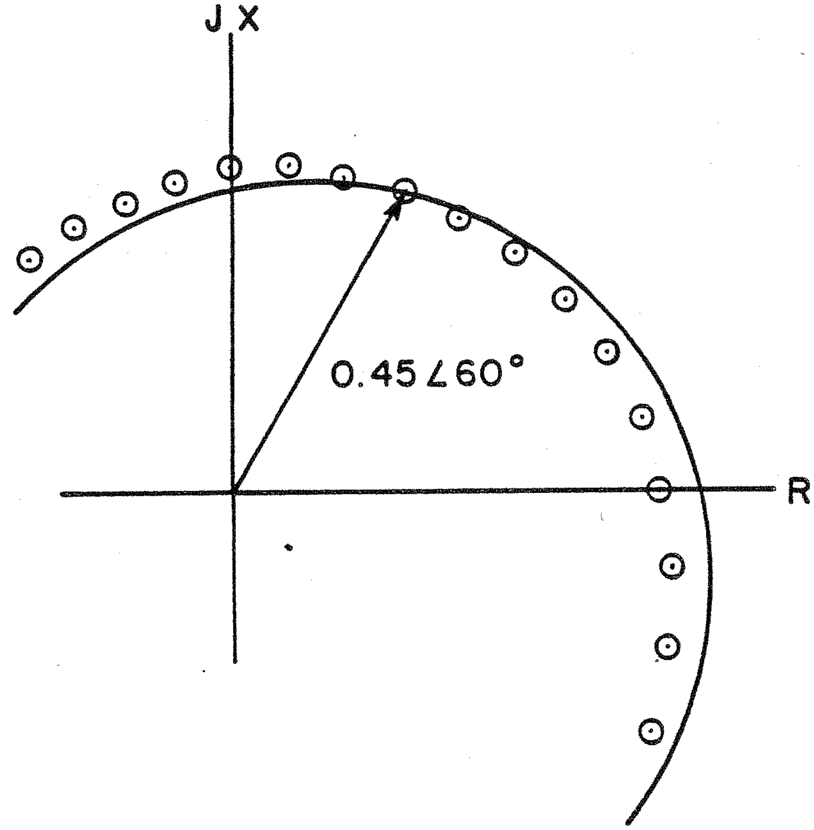


FIGURE 9

THS GROUND RELAY

$Z_n = 0.45\angle 60°$

$Z_s = 5\angle 90°$

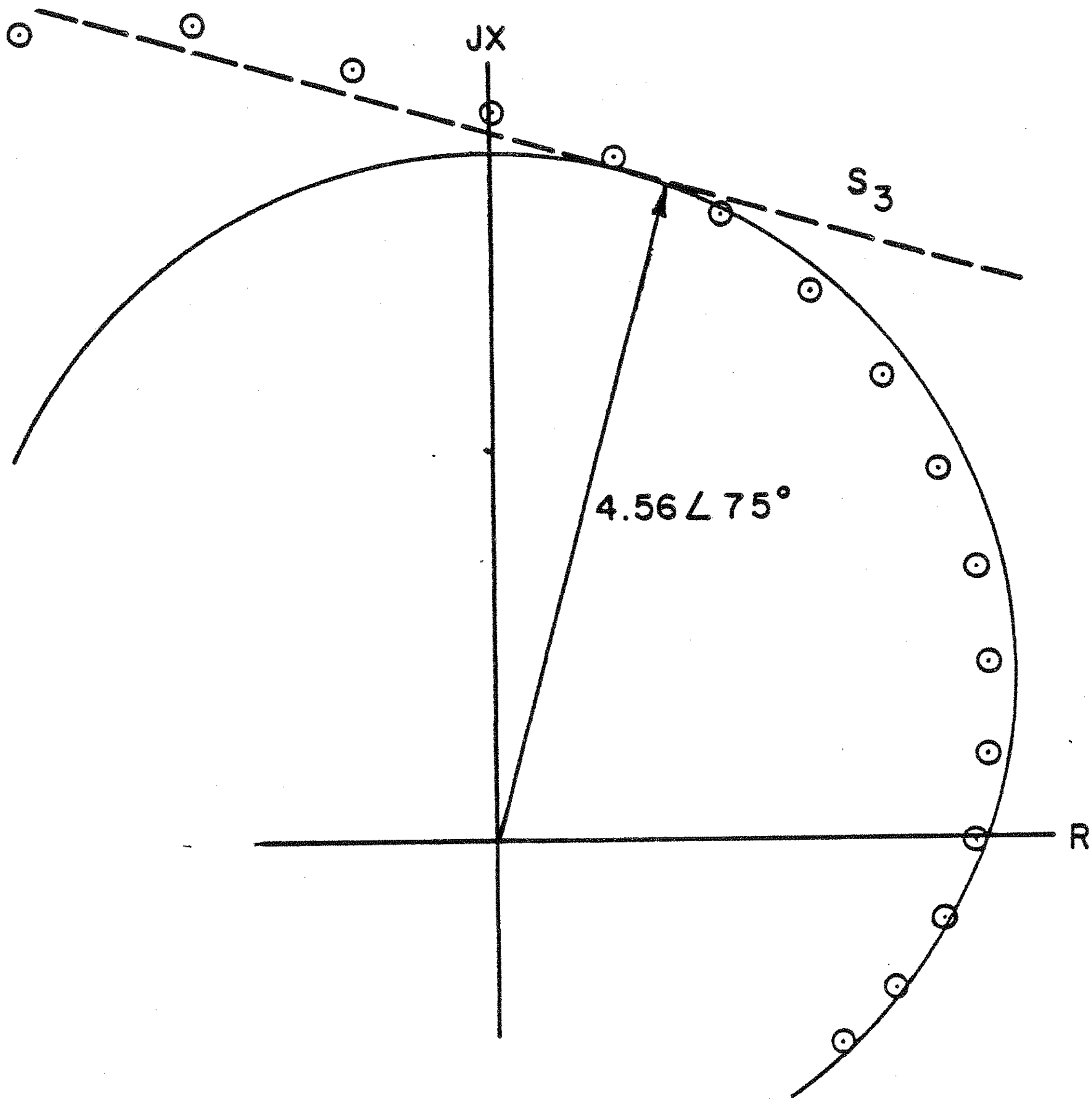


FIGURE 10

THR PHASE RELAY

$Z_n = 4.56\angle 75°$

$Z_s = 11.4\angle 80°$

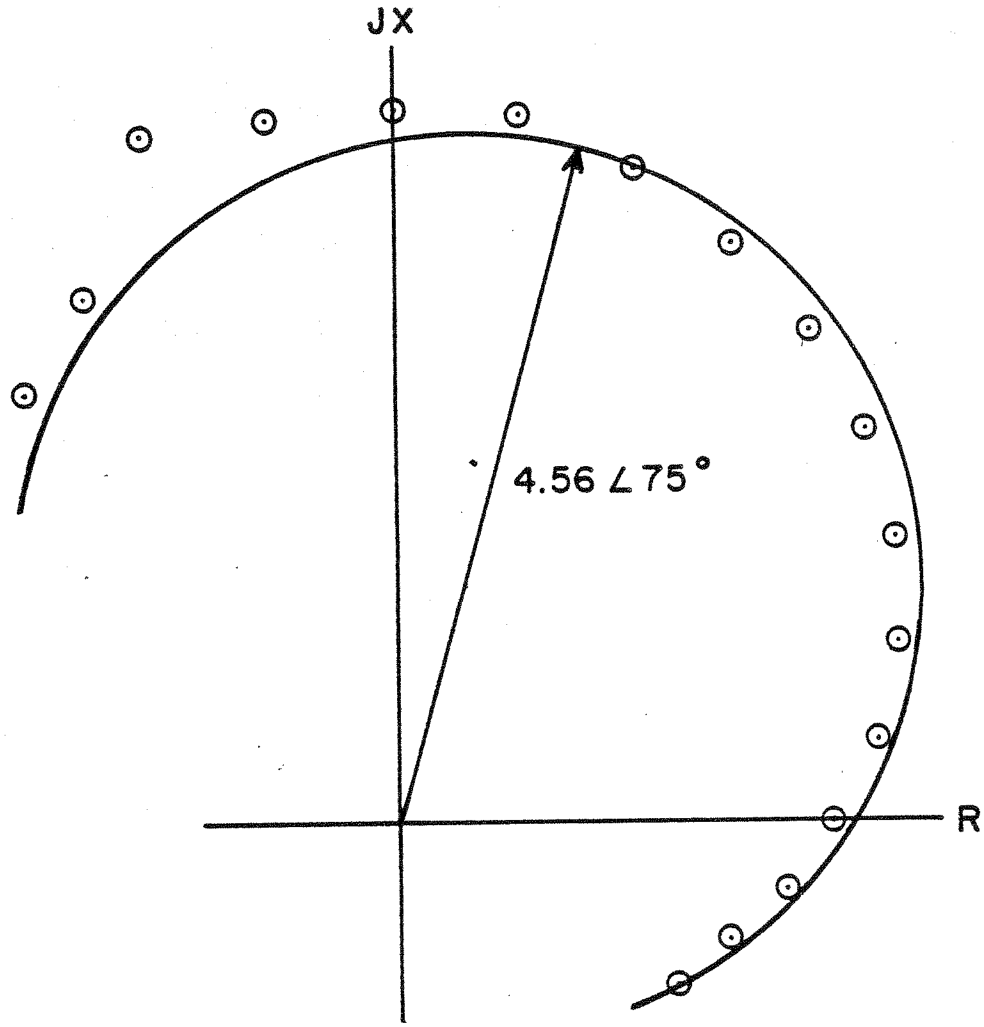


FIGURE 11
THR GROUND RELAY
$Z_n = 4.56\angle 75°$
$Z_s = 11.4\angle 80°$