TYPE TESTS ON DISTANCE RELAYS

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INTRODUCTION

During the period 1988 to 1992, B. C. Hydro plans to replace about 170 line protection systems which use obsolete electromechanical (balanced beam type) distance relays. These protection systems are applied on transmission lines rated from 60 kV to 230 kV. Some of the protection systems are communications assisted, but most are not.

B. C. Hydro decided to do extensive type tests on the distance relays proposed as replacements by various manufacturers. This decision was made partly because of the large investment in new equipment, and partly because of our special requirements. These tests were intended to determine whether the proposed relays would be suitable for general application on the B. C. Hydro system. The B. C. Hydro transmission line protection requirements are different from those of many utilities in two significant aspects. Firstly, protection systems must detect very high resistance single line-to-ground faults. The requirement for high resistance ground fault coverage means that ground distance relays are usually not sensitive enough and must be supplemented or replaced by directional ground overcurrent relays. Secondly, zone 2 and 3 settings are often less affected by the protected line impedance than by other factors. This means that required reach settings sometimes approach apparent load impedances, even on 60 kV circuits.

There are several reasons for the prevalence of high resistance ground faults on B. C. Hydro transmission lines. The lines usually have no shield wires since keraunic levels in much of British Columbia are low. Further, many of the lines are supported by woodpole structures with ungrounded hardware. Even where steel towers are used, the tower footing resistance may be in the order of several hundred ohms. Many of the lines traverse heavily forested areas, and tree contacts are frequent.

Similarly, there are several reasons why required reach settings are often unexpectedly high. One reason is that zone 3 reaches often need to cover adjacent lines beyond the remote terminal or, for communications assisted schemes, behind the local terminal. Another is that many lines have significant amounts of tapped load and the load currents are therefore not transmitted through the whole length of the line. Also, many of the tapped stations may be weak sources of infeed of fault currents to faults on the protected line, and this results in increased zone 2 reach setting requirements at the source of the protected line. Further, some lines may be connected to sections of additional lines under certain emergency or single contingency conditions. It is desirable that the same relay settings can be used to protect the line under these emergency conditions as well as under normal conditions.

This paper will primarily discuss B. C. Hydro type tests on distance relays, but some multifunction relays included directional overcurrent elements, and tests on these elements will also be mentioned.

The tests revealed problems with all the relays tested. Many of the problems were previously unrecognized by the manufacturers. Further, many limitations in the test equipment were discovered, and this paper will describe some of the required functions for test equipment used in type testing.

TYPE TESTS AND ACCEPTANCE TESTS

Type tests involve numerous tests on a few types of equipment. Acceptance tests involve relatively few tests on many pieces of equipment. In all cases, it is important to do enough tests to fully check the equipment, while not wasting time by doing unnecessary tests.

Acceptance tests are often based on a combination of manufacturer's recommendations and users experience with various pieces of equipment. These tests are intended to discover manufacturing defects and shipping or installation damage. This paper is not directed at acceptance tests.

Protective relay type tests are intended to discover design limitations with respect to application on a particular power system. Since B. C. Hydro has fairly unusual protection requirements, it was felt that it would be unwise to rely solely on manufacturers' type tests, which would be aimed at checking that the design solved common protection problems. As a starting point to define the required tests, B. C. Hydro used CIGRE recommendations (Ref. 1). The CIGRE recommended test procedure was modified to conform with available test equipment, available time, and intended application of the relay equipment.

Ref. 1 describes three different test series for distance relays: steady state tests, dynamic single source tests, and dynamic double source tests.

Steady state tests are intended to reveal the sensitivity, accuracy, and shape of the relay characteristics on the RX plane. The tests also explore the effect of varying source impedance, power supply voltages, ambient temperature, harmonics, and transient signals (SWC, etc.) on the steady state characteristics.

Dynamic single source tests measure the operating speed, directional integrity and dynamic characteristics. The dynamic characteristics may vary from the steady state due to the effect of memory polarizing, or transient dc offset of ac signals. Further, the effects of instrument transformer errors, and asymmetrical circuit breaker pole opening or closing on the relay performance can be tested.

Dynamic double source tests investigate the effects of load currents and power swings on the behaviour of the relay. Also, the security and dependability of unit protection schemes (including the communications channel) can be investigated.

Ref. 1 lists more than 600 steady state tests, 600 dynamic single source tests, 200 dynamic double source tests and further tests on various auxiliary functions (such as automatic reclosing). The total number of all tests listed is 1744. Obviously, a complete series of type tests is no small undertaking! In fact, B. C. Hydro decided to significantly reduce the scope of testing.

B. C. HYDRO TYPE TEST PROCEDURE

The reference setting of the relays for most tests was 4 ohms at 75°, and the reference source impedance was 8 ohms at 75°. Selected tests were also repeated with the relays at near maximum and near minimum settings of their respective ranges. Source impedances were also varied for selected tests, and source impedance to relay setting ratios varied from 0.25 up to about 100.

Steady state tests were extensive. However, due to lack of equipment, the effect of harmonics and dc power supply ripple on the steady state characteristics were not investigated. The effects of varying ambient temperature, varying source impedance, magnitude of dc power supply, transient disturbances, short interruptions of power supply, and radio frequency interference were investigated.

Included in the transient disturbance tests were the surge withstand capability, according to ANSI C37.90a-1974, and a "fast dc transient" test, which is similar to a proposed test to be specified in the next revision of ANSI C37.90a.

The radio frequency interference test was conducted as follows. With the relay energized, with normal in-service shielding in place and with operating quantities near the boundary of operation (i.e. just inside and just outside the operating locus), the radio antenna was brought within 1 metre of the relay. The radio transmitter was operated continuously and pulsed at 1 second intervals. The status of the relay was monitored. VHF and UHF transmitters rated 10 watts minimum RF output to the antenna were used.

Short interruptions of the power supply were created by a pulse generator driving a solid state switch as shown in Fig. 1. The dc was pulsed "on" for short intervals, and also pulsed "off" for short intervals. The lengths of "on" and "off" intervals were varied from about 5 milliseconds to 1 second.

Dynamic single source tests were also extensive. Due to lack of equipment, there were no tests to investigate the effect of instrument transformer errors on dynamic characteristics. Note that at voltages of 138 kV and above, capacitor voltage transformers are widely used by B. C. Hydro. However, most B. C. Hydro current transformers will not saturate during the first few cycles of faults near the end of reach of zone 1 distance relays. The effects of varying ambient temperature and source impedance on dynamic characteristics were observed.

Dynamic double source tests were limited for two reasons. Firstly, there was a lack of suitable test equipment to simulate power swings, fault current reversals, breaker pole discrepancies during opening or closing, or evolving faults. Secondly, many of the dynamic double source tests are aimed at testing the integrity of complete protection systems (including communications channels). Since only the distance measuring portion of a line protection system was being tested, many double source tests were not applicable. The effect of load currents on directional integrity were investigated using a single source test set, and these tests may be considered double source, because of the load flow. Otherwise, no double source tests were done.

The major equipment used for all tests, was a pair of Doble Engineering type F3D test sources synchronized together, and connected as shown on Fig. 2. Ref. 2 gives the background to the test procedure for dynamic tests. Each test set had only five channels (two voltage, two current and one voltage or current), so one set was used to provide three independently adjustable voltages, and the other three independently adjustable currents.

For steady state tests, the appropriate voltages were applied, then the faulted phase currents (with the appropriate phase angles) were gradually increased until the measuring element operated.

For dynamic tests, the test sets were simultaneously switched from prefault (or normal), to fault (or dynamic) modes. In the normal mode, the sets produced symmetrical voltages at nominal levels (69.4 V phase-to-neutral), and symmetrical currents of adjustable magnitude (0 to 5 A). The phase currents in the normal mode lagged the corresponding phase-to-neutral voltages by 30°, and this angle was not adjustable. In the dynamic mode, the sets produced preselectable currents and voltages at any phase angle, and of any magnitude. Fig. 18 shows the currents and voltages of a typical dynamic test. Note the very fast transition from prefault to post fault signals, and vice versa. Note also the absence of any transient dc offset component which would be expected in the currents of a real power system. There was no control over point on wave switching.

Test quantities were usually calculated using a LOTUS-123 spreadsheet when the expected characteristics were known. A partial layout of the spreadsheet used for single line to ground faults is shown in Fig. 3. Layouts for 3 phase faults and phase to phase faults were similar. The spreadsheet first calculated the expected reach, given the forward and reverse reach set on the relay, and the angle of the fault impedance. Then, given the expected fault impedance and the source impedance, the spreadsheet calculated the test quantities for an A phase-to-ground fault. If other types of faults were to be applied, the spreadsheet rotated the test quantities suitably. Vectors were handled in packets of four (two numbers in each of polar and rectangular coordinates). Fig. 3 also shows the layout for a single vector.

For single source dynamic tests, the relay dynamic characteristic at fault angles away from the maximum torque angle was often unknown, or significantly different from expected. In these cases, an operating point for a given source impedance was assumed, and the current adjusted until dynamic operation was obtained. If the observed fault impedance for dynamic operation was significantly different from first assumed, the test quantities were recalculated using the same source impedance, and a fault impedance assumed equal to the last observed impedance. This process was repeated, if necessary, until the observed impedance for dynamic operation was the same as assumed for calculation of the test quantities. This "search and find" test procedure is detailed in Ref. 3.

For determining dynamic operation, it was observed that there was no single fault impedance which precisely defined the boundary of operation. So two characteristics were defined. One was the "limit of dynamic operation" which was the impedance at which the relay would not operate for 10 out of 10 shots. If the fault impedance was reduced slightly below this limit, the relay would operate dynamically at least once in 10 shots. The other boundary was the "consistent dynamic operation", which was the impedance at which the relay would operate for 10 out of 10 shots. If the fault impedance was increased slightly above this limit, the relay would not operate dynamically at least once in 10 shots. In all cases, the test shots to determine these boundaries were applied at random points on prefault voltage waves. In all cases, there was no prefault current. Fig. 17 illustrates the concepts of the two boundaries.

The operating speed of the relay was determined by simulating faults at various distances from the relay location, with the fault angle equal to the maximum torque angle. The speed for any given fault condition was measured 10 times, and the maximum and minimum operating times recorded. Operating times were measured on a storage oscilloscope, with the 10 shots being superimposed one on the other to give a resulting image (see Fig. 4) which clearly showed maximum and minimum times. The 10 tests for each fault were at random points on prefault voltage waves. In all cases there was no prefault current.

The directional integrity of the relay was tested with close-in faults with 0 volts across the faulted phases. The security of the relay during reverse faults was tested with maximum relay reach setting and maximum available test currents. The dependability of the relay was tested with near minimum relay reach setting and minimum fault currents. The effect of load currents during the prefault and fault periods on the directional integrity was also determined. Test quantities including load currents were usually calculated using the Power Technologies Inc. (PTI) PSS/E computer program to study faults on a small system similar to that shown in Fig. 5. The base MVA and base voltage of the PSS/E systems were chosen so that calculated fault currents and voltages could both be divided by 1000, and applied directly to the relay as secondary quantities. This had the advantage of simple derivation of secondary quantities, and also meant that apparent primary impedances calculated by PSS/E were equal to secondary impedances seen by the relay. In one case, when the validity of the directional integrity test signals from the test sets was in question, the tests were repeated with a "poor man's model power system" as shown in Fig. 6. Each directional integrity test was normally repeated 10 times with random point on prefault voltage wave switching. In some cases, where there was doubt about the directional integrity of the relay, the tests were repeated up to 50 times. The security of the relay during the removal of reverse fault conditions (and restoration of prefault conditions) was also checked.

TEST RESULTS

Note that in all the diagrams of results, measured data points are clearly shown. Lines connecting the points are assumed characteristics.

In nearly all cases, the steady state response of mho elements for 3-phase faults closely matched the expected, as shown in Fig. 7. However, two relays showed overreach errors exceeding specified tolerances at near minimum settings. Measuring elements that had resistive or reactive blinders, often had small, but significant deviations from expected angles of the measured characteristics. One example of this is shown in Fig. 8. In the case of Fig. 8, the manufacturer confirmed that the measured angles were correct, and the angles specified in the relay specification should be different.

The steady state response for two phase faults depended on the amount of cross polarization, as can be seen from Fig. 9. Ref. 4 gives details of the relationship of expected response to amount of cross polarization. In the case of one type (a fully cross polarized relay), the measured reach was significantly less than expected at fault angles not equal to the maximum torque angles. This is shown in Fig. 10. The manufacturer of this relay confirmed that this underreach was expected. He would have to provide expected characteristics for phase-to-phase faults if B. C. Hydro was to apply the relay.

One type of relay failed the short dc interruptions test. The design of the power supply in that relay was modified by the manufacturer, and it is now satisfactory.

Two types of relay failed the fast dc transient test. In one case the manufacturer subsequently stated that the relay tested was a prototype version, not a production version. However, the design of production versions was also modified to improve the transient immunity. In the other case, the solution to the problem of the failure has not yet been determined.

Two types of directional ground overcurrent relays were tested during the distance relay test program. Some steady state directional characteristics are shown on Fig. 11. The sensitivities of the relays at maximum torque angles were also measured and some results are shown in Fig. 12. One of the directional ground relays tested was an integral part of a multifunction transmission line protection relay, and it can be seen from Fig. 12 that the sensitivity of the directional ground fault detector element is related to the setting of the phase fault distance measuring element. This relationship was unexpected, until the manufacturer explained the reasons for it. The manufacturer also defined the relationship.

The operating times of the distance relays were usually as expected. Fig. 13 shows some selected results. In one case operating times of a relay were found to be 1-3 ms different from the times quoted by the manufacturer. This discrepancy was traced to a test set. The test set was putting out a "start timer" signal 1-3 ms after the test signal was applied. When measuring short operating times, it is important to ensure the "start timer" signal starts sufficiently close to the instant of the signal application. One other relay was found to be occasionally operating up to 20 ms slower than claimed by the manufacturer for phase to phase faults. The manufacturer in this case claimed that the observed slow operating time was caused by incorrect simulation of the fault current (i.e., there were no transient dc offsets in currents starting near their peaks). There was no way to dispute this claim. Note that the "poor mans' model power system" was not available at that time.

For interest, the operating times of two types of relay for identical faults were compared. This comparison was made by connecting the current inputs of the relays in series, and the voltage inputs in parallel. Fig. 14 is an oscillograph of one of the comparison tests.

The most surprises were obtained during the dynamic characteristic measurements. Four of the five relays tested were found to have significant and undesirable transient overreach in the reactive direction. Some typical results are shown in Figs. 15, 16 & 17. In the case of Type A, the manufacturer discovered the occasional overreach in the reactive direction was caused by jitter in the memory polarizing signal. This jitter cannot be changed. For Type B, the overreach was corrected by design changes. For type D, the overreach was caused by a combination of a manufacturing defect in the relay tested, and a design defect. Type D performed as expected after correction of the defects. The overreach in Type E has not been explained yet. Note that for Type E, the overreach in the resistive direction is not a concern.

There were also some surprising failures of the directional integrity tests. Type B would not reliably detect zero voltage three phase faults in the forward direction. This problem was inherent in the design of the relay. Type C had some initial security problems, in that it misoperated for some reverse faults. However, the design was modified, and it subsequently proved to be reliable. Type D also had some problems during the directional integrity tests. These were mainly related to the problems causing the dynamic overreach. However, even after repair of the manufacturing and design defects, the relay still misoperated after removal of zero voltage three phase faults close to the relay. These misoperations only occurred if the fault was removed after the expiration of the memory voltage. The manufacturer believes the misoperations are due to incorrect simultaneous cutoff of the fault currents instead of cutoffs near natural zeroes, as would occur in real life. Fig. 18 is an oscillograph of one of the tests on the repaired relay showing the reverse looking element misoperating for a forward fault.

Further, it was found that one relay would misoperate for some reverse SLG faults when load flow was involved. Fig. 19 shows a typical reverse fault test. It was found that the ground distance element in the phase leading the faulted phase would misoperate if the reach was set too far with respect to the load. Note that in this case, the load flow was in the reverse direction as far as the relay was concerned, and would not normally have been considered in application calculations.

CONCLUSION

All relays tested showed some deviation from expected results in some cases. Three of the five relays had design deficiencies corrected by the manufacturer. The two other relays showed design deficiencies which are minor enough to remain uncorrected by the manufacturer. In all cases, application limitations were discovered which would not have been discovered from the relay's instruction manual or specifications. It is interesting to note that in spite of the lack of transient dc component in fault currents, the dynamic tests revealed several design problems which were acknowledged by the manufacturers. In some cases however, the limitations in dynamic tests caused inconclusive results.

There were several limitations in the test equipment used, and the following items are listed as desirable in test sets to be used in type testing of protection equipment:

1. Six channel output (three voltages and three currents). This is important to simulate the effects of pre fault load.

2. Ability to independently set prefault and fault quantities and to switch instantaneously between them. Prefault quantities may be adjusted symmetrically, but the angle of the prefault currents with respect to pre fault voltages must be adjustable.

3. Ability to simulate transient dc offset in fault currents. This feature is important to simulate fault currents in real power systems, and lack of this feature often caused doubt in the validity of certain tests. Note that switching at natural current zeros will not satisfactorily eliminate the need for this feature. This is for two reasons. Firstly, for three phase faults and double line to ground faults, fault currents must start simultaneously in all phases, and this is not possible if they must also start at a natural zero. Secondly, the dc component of fault currents often affects relay performance, therefore, it is important to have this component present.

4. Ability to control point on prefault voltage wave switching. This will reduce the need for multiple application of faults at random point on wave switching. It will also ensure more complete testing of the equipment since the complete spectrum of points on wave can be covered with the fewest possible tests.

5. Ability to switch phases independently. This is required to simulate circuit breaker pole discrepancy upon closing, and interruption at natural current zeroes on opening. It will also allow the simulation of evolving faults.

6. Ability to accept generalized fault signals from digital sources. This will allow better simulation of real power system faults by programs such as the Electromagnetic Transients Program (EMTP). It would also allow use of recorded data from actual or staged faults on the real power system for tests.

7. Current channels should have continuous ratings of about 15 A rms, and short time ratings of 30 A rms or more. While CT secondary currents may go up to about 100 A rms, it is recognized that test equipment with such high short time ratings may be prohibitively expensive.

In short, utilities cannot usually afford a full fledged model power system, because they do not do relay type tests all that often. However, utilities usually have computer facilities to simulate power system faults in reasonable detail. Therefore, test equipment which is able to use that computer output (and therefore keep down the price of the equipment) would probably be a useful compromise.

PC spreadsheet programs are valuable in assisting type tests. In the B. C. Hydro tests, the spreadsheet was not only used to calculate test quantities, but also used to tabulate test results, and to convert test results into a suitable format for plotting by a mini computer. With over 30 tables of results being produced for each set of type tests, the need for careful data handling is evident, and the spreadsheet helped significantly in that handling. Note that test equipment manufacturers routinely produce computer programs for acceptance or maintenance tests on various specific types of relays. However, utilities type tests are of much greater scope than acceptance tests, and also are required for new or uncommon types of relays. Test equipment manufacturers cannot be expected to produce programs for such tests. Therefore the flexibility and ease of generalized programming provided by spreadsheets is very useful.

Finally, utilities are encouraged to do their own type tests on equipment which is, or is about to be applied widespread on their systems. Even if the lack of equipment or time limits the scope of the tests, testing will provide benefits in three ways. Firstly, design shortcomings or application limitations on their particular systems may become apparent. Secondly, the utility engineers will get useful education in the design of the relays. Finally, relay manufacturers will get useful feedback on the application needs of the utilities.

ACKNOWLEDGEMENTS

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The author also thanks D. N. Pettet for provision of the computer plotting programs which were used to provide many of the diagrams for this paper and for the test reports.

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1. CIGRE-SC34-WG04, "Evaluation and Performance of Power System Protection Relays and Protective Systems" - Chapter 2. Guide dated January 1986.

2. K. H. Engelhardt, "Dynamic Performance Testing of Mho Relay Memory Action". Proceedings, 1982 Western Protective Relay Conference, Spokane. Washington State University.

3. W. O. Kennedy, B. J. Gruell, C. H. Shih and L. Yee, "Five Years Experience With a New Method of Field Testing Cross and Quadrature Polarized Mho Distance Relays", Parts I and II. IEEE Papers No. 87 WM110-0 and 87WM111-8 presented at the 1987 Winter Power Meeting.

4. W. O. Kennedy, "Distance Relay Testing - One Utility's Perspective". Proceedings, 1985 Western Protective Relay Conference, Spokane. Washington State University.

FIGURE I
TEST SET-UP FOR SHORT INTERRUPTIONS OF DC POWER SUPPLY

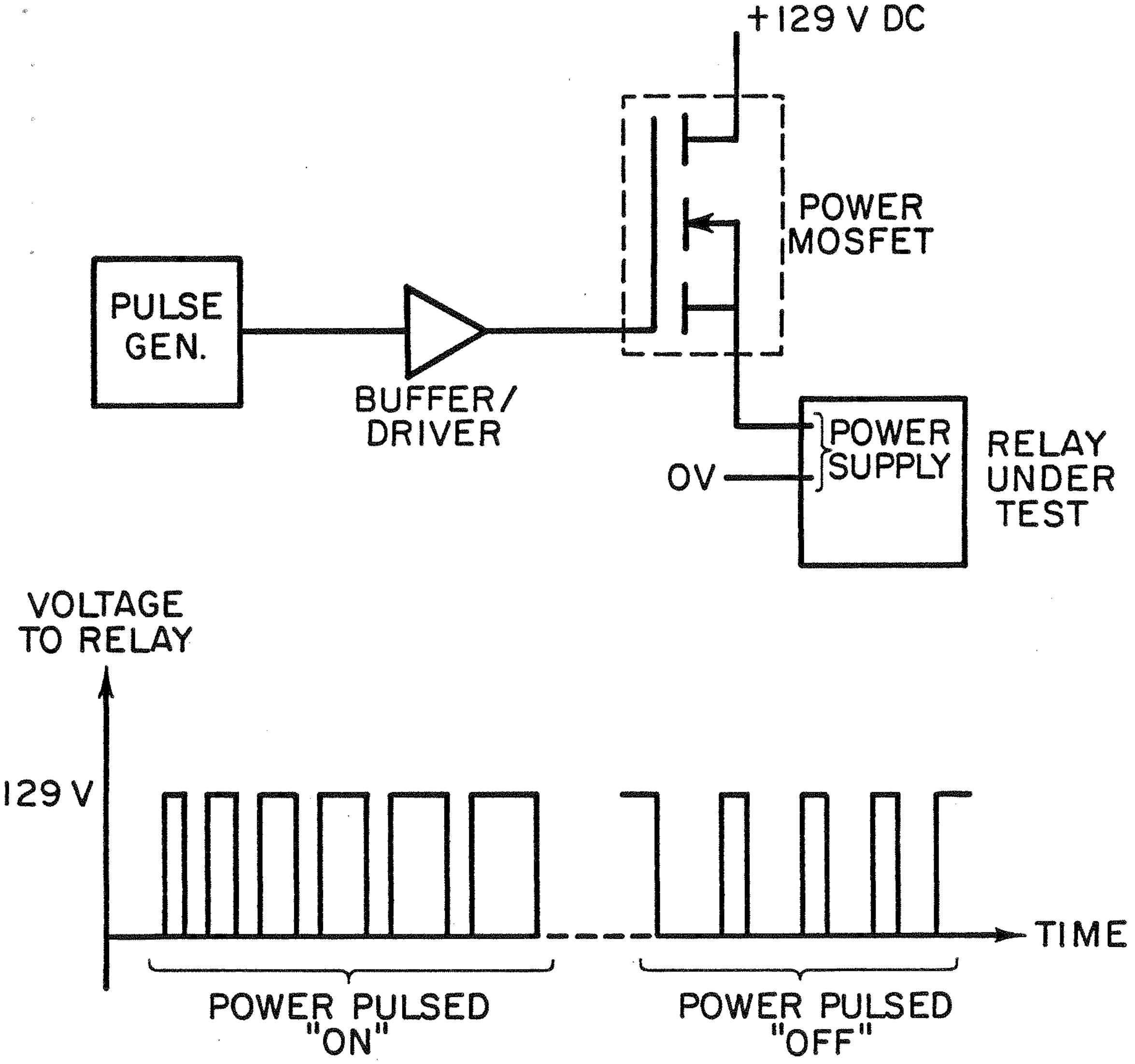


FIGURE 2

TEST SET-UP FOR STEADY STATE AND DYNAMIC TESTS

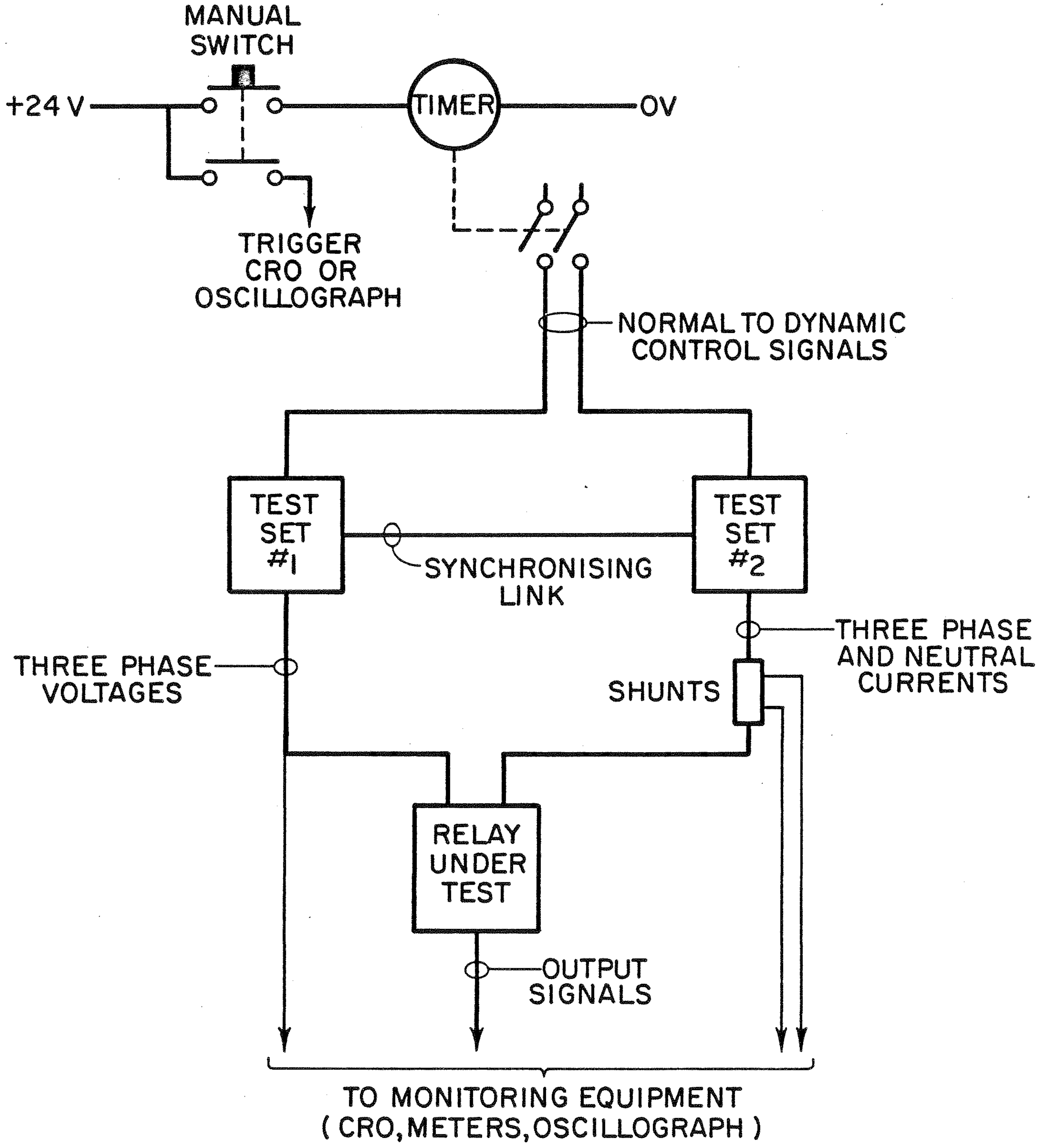
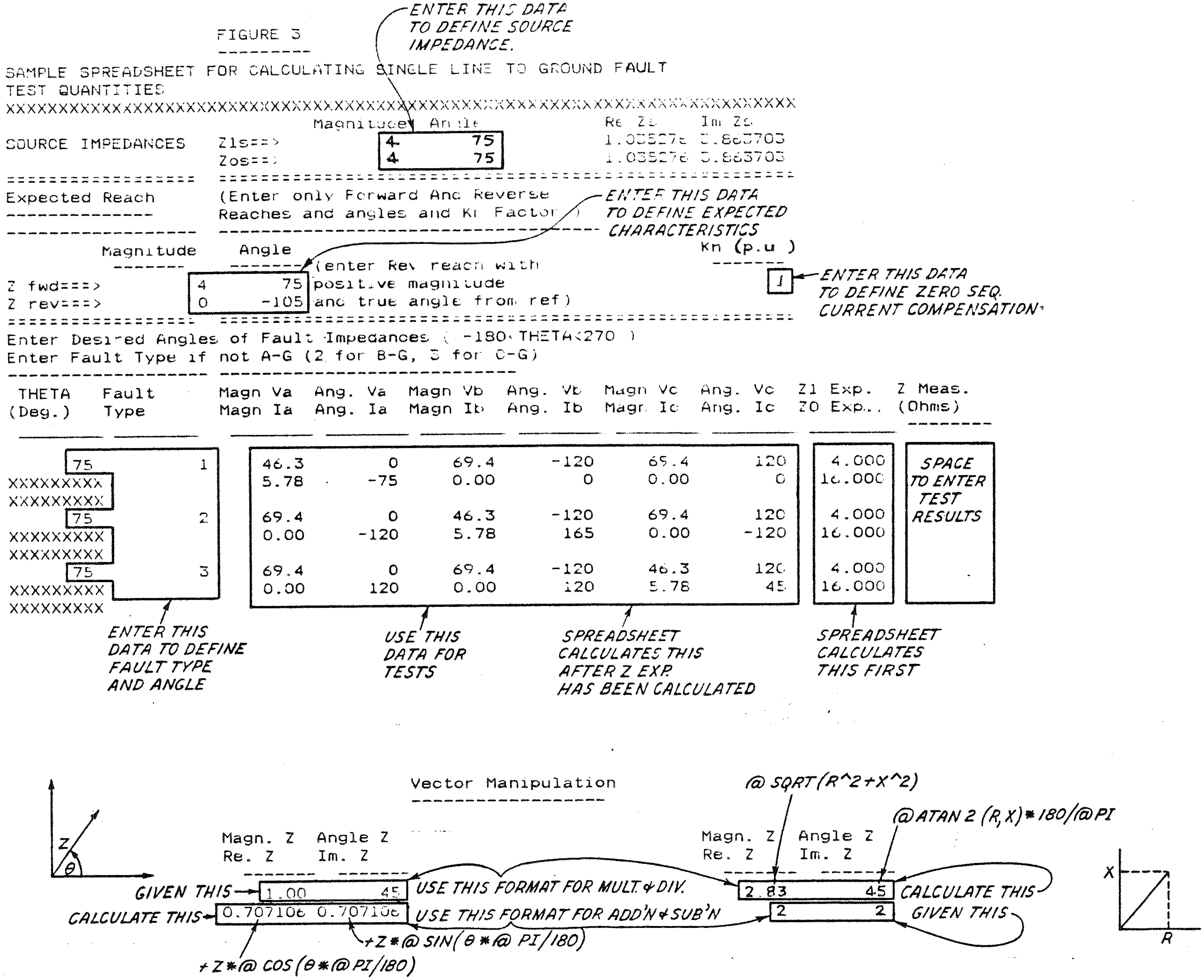


FIGURE 3



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SAMPLE SPREADSHEET FOR CALCULATING SINGLE LINE TO GROUND FAULT
TEST QUANTITIES
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
                                  Magnitude  Angle                  Re Zs     Im Zs
SOURCE IMPEDANCES       Z1s==>    4          75                     1.035276  3.863703
                        Zos==>    4          75                     1.035276  3.863703
==================      ==============================================================
Expected Reach          (Enter only Forward And Reverse
--------------          Reaches and angles and Kl Factor )
------------------      --------------------------------------------
          Magnitude        Angle                                          Kn (p.u )
          -------        -------  (enter Rev reach with                   -------
Z fwd===>     4             75    positive magnitude                        1
Z rev===>     0           -105    and true angle from ref)
==================      ==============================================================
Enter Desired Angles of Fault Impedances ( -180<THETA<270 )
Enter Fault Type if not A-G (2 for B-G, 3 for C-G)
------------------      ----------------------------
 THETA    Fault         Magn Va   Ang. Va   Magn Vb   Ang. Vb   Magn Vc   Ang. Vc   Z1 Exp.   Z Meas.
(Deg.)    Type          Magn Ia   Ang. Ia   Magn Ib   Ang. Ib   Magn Ic   Ang. Ic   Z0 Exp..  (Ohms)
 -----    --------      -------   -------   -------   -------   -------   -------   -------   --------
     75          1      46.3        0       69.4      -120      69.4      120        4.000
XXXXXXXXX               5.78      -75       0.00         0      0.00        0       16.000
XXXXXXXXX
     75          2      69.4        0       46.3      -120      69.4      120        4.000
XXXXXXXXX               0.00     -120       5.78       165      0.00     -120       16.000
XXXXXXXXX
     75          3      69.4        0       69.4      -120      46.3      120        4.000
XXXXXXXXX               0.00      120       0.00       120      5.78       45       16.000
XXXXXXXXX
```

Vector Manipulation

```
           Magn. Z   Angle Z                           Magn. Z   Angle Z
           Re. Z     Im. Z                             Re. Z     Im. Z
           -------   -------                           -------   -------
           1.00         45                             2.83         45
           0.707106  0.707106                          2            2
```

FIGURE 4

MEASURING RANGE OF OPERATING TIMES USING STORAGE C.R.O.

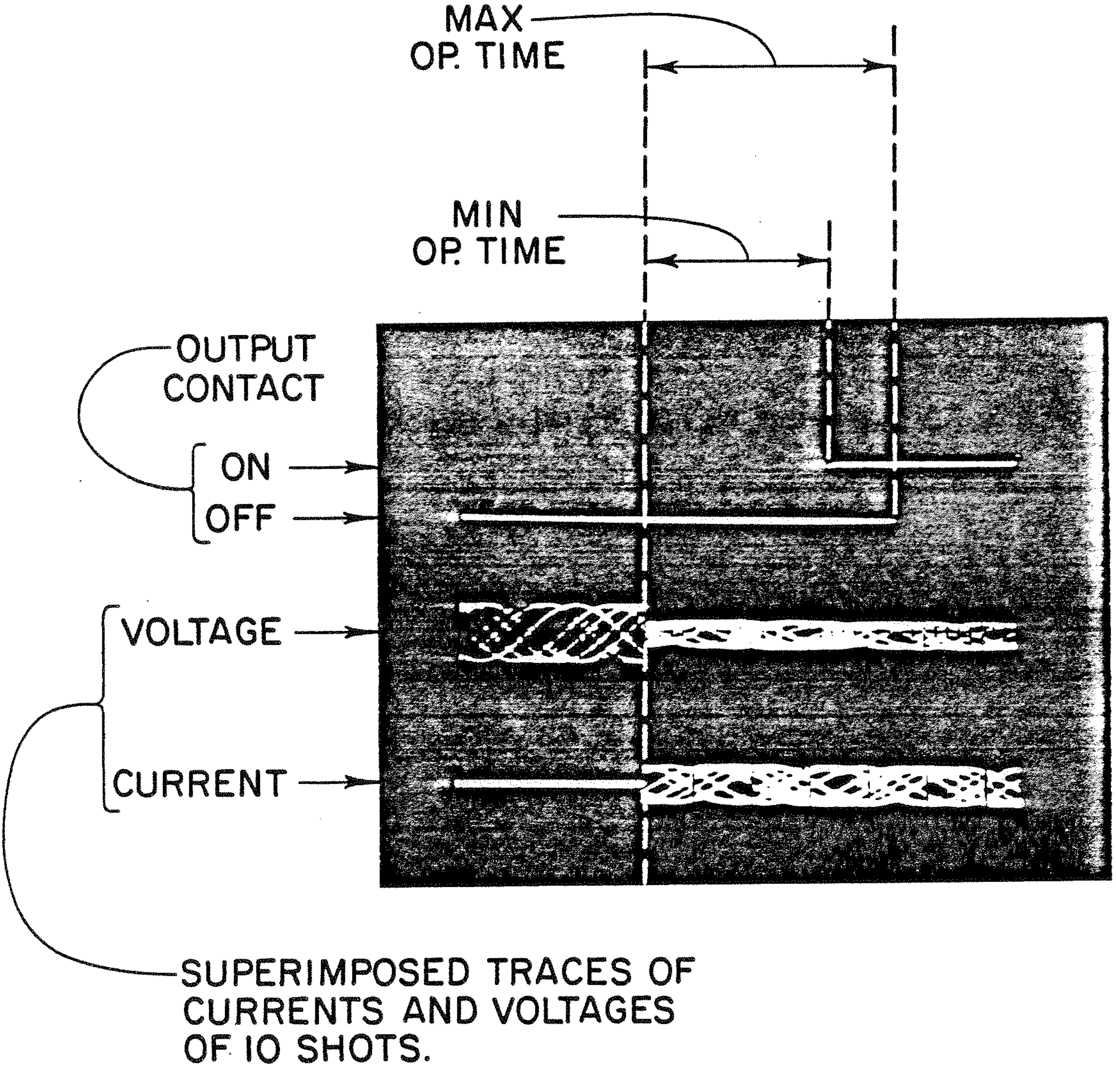
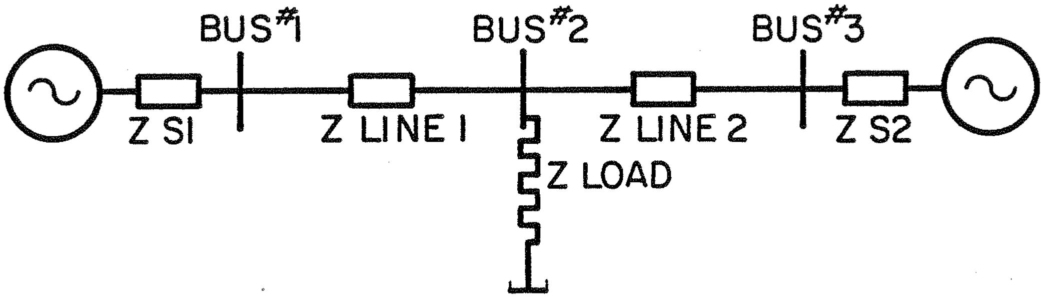


FIGURE 5

TYPICAL PSS/E MODEL FOR FAULTS WITH LOADS



RELAY LOCATION BUS #2
FAULT LOCATION ANYWHERE ON LINE 1 OR 2

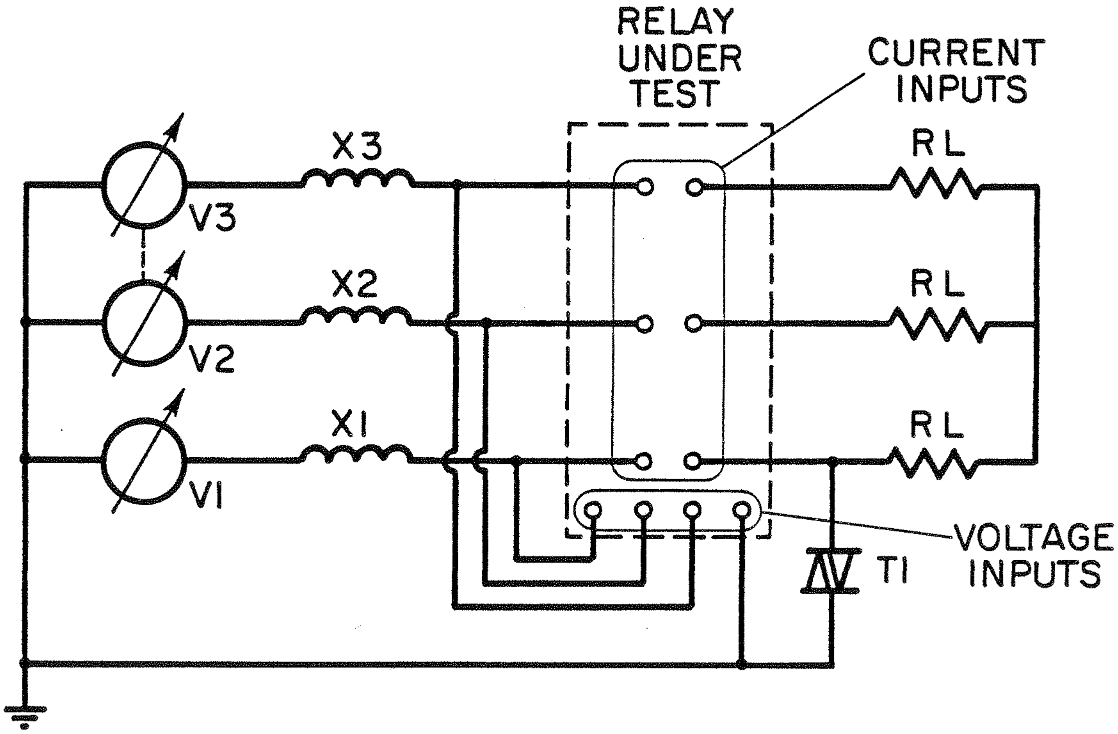
CASE PARAMETERS

BASE:
- MVA = 1039.2 MVA
- KV = 120 KV
- CURRENT = 5000 A

	Z1 (=Z2)	Z0
Z S1	1Ω∠75°	1Ω∠75°
Z S2	1Ω∠90°	1Ω∠90°
Z LINE 1	7Ω∠75°	28Ω∠75°
Z LINE 2	4Ω∠75°	16Ω∠75°
Z LOAD	13.9Ω∠0°	∞

FIGURE 6

SIMPLE MODEL POWER SYSTEM



V1——10A VARIAC

V2, V3——3A VARIACS (GANGED)

X1——5.9 Ω∠84° AIR CORE INDUCTANCE

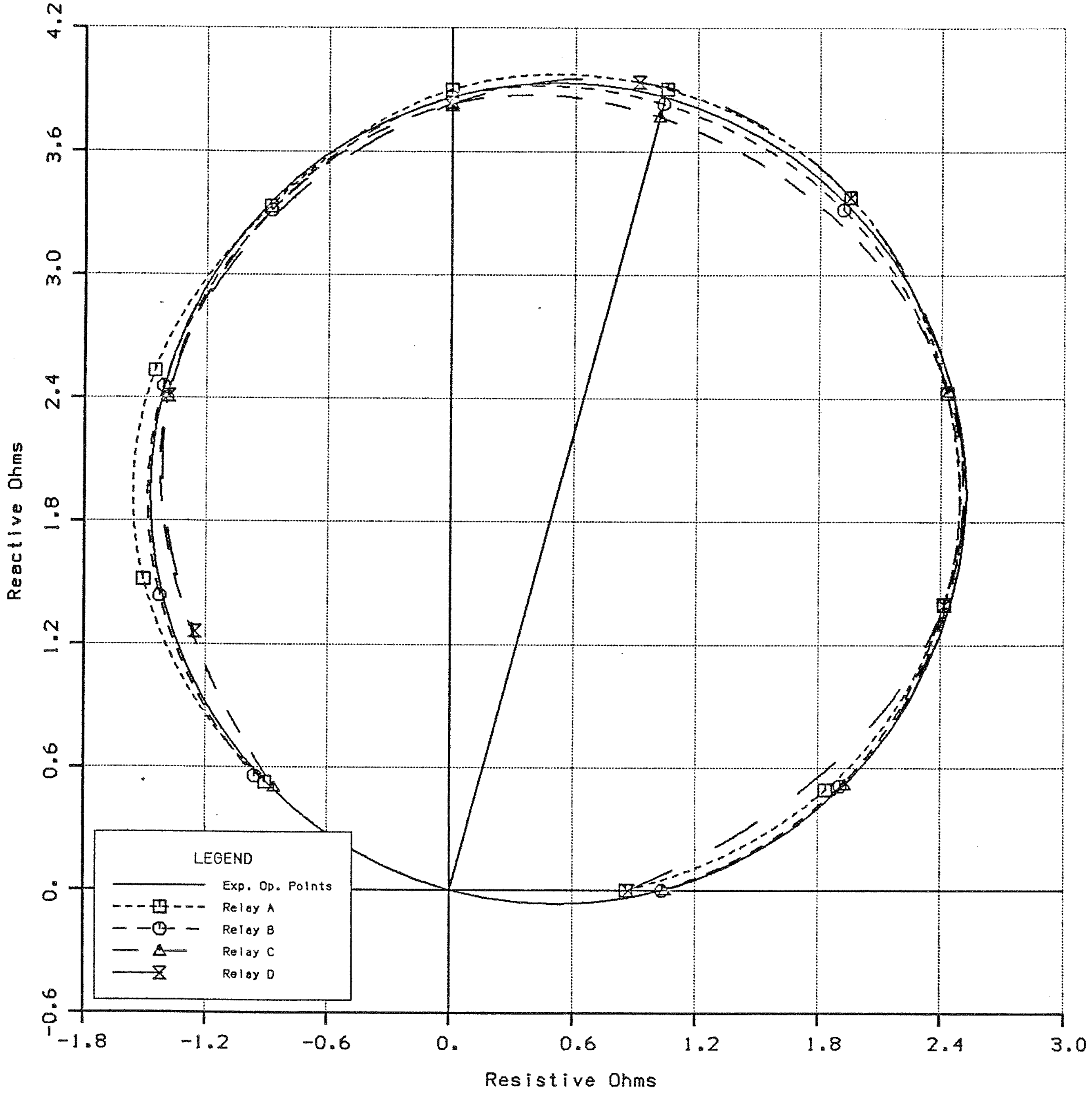
X2, X3——6.2 Ω∠85° IRON CORE INDUCTANCE

RL——APPROX. 21 Ω LOAD RESISTANCES

T1——FAULT MAKING TRIAC (WITH POINT ON WAVE CONTROL)

FIGURE 7

STEADY STATE CHARACTERISTICS FOR THREE PHASE FAULTS AT REFERENCE SETTINGS



22 Sep. 1987,   9:11 am

FIGURE 8

ZONE 2 SS RESPONSE TO 3 PH FAULTS AT MAX SETTINGS

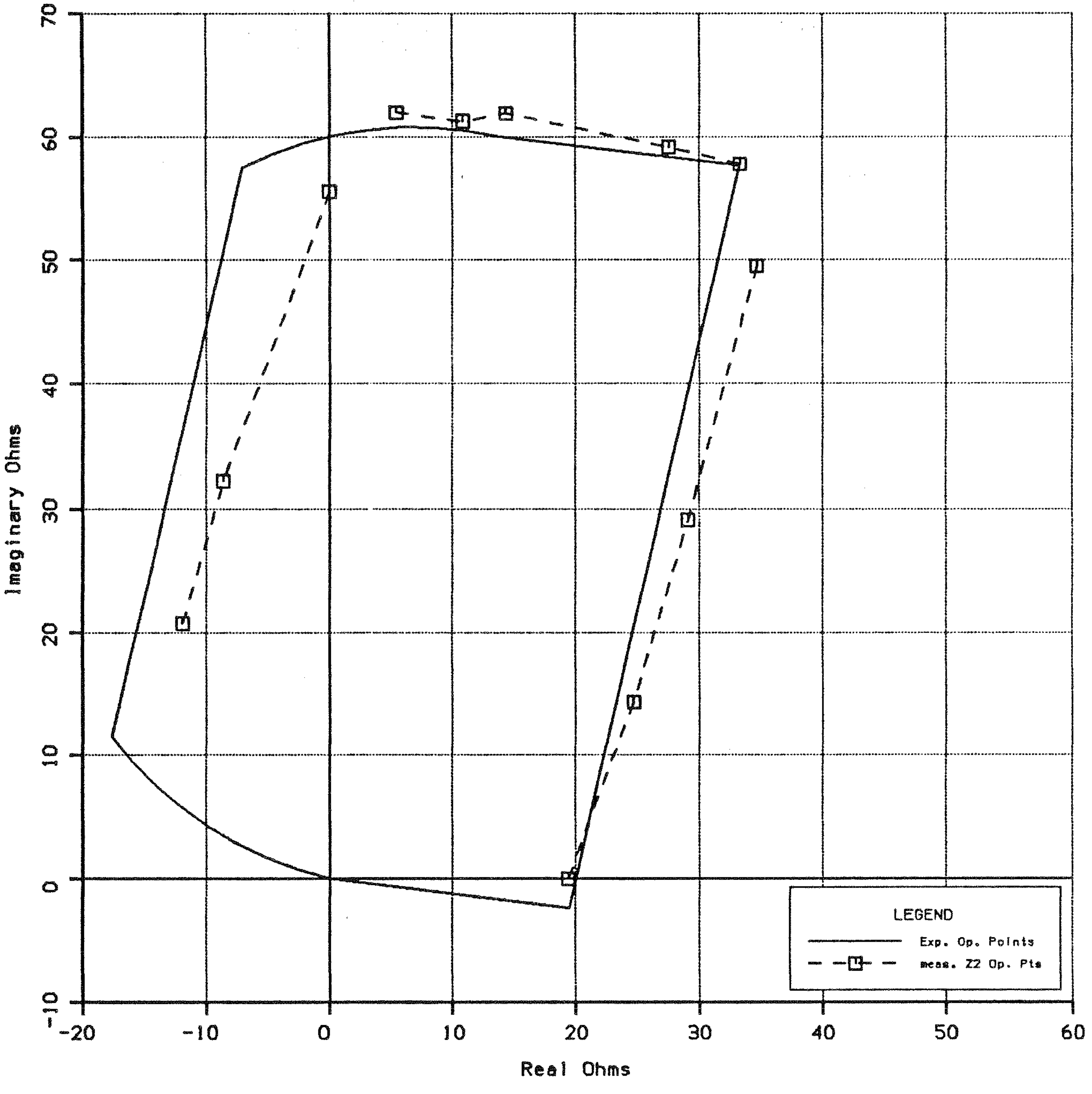
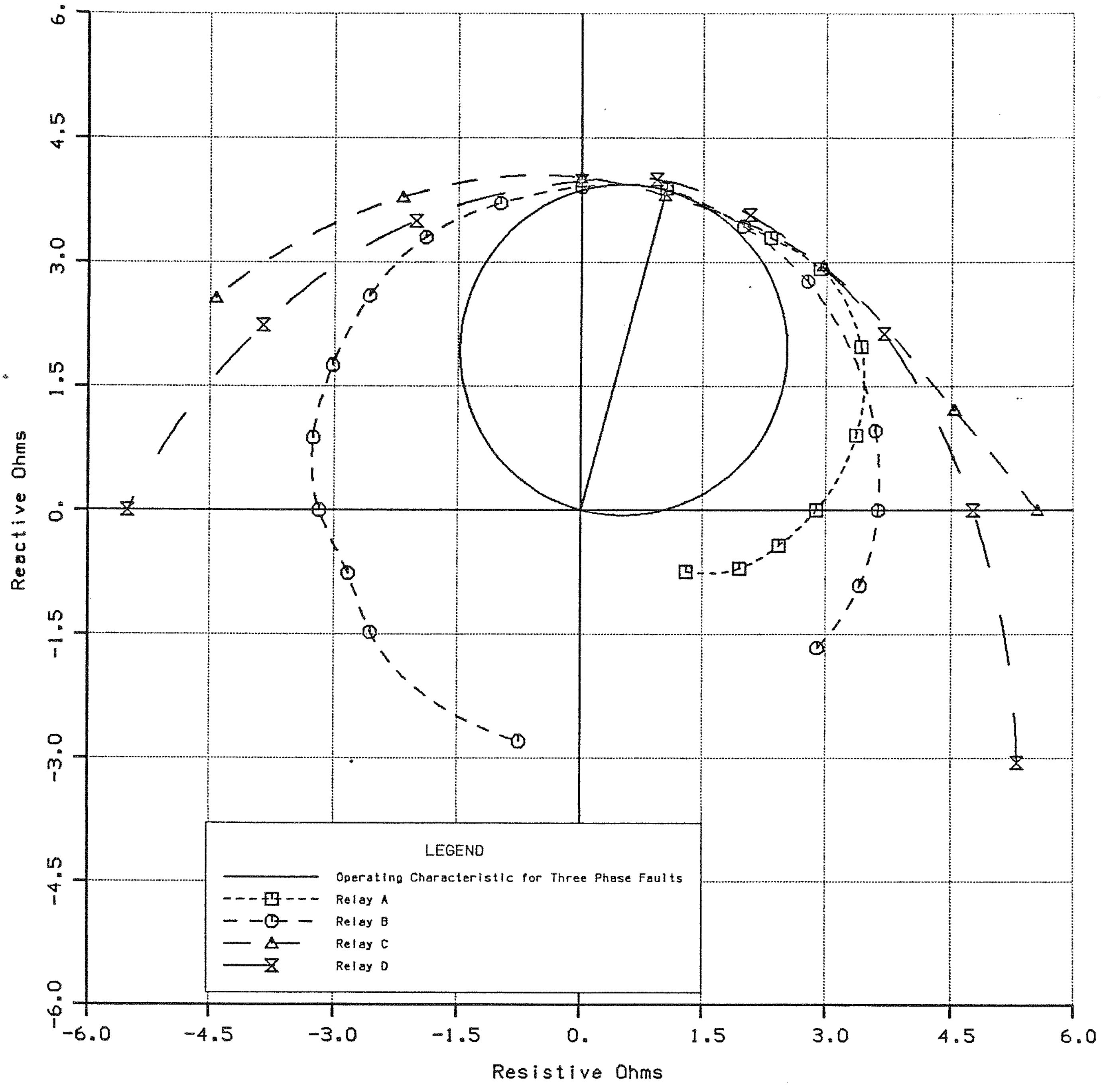


FIGURE 9

STEADY STATE CHARACTERISTICS FOR PHASE TO PHASE FAULTS AT REFERENCE SETTINGS

(With 8 Ohm @ 75 Degrees Source Impedance)



22 Sep. 1987, 10: 8 am

FIGURE 10

ZONES 1 AND 2 SS RESPONSE TO B-C PH FAULTS AT REF SETTINGS

(Z Source = 8 Ohms at 77 Degrees)

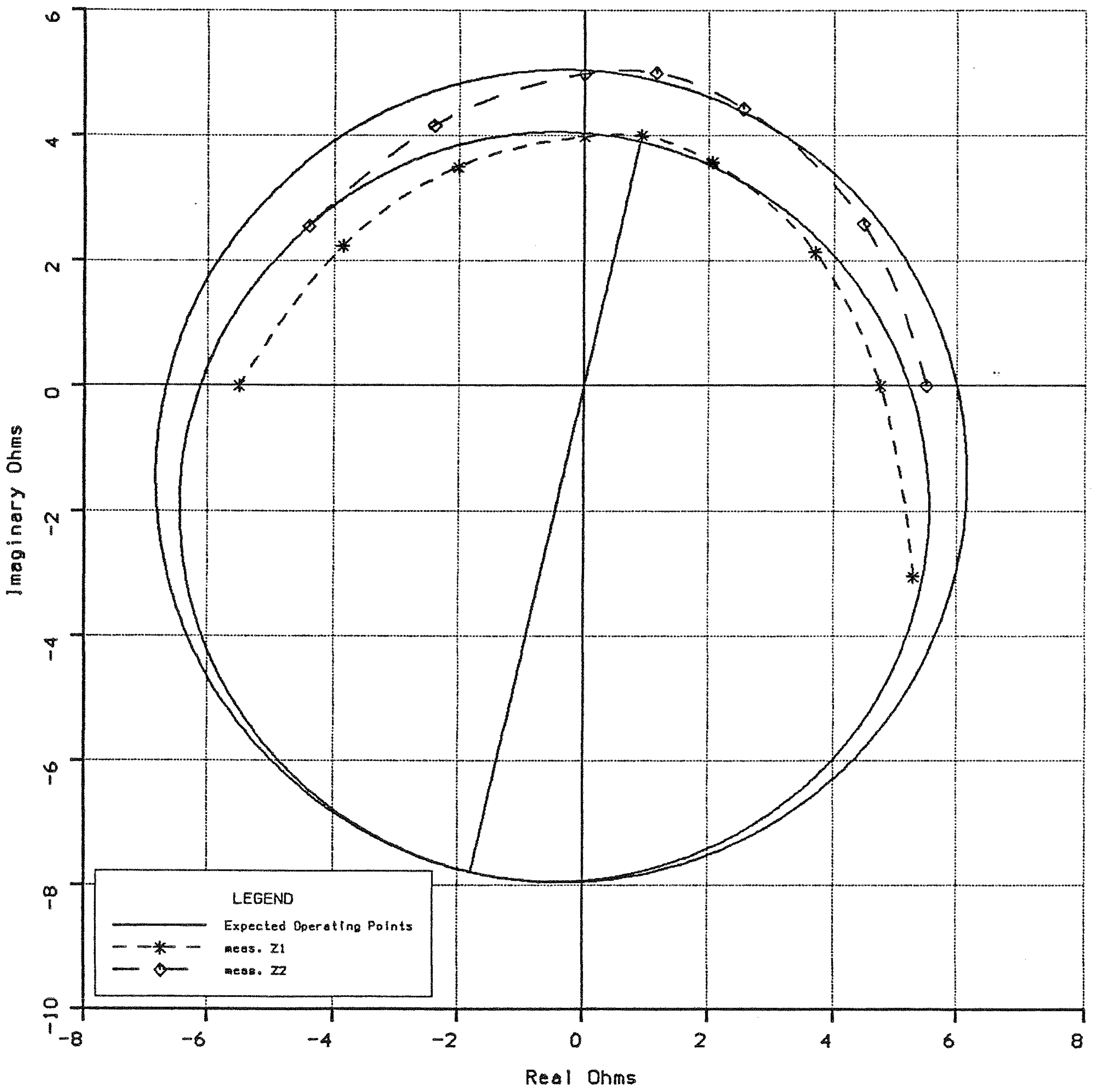


FIGURE 11

STEADY STATE SENSITIVITY OF DIR. GND. RELAYS

(WITH VARIOUS LEVELS OF OPERATING CURRENT)

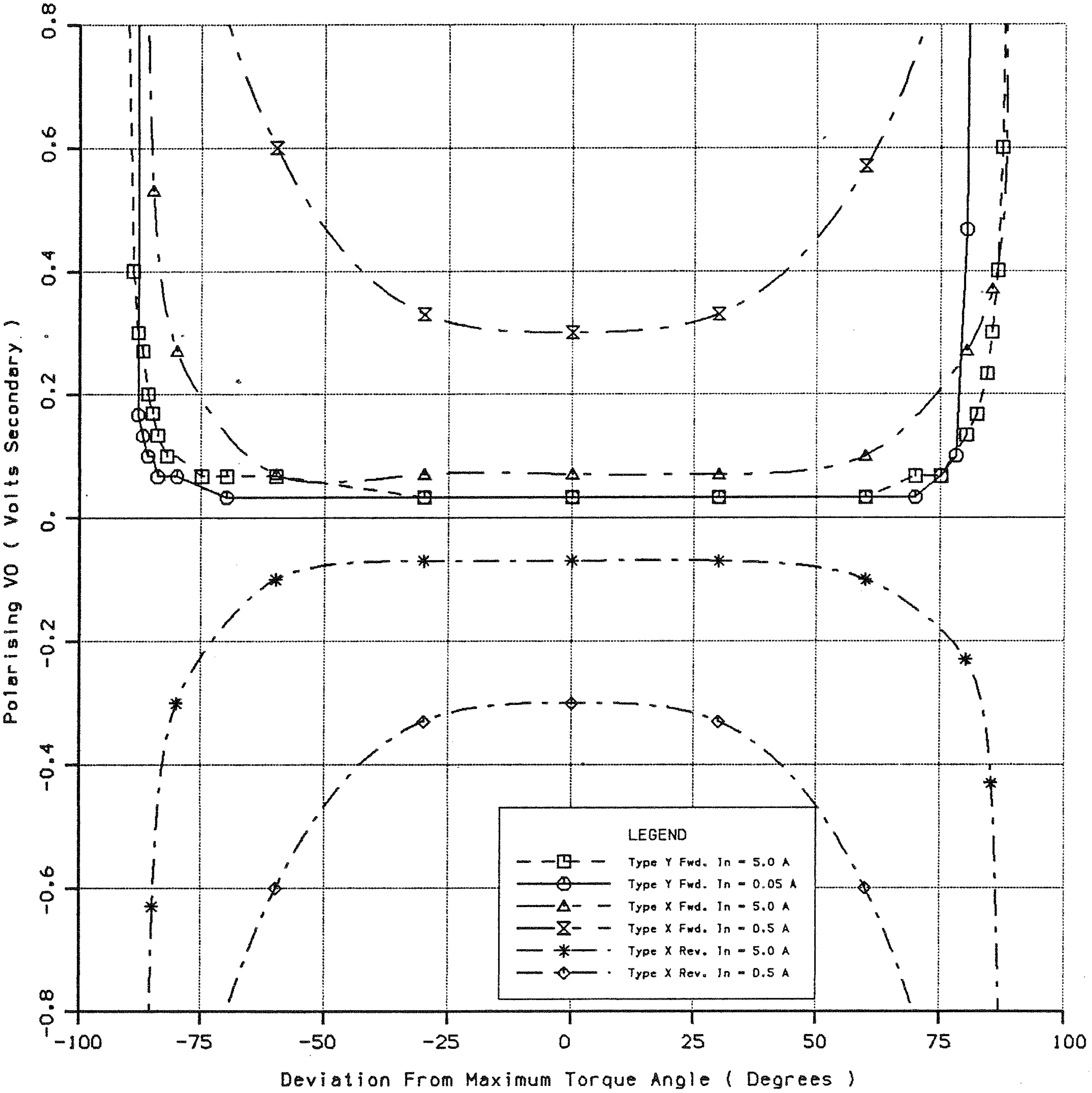


FIGURE 12

STEADY STATE SENSITIVITY OF DIR. GND. RELAYS

(AT MAXIMUM TORQUE ANGLE)

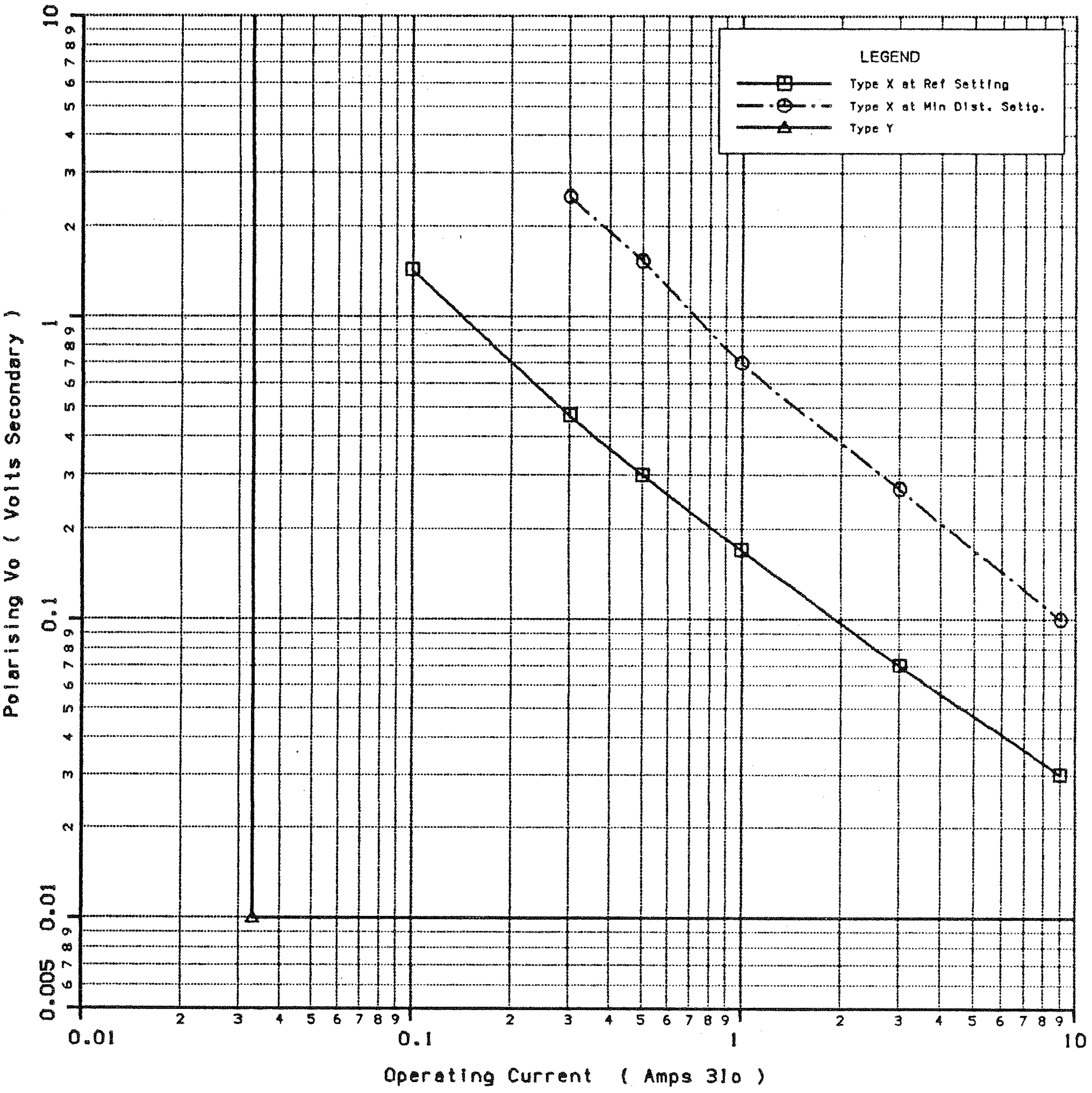


FIGURE 13

MAXIMUM OPERATING TIMES AT REFERENCE SETTINGS FOR ALL TYPES OF FAULTS

(With SIR of 1)

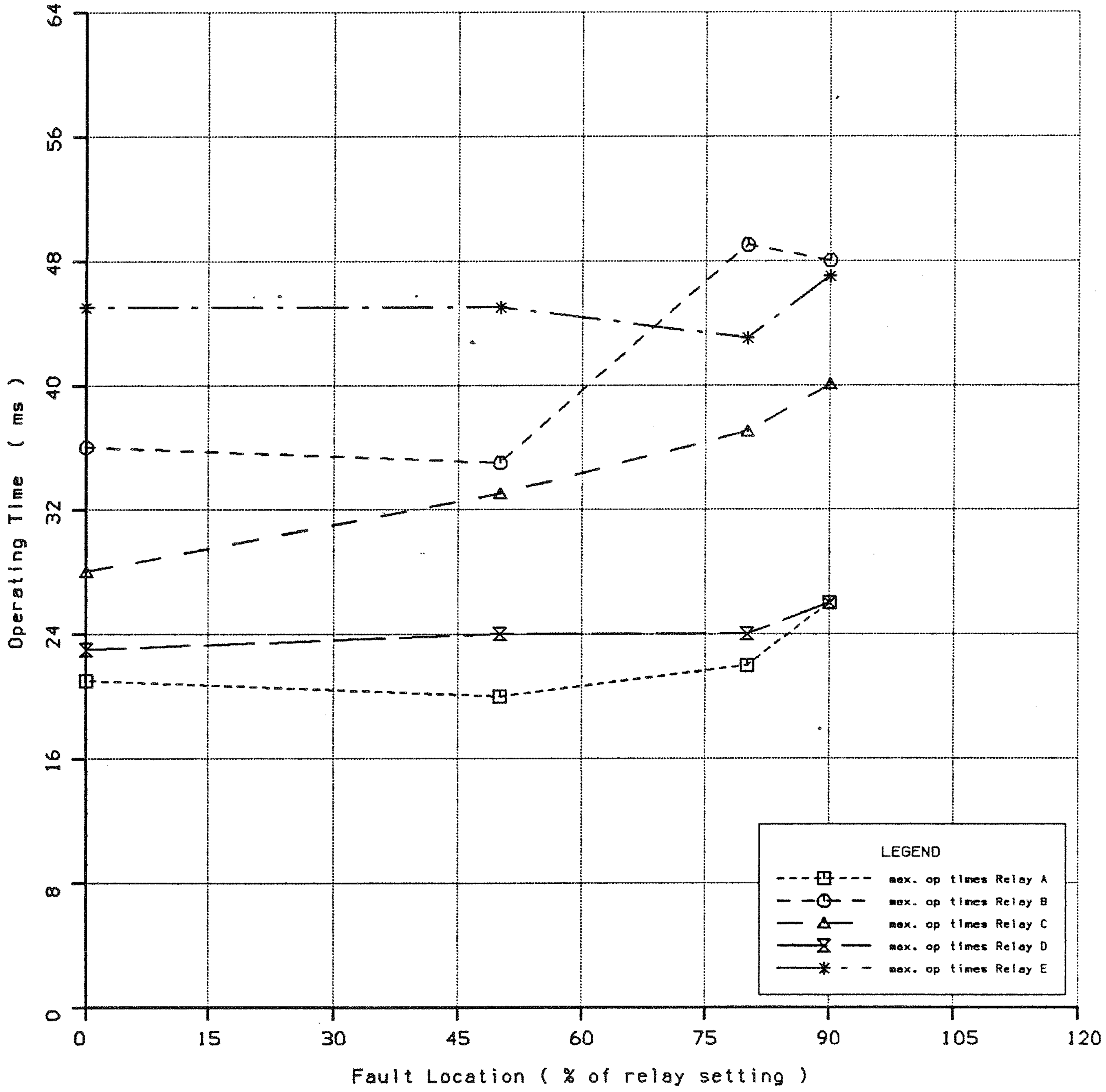


FIGURE 14

COMPARATIVE OPERATING SPEEDS OF TWO TYPES OF RELAY FOR SAME B-C FAULT

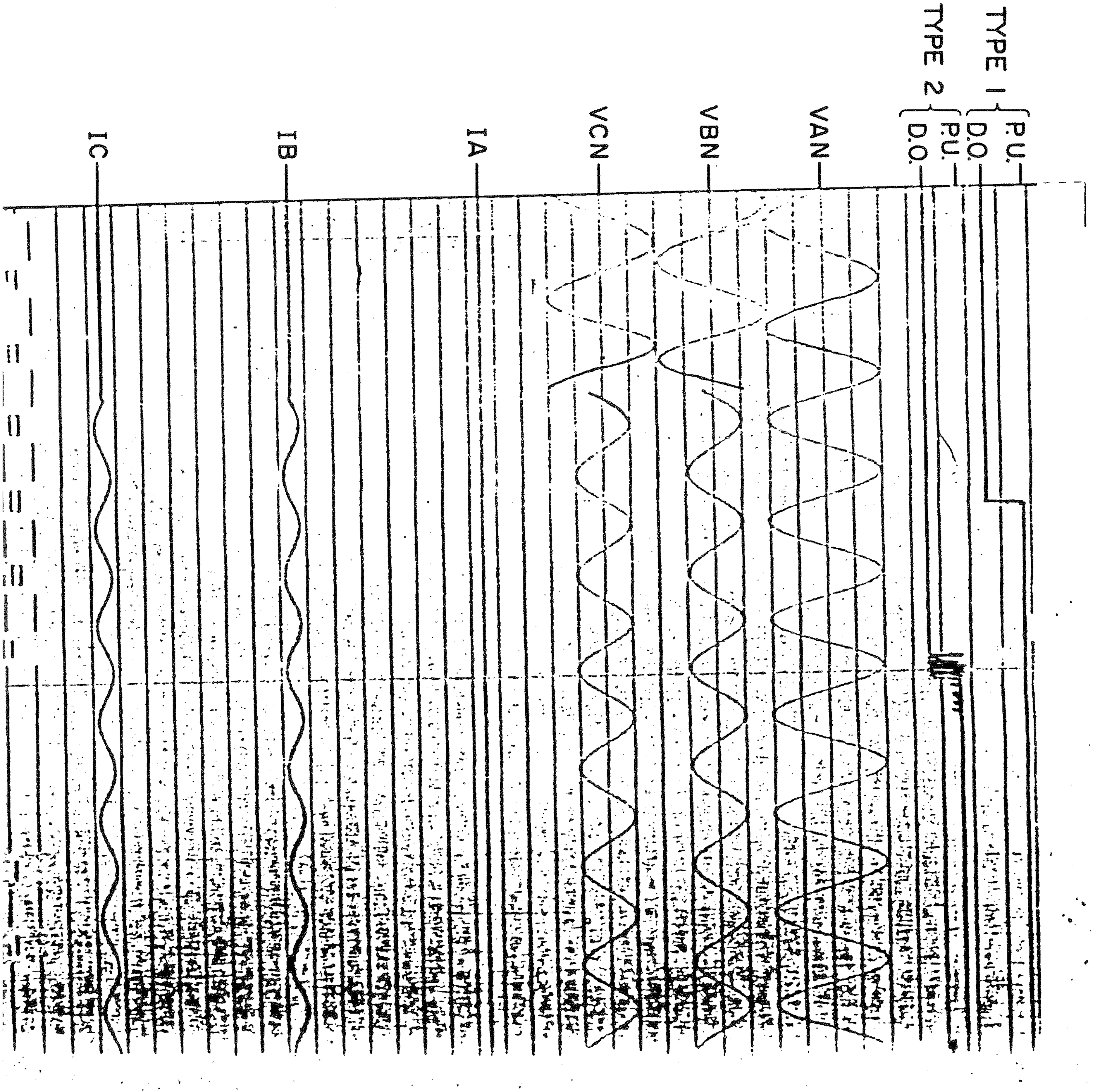


FIGURE 15

LIMITS OF DYNAMIC REACHES FOR RELAY A AND RELAY B AT REFERENCE SETTINGS

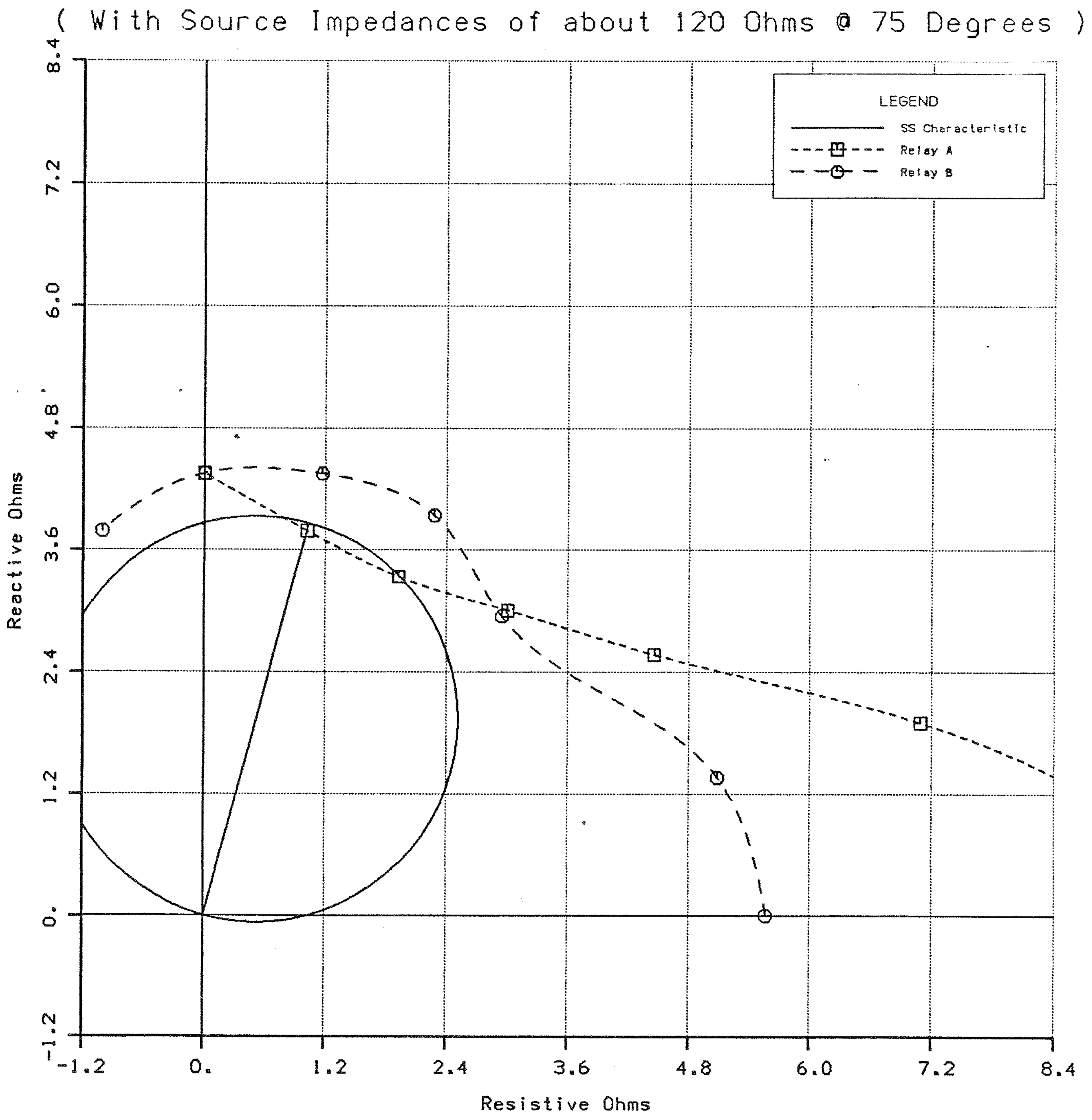


FIGURE 16

LIMITS OF DYNAMIC REACHES FOR RELAY C AND RELAY D AT REFERENCE SETTINGS

(With Source Impedances of about 80 Ohms @ 75 Degrees)

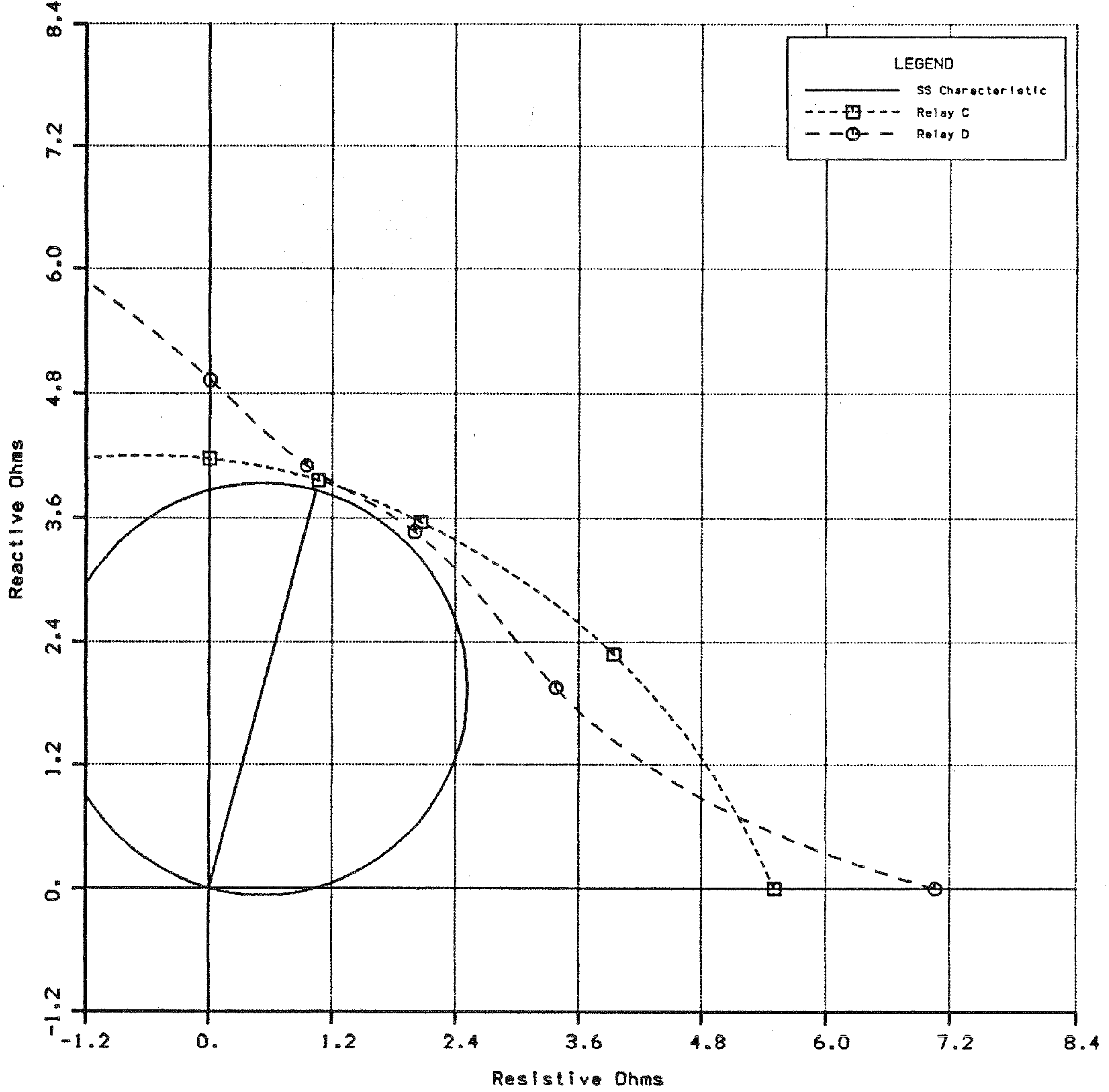


FIGURE 17

DYNAMIC ACCURACY OF TYPE E RELAY FOR 3 PHASE FAULTS AT MAXIMUM SETTINGS

(Zs = 8 ohms at 75 Degrees)

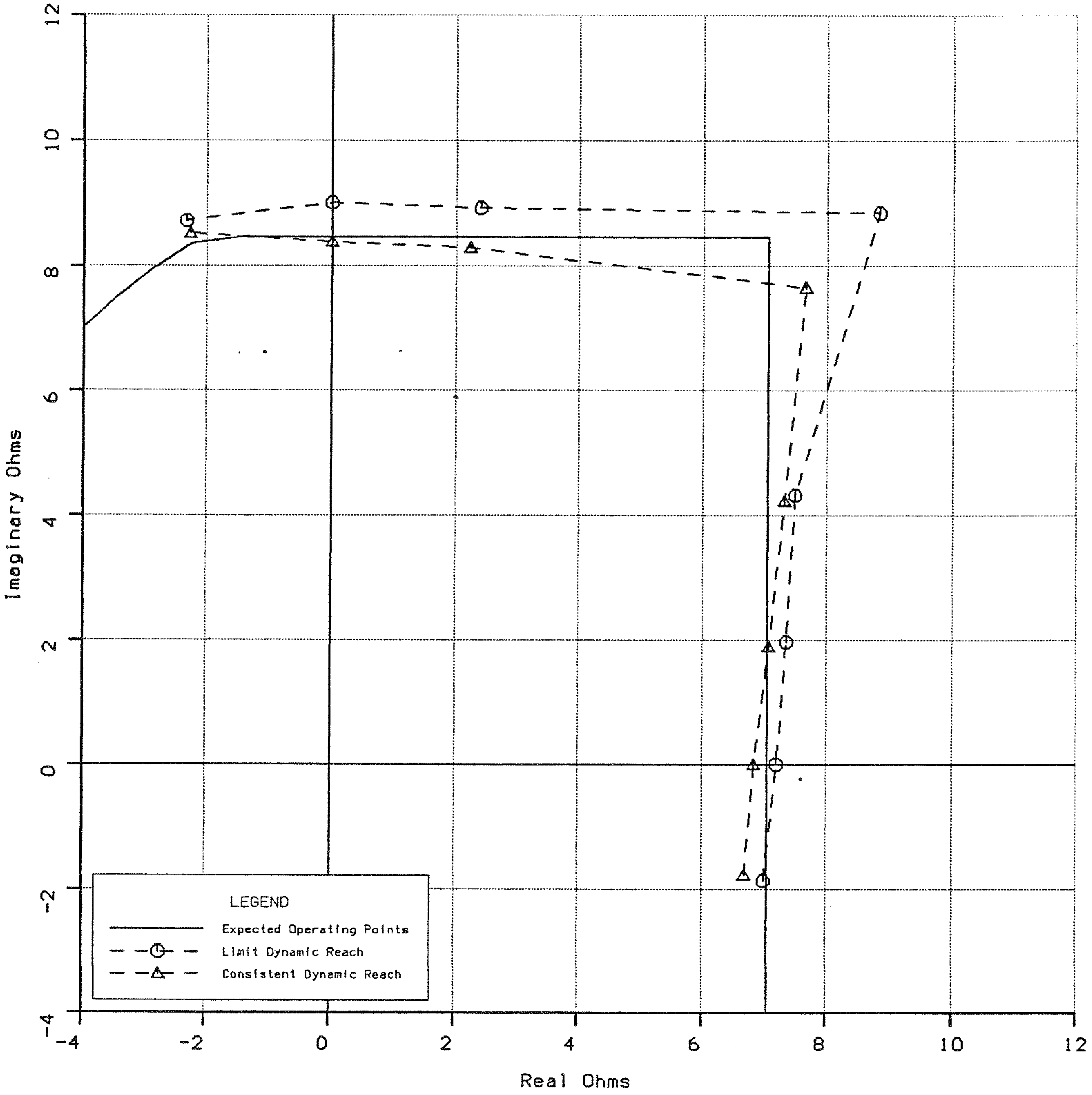


FIGURE 18

FORWARD 3 PH. FAULT

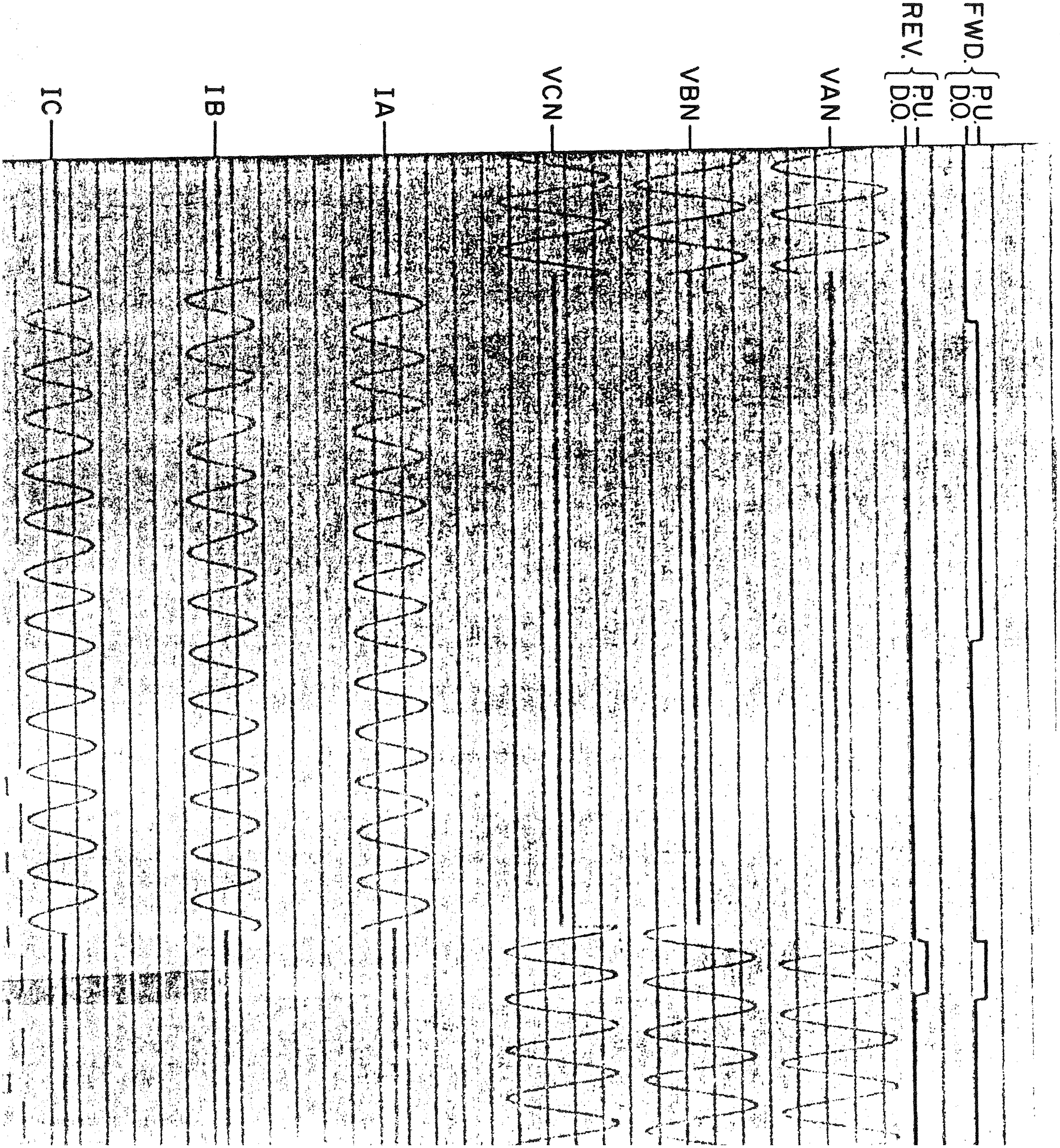


FIGURE 19

A-G REVERSE FAULT ON LINE WITH TAPPED LOAD BEHIND RELAY