INSTALLATION TESTS
FOR
DIRECTIONAL OVERCURRENT RELAYS
FOR GROUND FAULT PROTECTION

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Introduction

Directional overcurrent relaying is probably the commonest form of protective relaying installed for ground fault protection of transmission lines.

The relays used for such protection usually consists of one or two directional units, responding to the fault current direction, and controlling an induction disc overcurrent relay for time graded overcurrent protection. Often, an instantaneous overcurrent unit, also controlled by the directional unit(s), is provided for high speed clearing of the faults nearer the line terminal.

The response of the directional units to current direction is obtained by the response of such units to the phasor relationship existing between two quantities: The polarizing and operating quantities. That is, for electromechanical relays, the torque equation of directional units may be written:

$$T = K1 \; P \; O \; \mathrm{Sin}\, \theta - K2$$

Where =

K1 = a constant of proportionality and is determined by the relay designer.

P = Polarizing quantity

O = Operating quantity

θ = Angle between P and O

K2 = Restraint constant - a spring usually

An analogous equation can be written for static relays.

Polarizing Quantity

Since directional discrimination depends on angle θ, one of the two quantities applied to the relay must be considered the reference.

Universally this is the polarizing quantity.

The term "directional" of course refers to the direction of the fault current in the line or circuit to which the relay is connected so it is essential that the polarizing quantity is one which itself does not shift its phasor relationship, or direction, as does the line current for various fault locations.

Commonly used polarizing quantities for ground fault relaying are:

Bus zero sequence voltage

A local source of zero sequence current

Bus negative sequence voltage

Operating Quantity

The common operating quantities are:

Line zero sequence current

Line negative sequence current

Relay Types

Relays utilizing a combination of bus zero sequence voltage and line zero sequence current are the potential polarized relays.

Those using zero sequence current for both polarization and operation are the current polarized relays.

Those using negative sequence quantities are the negative sequence relays.

For the rest of this discussion only the zero sequence polarized relays will be considered. The filters needed to obtain negative sequence quantities for the negative sequence relays are invariably part of the relay and the manufacturer's data explains how to check out the filters. Of course, for proper filter output the external relay connections must be correct but a check of these conditions is trivial.

Polarization Sources

a. Potential Polarization:

The commonest potential polarization source is the second potential transformer secondary coil set connected in broken delta.

Where the second potential transformer secondary is not available for such application, a set of auxiliary potential transformers connected wye ground-broken delta is used to optain polarizing potential.

b. Current Polarization:

Current polarized directional overcurrent relays for ground fault protection can be applied only at those locations having a suitable source of polarizing current. Common sources of polarizing current are shown in Figures 1, 2, 3, and 4.

Wherever three winding transformers, grounded both on the high and low voltage, are used as local zero sequence sources and hence sources of current polarization, at least an elementary analysis must be made to determine such sources are proper polarization sources - that is that the direction of the polarization current does not reverse as the assumed fault location is moved about the system.

Although the use of one or three current transformers in the tertiary of an auto-transformer, as shown in Figure 4, will usually provide proper polarization for ground relays for circuits connected to either the "H" or "X" bushings of the transformer, for a few rare combinations of system and transformer zero sequence impedance, this source can also result in improper polarization.

The problems of obtaining correct polarizing current from multi-winding transformers (three or more windings) have been extensively covered in the literature (1, 2, 3, 4, 5, and 6). Refer to any of these references for more information.

Relay Connections

The needed connections to obtain proper response of any relay are always illustrated in the manufacturers' bulletins. The illustrated connection diagrams are invaribly in elementary form but the essential data are always shown.

Since the essential response (direction) of the directional units of directional overcurrent relays is contingent on the phasor relationship between polarization and operating currents, the polarities of the polarization and operating sources and the polarity of the relay itself are the most important data shown on these diagrams.

The manufacturers diagrams show the trip direction for the relay connected as illustrated. One large relay manufacturer even provides polarity marks on his diagrams to illustrate the desired relay polarity. The other large US manufacturer apparently assumes those using the diagram have sufficient intelligence to determine this point themselves.

Regardless of the design of any relay, notwithstanding the sophistication or elaboration of its operating principles, be it electromechanical, static or microprocessor, it must be connected to the system. Wiring diagrams of the specific application must be made and these diagrams used for the physical connections. Errors occur in this process - indeed they seem to crawl out of the woodwork - and these errors result in incorrect relay operations. And unless the proper connections are used, no relay can be expected to operate properly. Indeed, the relay itself may be the least important part of the relay connections.

The results of incorrect relay operations - trips for faults outside the zone of protection, blocking response rather than trip for faults inside the zone - will vary from embarrassment to system shutdown. All completed relay connections should be inspected for assurance correct relay operations will ensue. Those inspections, whether called installation, energization, commissioning or phasing in tests, as applied to directional overcurrent relays for ground fault protection, are the subject of this paper. Everything heretofore presented is preliminary.

Installation Tests

The installation tests of relays operating for a single quantity are invariably simple and straightforward but for relays operating in response to two or more quantities, especially when one quantity is the phase angle between the quantities, the tests become more complex and time consuming.

a. Potential Polarized Ground Relays

A common test is to reconnect the potential transformer secondary connections to produce a polarizing voltage equal to one of the phase voltages or its negative and then reconnect the operating circuit current transformer connections to produce an operating current equal to a line current (or its reverse). Reference 1 discusses this test in detail.

Figure 5 shows the results of such a test.

Prior to reconnecting the potential and current transformers, a load check was made; i.e., the line currents were read and recorded, both magnitude and phase angle - the angle being in respect to Vab.

The potential transformer was then reconnected to produce a polarizing voltage equal to Va.

The current transformers were reconnected to produce an operating current equal to minus Ia.

The relay polarizing and operating quantities were then read and recorded.

The predicted quantities (Va and -Ia) being found, the relay is correctly connected.

One also visually observes the response of the directional unit. For this test, it should have blocked and did so.

Note the procedure was to predict the quantities which would appear at the relay if it were properly connected and tests were then made to determine the prediction was true.

Had the predicted quantities not been found, a search would have been made to find the erroneous connection and correct it, followed by another prediction and test.

b. Current Polarized Ground Relays

Unfortunately, with the usual connections used for polarizing current, as illustrated in Figures 1, 2, 3, and 4, there is no way to produce a polarizing current having any known relationship to system quantities by the methods normally used. Other means to check the connections must be adopted. These are:

1. Wait and See

The relays are put into service and the resultant behavior during ground faults scrutinized. If the relay responds correctly, or seems to, the connections are assumed correct. If response is not, or does not appear to be, correct, changes are made in the relay connections and one waits for further activity. One can happily spend some years at this process and still have incorrect relay operations.

This is not a test system at all, rather it is a special case of the famous management system of decision by procrastination.

2. Visual Test

A careful visual inspection of the wiring from the current transformer secondary terminals to the relay terminals and return for both the polarization and operating coil loops.

Even if the inspector is conscientious, patient, and knowledgeable, as he should be, some doubt always exists and one still must wait for one or more faults to confirm the inspection. And, of course, the inspector seldom has all the desired characteristics, or he may assume certain conditions. No proof of the connections is given by this test, but it is vastly preferable to the "wait and see" method.

3. DC Transient Current Check

This test is an extension and elaboration of the commonly used d.c. test of current transformer polarities.

Figure 6 shows the basic connections for this test in elementary form where the polarizing current transformer is located in the tertiary of an autotransformer. No modifications to the test are needed for other locations of the polarizing current transformer.

The battery is connected such that Franklin current will flow in the tripping direction when switch "Sw" is closed.

D.C. milliammeters or millivoltmeters are connected in series with the operating and polarizing coils of the directional ground overcurrent relay 67N. The meters are connected to the current transformer sides of the polarity terminals of the relay coils, meter positive (+) terminal toward the current transformer and meter negative (-) terminal toward the relay. (Actually, so long as both meters are connected identically, the precise meter polarities are not significant.)

Close switch "Sw" and observe the meter deflections simultaneously. Open "Sw" and again observe the deflections. If the relay is correctly connected, both meters deflect in the same direction ("up" for closing and "down" for opening of "Sw" if the connections shown are used).

If the meter deflections are opposed; i.e., one "up" and one "down" for both closing and opening, then the relay is improperly connected and the leads to either the polarizing coil or the operating coil must be reversed.

Before reversing any connections or before accepting the test results, check the test connections - an error is easily made. However, with proper test connections, the relay connections are proven correct.

Note where only one current transformer buried in the tertiary is used for polarization, the battery is connected to the same phase as the polarizing current transformer. Where three current transformers in the tertiary are used, or if the polarizing current transformers are located in the neutral of the transformer any phase may be used for test.

For large high voltage transformers, a high voltage battery - 50 to 125 volts - will probably be needed.

In very large substations, even the substation battery may not provide sufficient energy to deflect the meters.

There is also a small probability of damaging insulation when switch "Sw" is opened. The resultant arc is startling so one opens the circuit rapidly. On the other hand, if the circuit is not opened soon enough, the battery can be damaged.

Other variations of this test have been used.

This an excellent test and does prove the connections, but it means an outage to almost the entire substation so it usually can be used only during the initial construction of a substation. It is very difficult to obtain dispatcher's approval for a major substation outage to check the relays when a new line is being added to an existing substation.

4. Staged Fault Test

The ne plus ultra of all installation tests for proper connections of relays. Simply stage a single line to ground fault on the circuit protected by the relay in question.

Objections to staged fault tests are based neither on technical nor operational reasons, only some woolly theme which is either never articulated or never rationalized. There can be no good objections.

Especially whenever a new major transmission line position is being added to an existing power plant substation, staged fault tests to prove the relaying circuits are well warranted because if the line relays fail to trip for a fault on the circuit, the best case results to be expected are line burndown. The worse case results are system collapse.

Naturally proper and reasonable precautions must be taken. Switch the line so the fault is radial from the terminal in question. Convert the ground relays to simple overcurrent relaying, or install (temporarily) overcurrent relays and prove the converted or temporary relays can and will trip the breaker to clear the fault.

An oscillograph is essential for this test - connect elements to record the operating and polarizing quantities of the relay and connect at the relay terminals - perferably by using the relay test facilities.

If jumpers, rather than wedges, are used to bypass the directional unit contacts (assuming the relay is converted), a visual observation of the directional unit response can be made too.

It is essential to check and record the oscillograph connections so one can relate the fault traces to system conditions. It is most disconcerting to be told that visually the relay directional unit(s) operated to trip when the oscillogram traces demonstrate conclusively the directional unit must have blocked.

Staged fault tests not only prove the relay connection correct, they can also demonstrate all the other relay circuitry is proper.

Staged fault tests should always be considered as a test means for all such important lines.

5. Single Phase the Line

By test loading a line with one phase open, one simulates a ground fault. Zero sequence currents will flow in the line and in the zero sequence sources at each end. A reading, either by a phase meter, or by use of an oscillograph, will show the phase angle between the operating and polarizing currents of the relay in question offering proof of proper relay connections.

This zero sequence current will primarily be limited to the loop of the zero sequence current sources at each end of the line and the line itself - only a small percentage of the total will flow to other parts of the system.

The negative sequence current is a different matter since the generators are the primary source of negative sequence current.

Any restrictions on the use of this test should be due to the negative sequence current. If this test were done on a heavily loaded line adjacent to a power plant, the negative sequence current might cause loss of the units by the negative sequence overcurrent relaying. Obviously, at most, this merely means rescheduling the test for a time when the load is reduced.

However, once assurance can be made that the negative sequence current will not be sufficient for such misoperation, this test offers a simple and convenient means of proving connections of current polarized directional ground relays. An especially attractive feature is that the testing can be done relatively slowly and can be repeated at will.

To single phase the line, the most convenient means is to open one pole of the three single pole breaker disconnects when single pole disconnects are used.

If the disconnects are three pole as is usually the case for 230 kV and higher voltage construction, one phase jumper between the breaker disconnects and the breaker could be removed. (One maintenance superintendent estimated that at 230 kV, two men could remove such a jumper in 20 minutes actual work time and restore it in 40 minutes. Of course the clearance procedures to be followed will lengthen the total time to at least one half a day and perhaps a full day.)

If the line breakers trip single pole, then an even more convenient means is at hand for both initiating the single phase condition and terminating it, since all single pole systems have provision to trip three poles if an open pole is not closed after a short time.

Other means of single phasing a line can no doubt be found. One should use the most convenient.

Figures 7 and 8 are oscillograms taken during a single phase condition on a 115 kV line. Load prior to singe phasing was 14 MW out, 5 MVAR in. When the line was single-phased, the load decreased by 50 percent.

Note that the operating and polarizing currents are in phase showing proper connections to the relay.

The bottom trace on these oscillograms records the polarizing voltage during the single phase condition. Note also that the operating and polarizing currents lead the polarizing voltage - which may seem incorrect. However a little thought shows that the zero sequence current, being the sum of two phase currents, comes into the bus (assuming the phase currents are "out") so the oscillograms show both current and potential polarization are correct.

It is not so obvious, but from these oscillograms one draws the interesting conclusion that a single phase condition on a line appears to be an external fault to potential polarized relays but an internal fault to current polarized relays.

The oscillograph is not essential for this test since all the quantities are steady state ones. One can use only an ammeter and a phase angel meter.

Figure 9 shows the data obtained for a single phase test at another substation and line terminal using ammeters and a phase angle meter.

Again a load check was made. From the load check one predicts the angular relationships which will exist during a single phase test and then the test confirms the prediction.

The exact magnitudes of current and/or voltage found are not significant (unless the magnitudes are vastly different from expected), the important reading is the phase angle.

Summary

Since the proper response of directional relays is so dependent on proper connections, a test or check should be made of the relay connections prior to putting the protected circuit in service.

The tests for proper connections of potential polarized ground relays are relatively straight forward and well known.

Tests for proper connections of current polarized ground relays are neither so straight forward nor so well known.

Several tests have been outlined and what is believed to be a new test (the single phase test) has been described.

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3. Protective Relays: Their Theory and Practice, A. R. van C. Warrington, Chapman and Hall, London, 1962.
4. Directional Sensing for Ground Relaying, J. L. Blackburn, presented at the Pennsylvania Electric Association Relay Committee Meeting, Philadelphia, Pennsylvania, February 1962.
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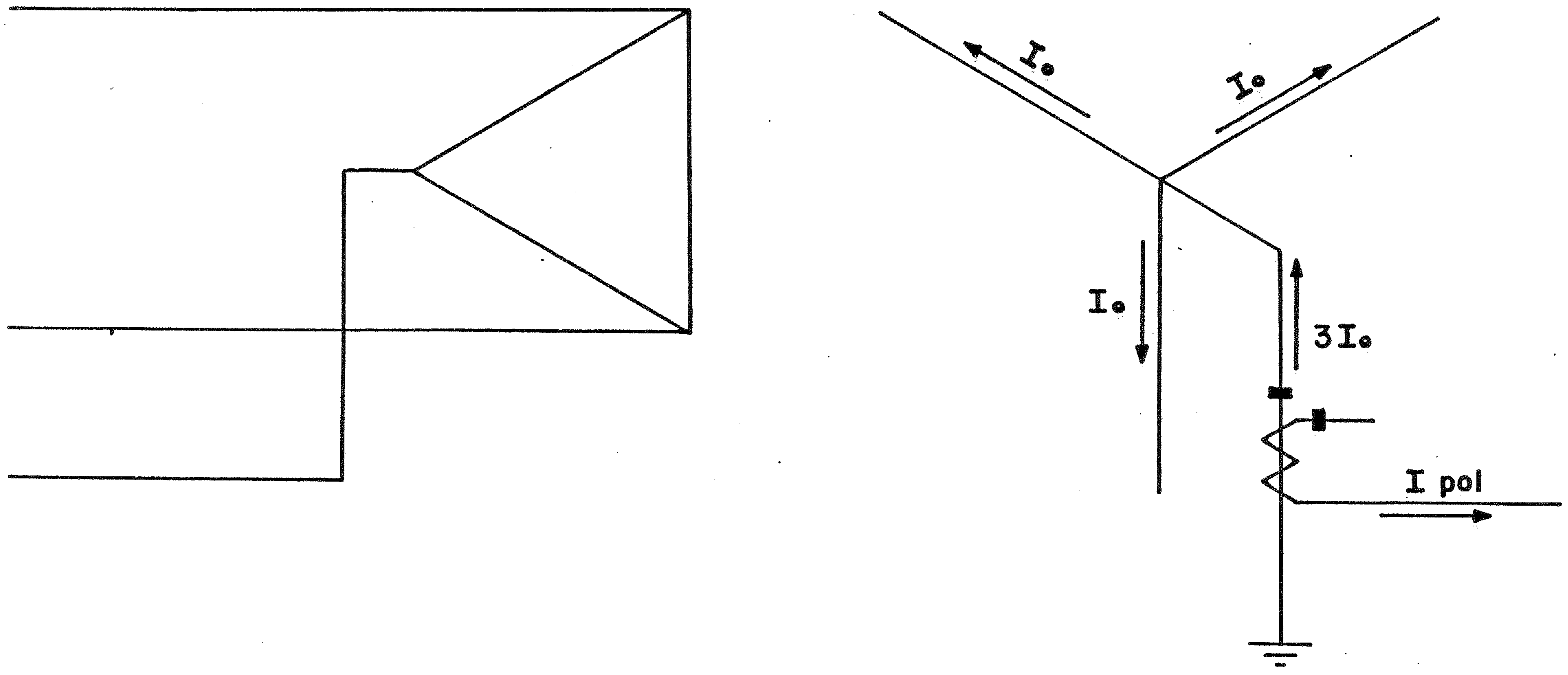
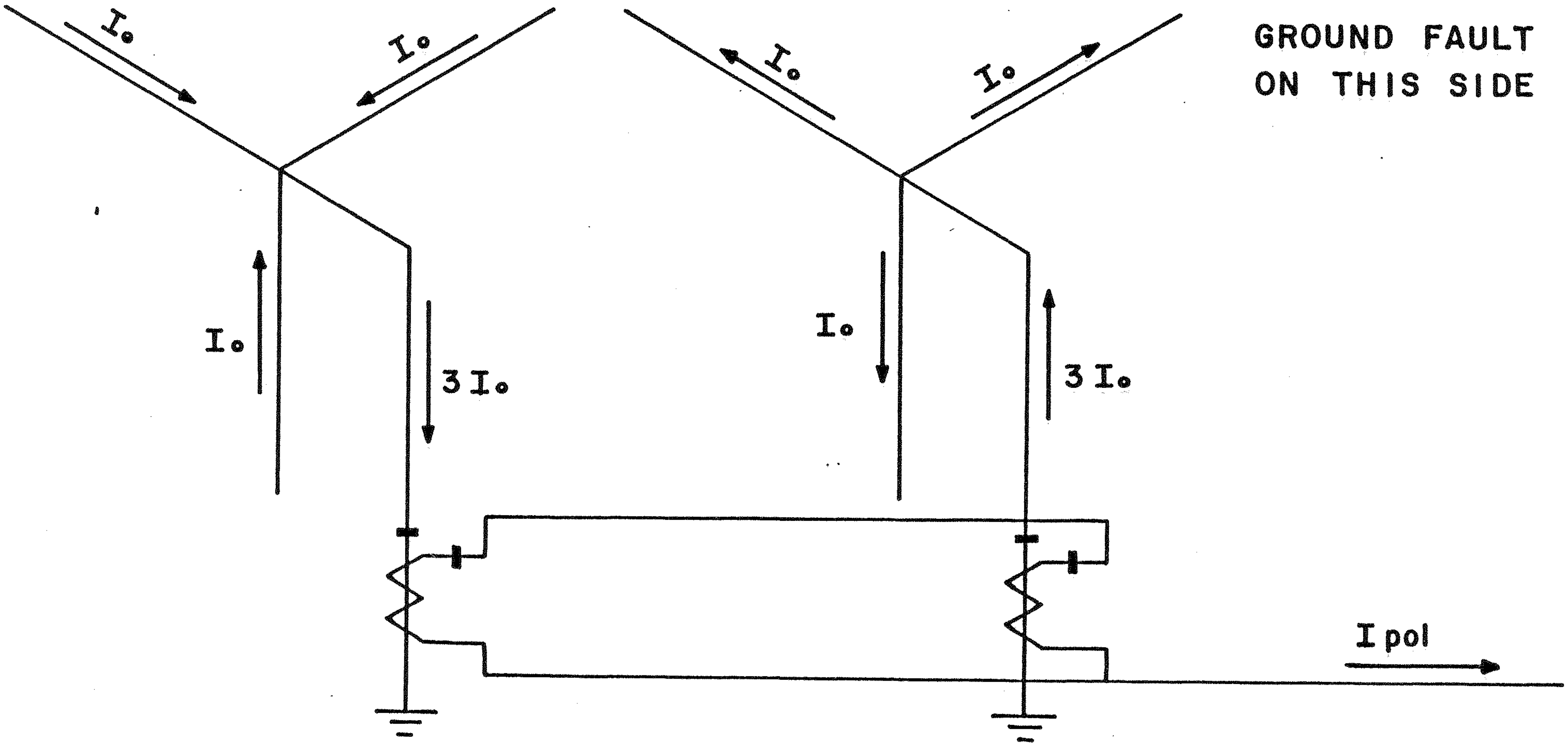
6. Special Circuits for Ground Relay Current Polarization from Autotransformers Having Delta Tertiary, P. A. Oakes, AIEE Transactions Paper 59-797, December 1959.



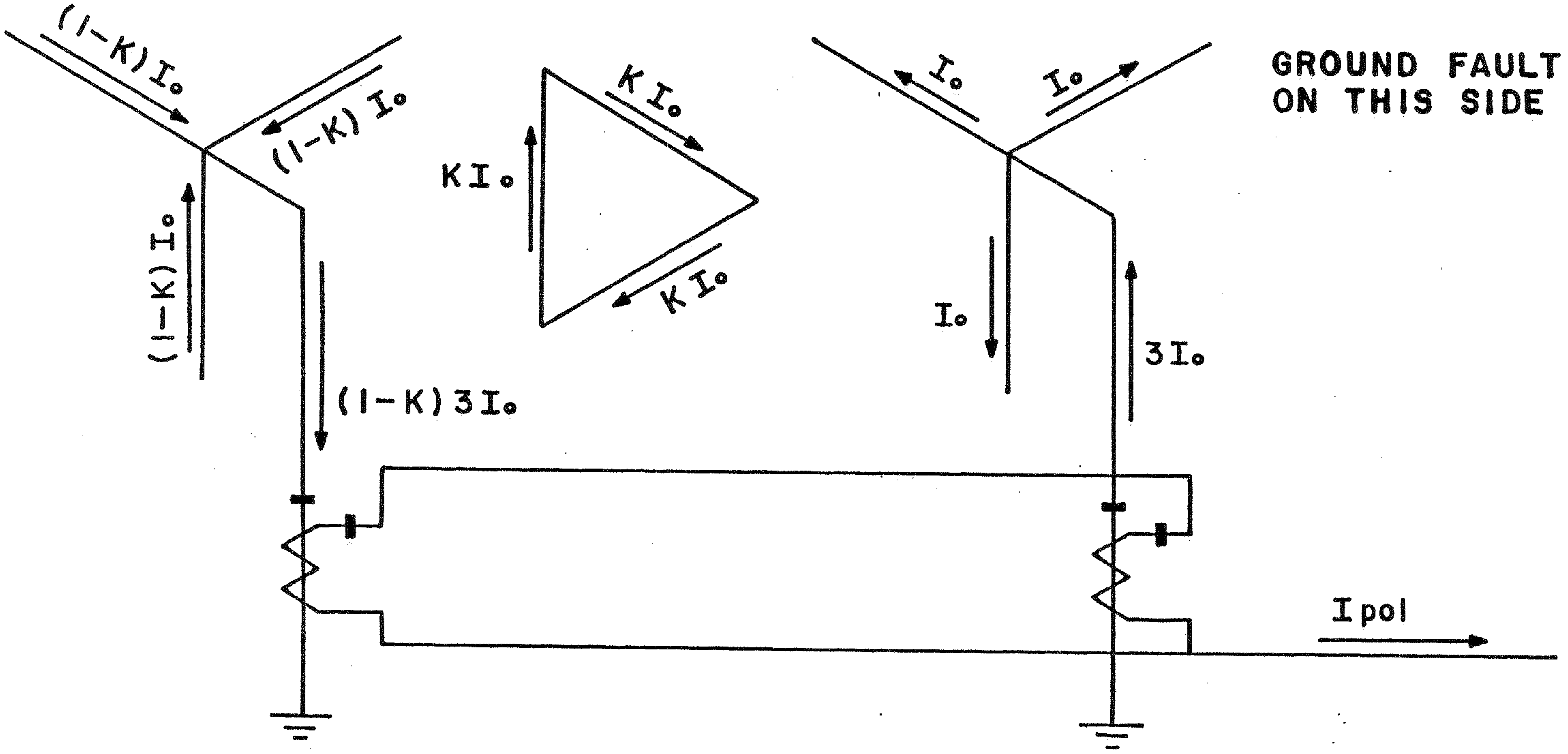
DELTA — WYE GROUNDED TRANSFORMER

FIGURE 1



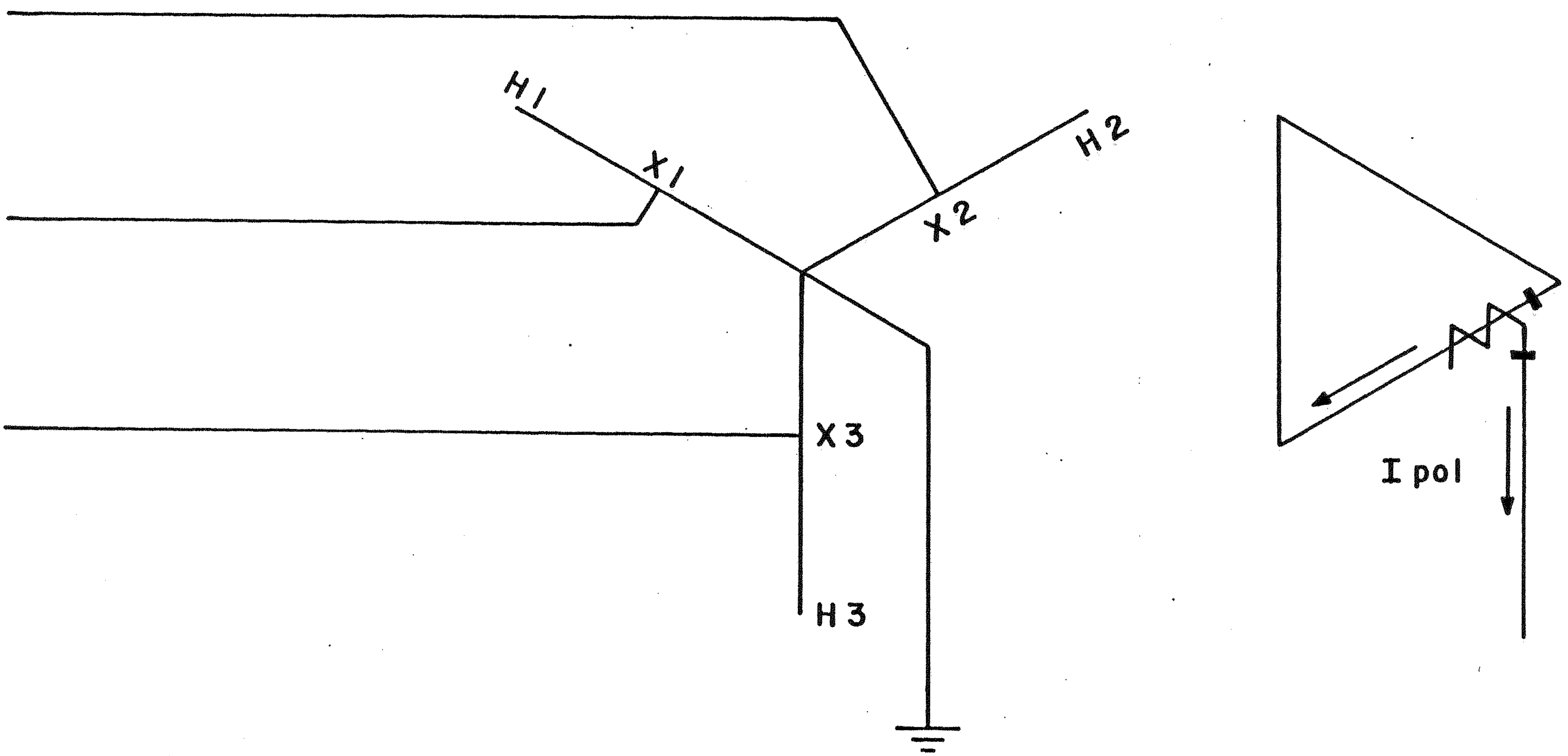
WYE GROUNDED — WYE GROUNDED TRANSFORMER

FIGURE 2



WYE GROUNDED — WYE GROUNDED TRANSFORMER WITH TERTIARY

FIGURE 3

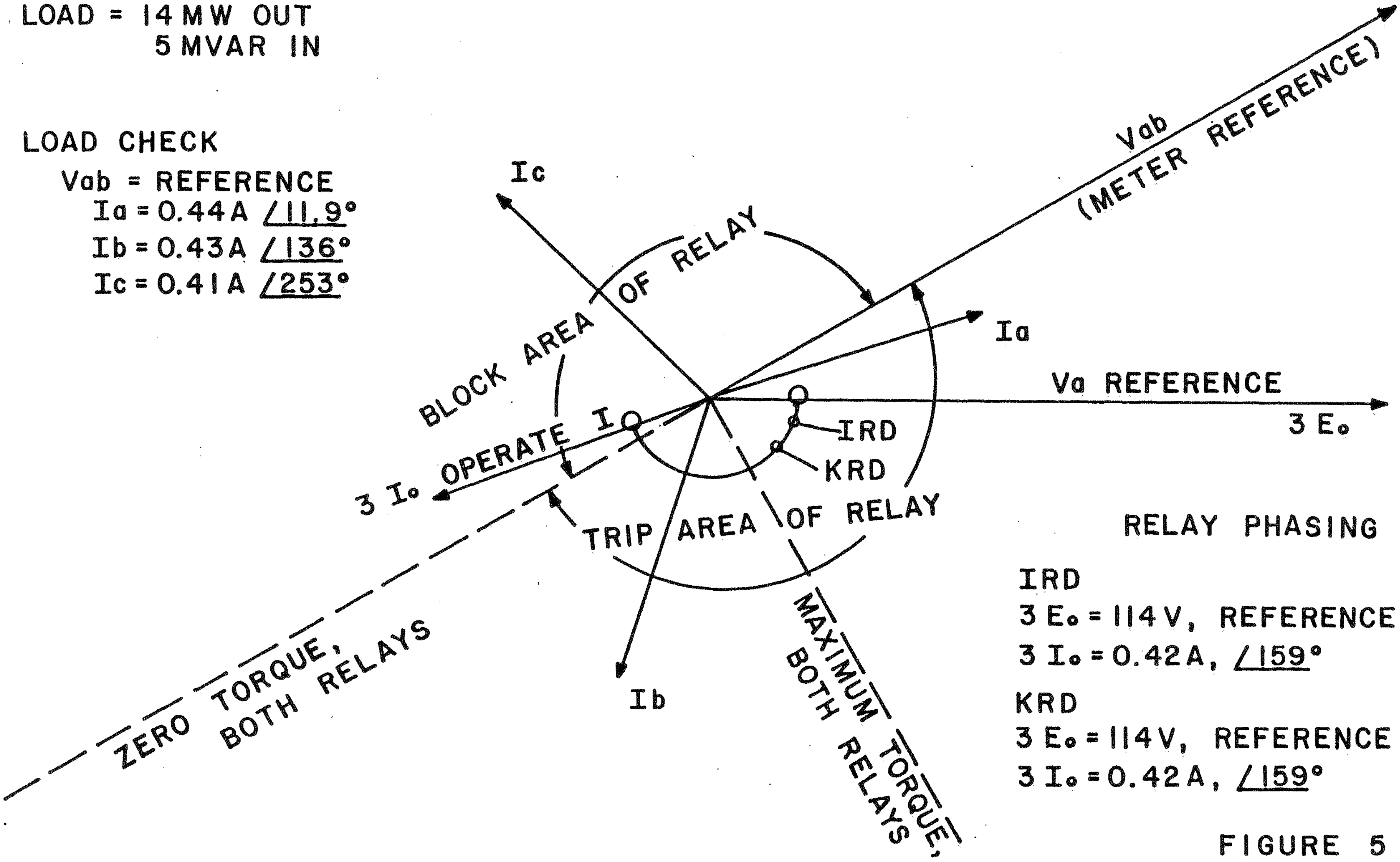


AUTOTRANSFORMER WITH TERTIARY

FIGURE 4

LOAD = 14 MW OUT
5 MVAR IN

LOAD CHECK
Vab = REFERENCE
$I_a = 0.44A \ \underline{\angle 11.9^\circ}$
$I_b = 0.43A \ \underline{\angle 136^\circ}$
$I_c = 0.41A \ \underline{\angle 253^\circ}$



RELAY PHASING

IRD
$3E_o = 114V$, REFERENCE
$3I_o = 0.42A, \ \underline{\angle 159^\circ}$

KRD
$3E_o = 114V$, REFERENCE
$3I_o = 0.42A, \ \underline{\angle 159^\circ}$

FIGURE 5

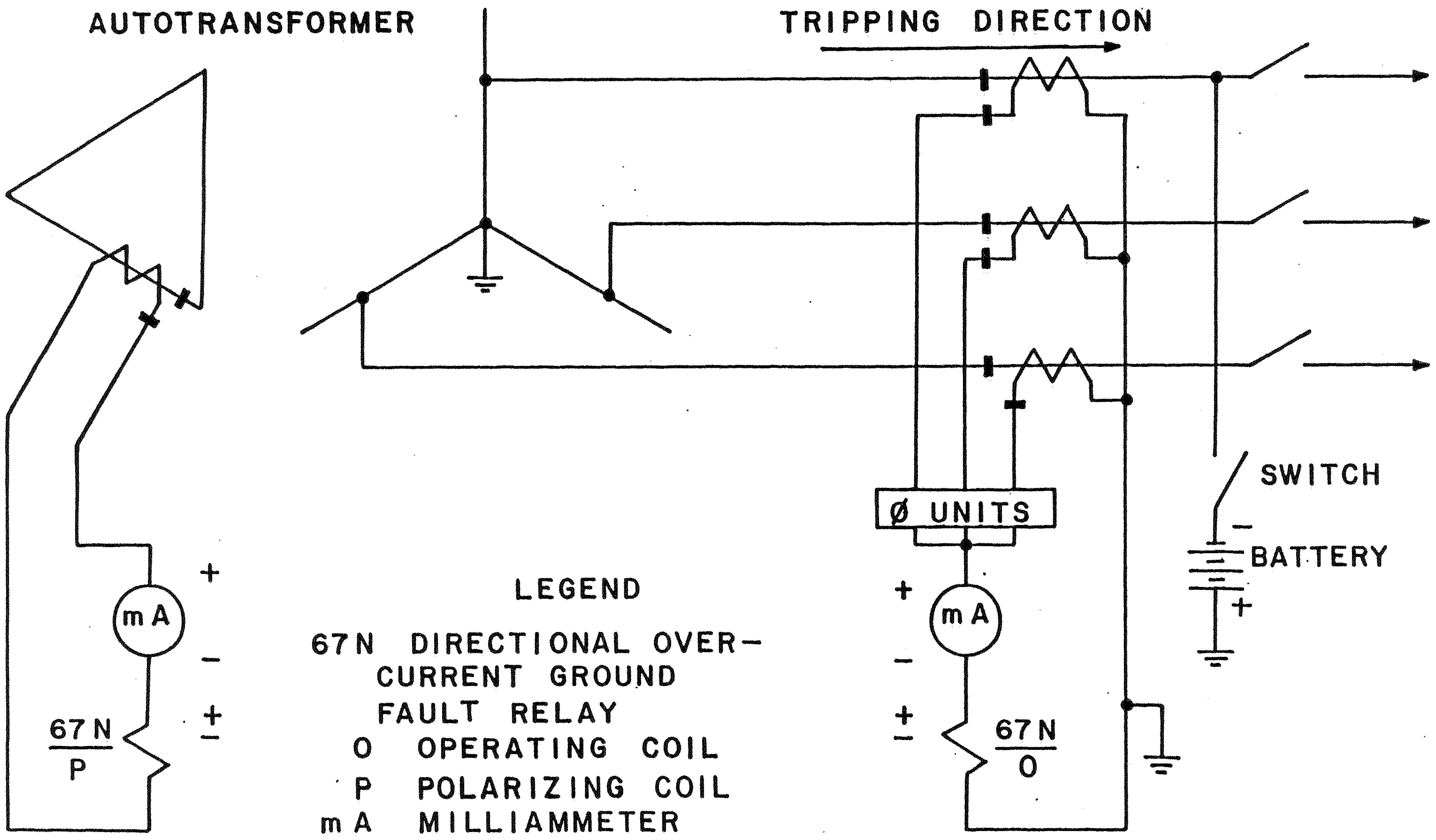
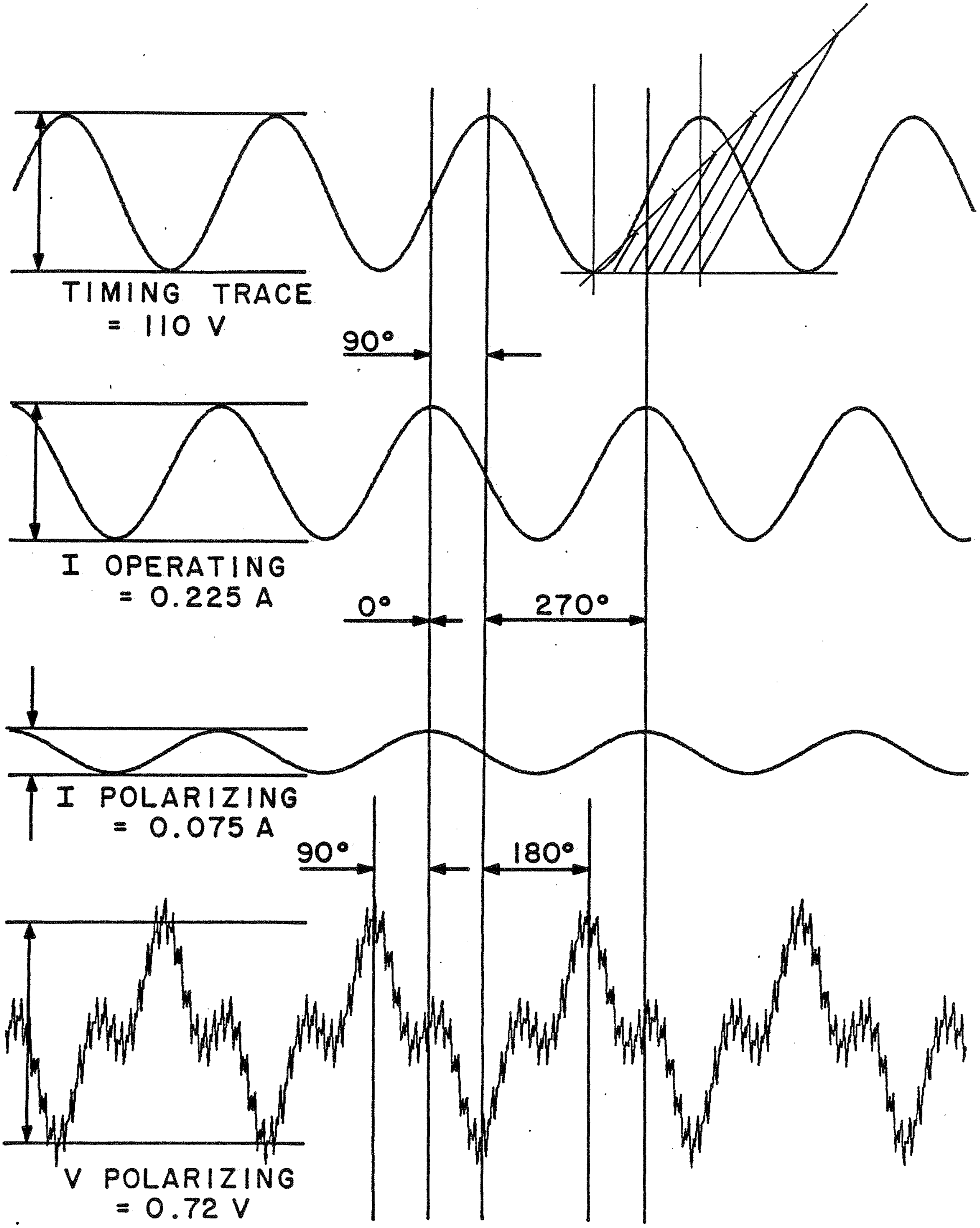

AUTOTRANSFORMER
TRIPPING DIRECTION
SWITCH
BATTERY
Ø UNITS
mA
+
−
±
67N/P
mA
+
−
±
67N/O
LEGEND
67N DIRECTIONAL OVER-CURRENT GROUND FAULT RELAY
O OPERATING COIL
P POLARIZING COIL
mA MILLIAMMETER

FIGURE 6



TIMING TRACE
= 110 V
90°
I OPERATING
= 0.225 A
0°
270°
I POLARIZING
= 0.075 A
90°
180°
V POLARIZING
= 0.72 V

FIGURE 7

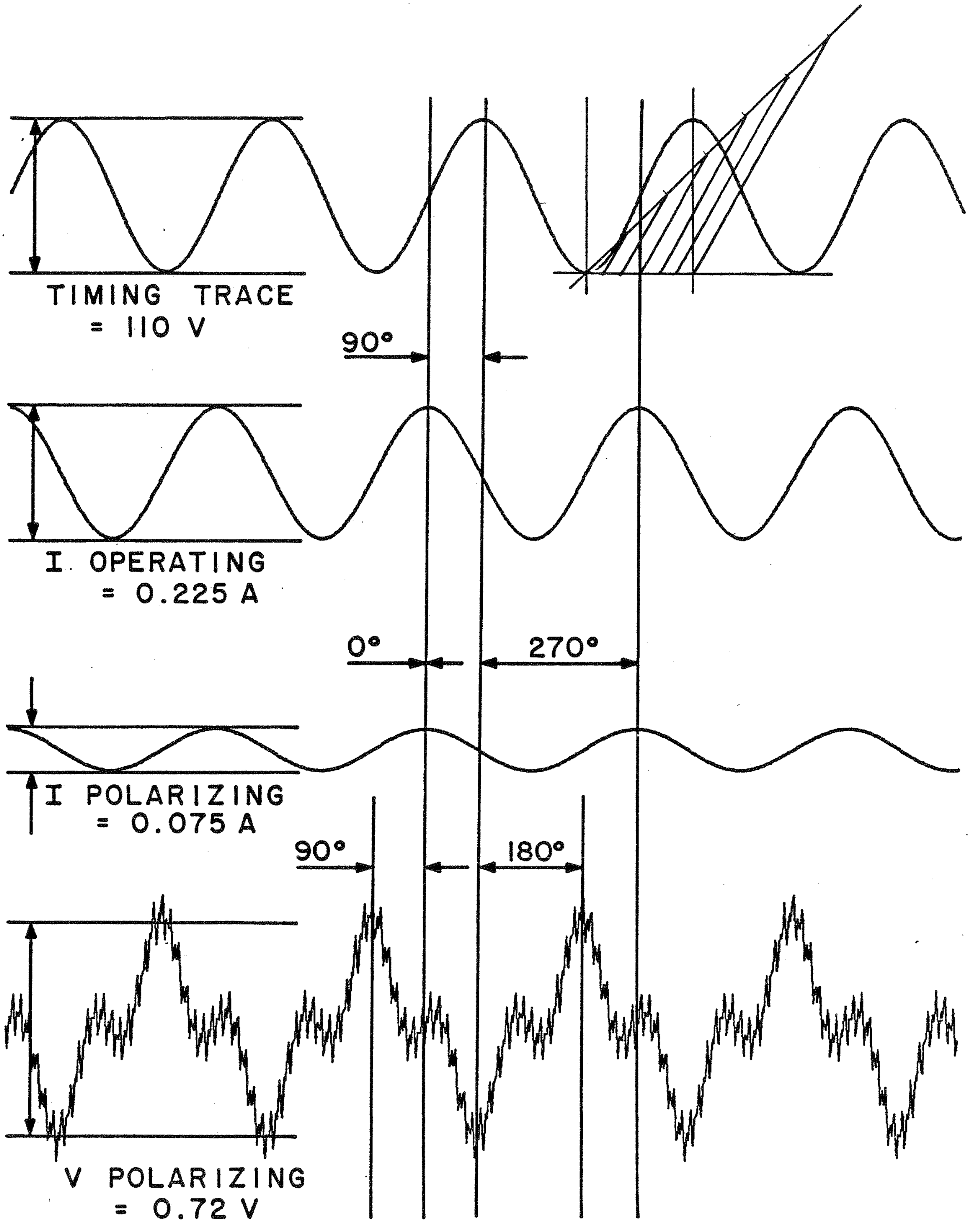

TIMING TRACE
= 110 V
90°
I OPERATING
= 0.225 A
0°
270°
I POLARIZING
= 0.075 A
90°
180°
V POLARIZING
= 0.72 V

FIGURE 8

LOAD CHECK:

LINE NORMAL

Ia = 0.234 A ∠250°
Ib = 0.22 A ∠7°
Ic = 0.22 A ∠120°

AØ OPEN

Ia = 0
Ib = 0.23 A ∠5°
Ic = 0.25 A ∠119°

RELAY CURRENT
AØ OPEN

I OPERATE = 0.27A ∠64°
I POLARIZE = 0.94A ∠66°

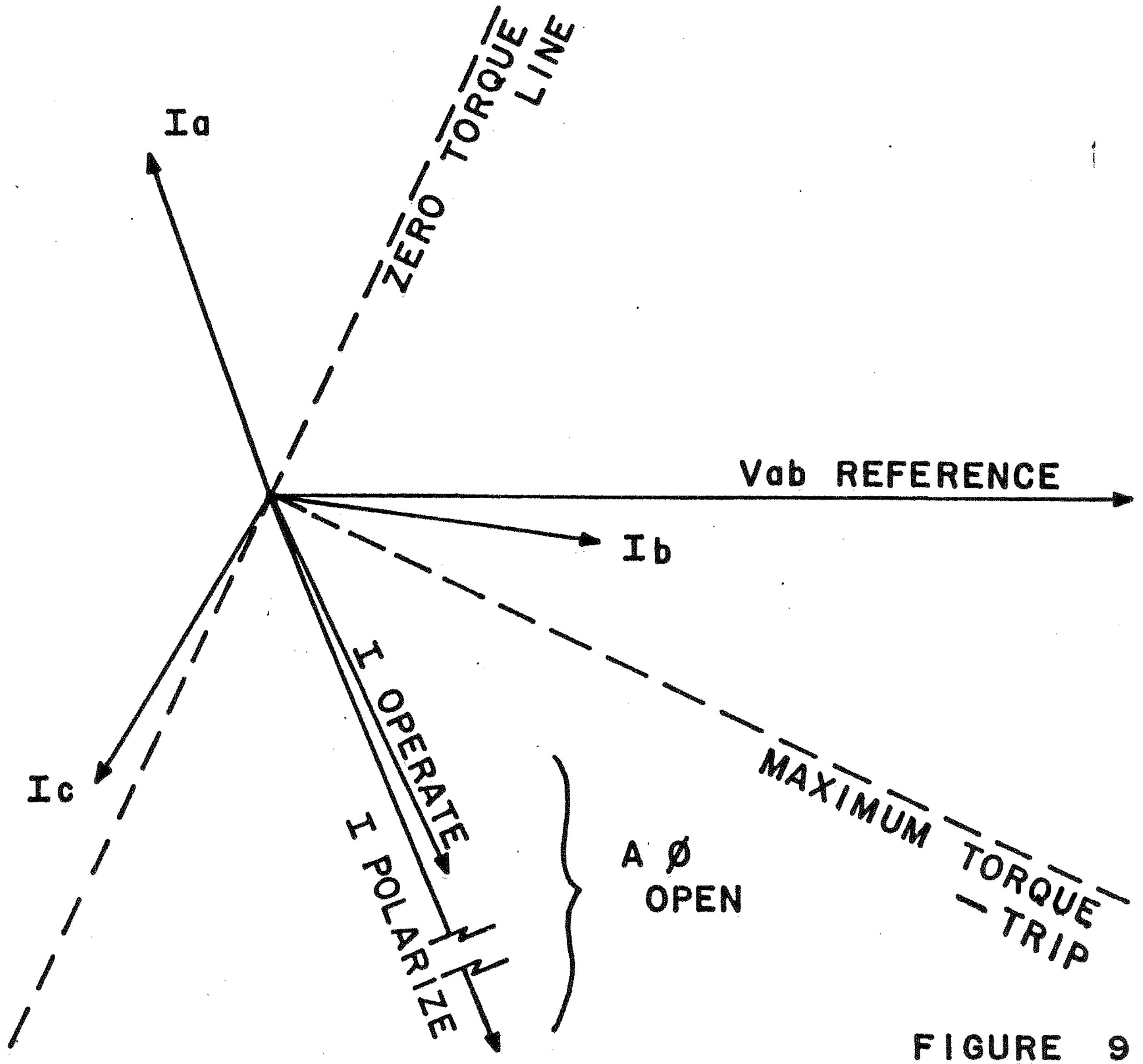


FIGURE 9