A PRACTICAL REMEDY
FOR
ZERO SEQUENCE REVERSAL

by

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INTRODUCTION

Directional relays require a polarizing (constant direction) reference with which to compare operating current for directional sensing. Directional ground overcurrent relays for transmission lines usually use zero sequence voltage and/or current for the polarizing quantity. If properly chosen (avoiding current polarizing from auto-transformer neutrals for example), zero sequence makes a good, simple polarizing quantity.

Zero sequence quantities, however, are not always a reliable polarizing source. Ground currents flowing for a fault in one transmission line may cause a reversal of the zero sequence polarizing quantities at substations connected to a parallel transmission line. Incorrect relay operation can be the result of this zero sequence polarizing reversal. This problem may be solved by installing a directional ground relay which is polarized by negative sequence rather than zero sequence quantities, or by replacing the directional ground overcurrent relay with a ground distance relay.

This paper will discuss the causes of the zero sequence reversal, explore system configurations where the reversal may be anticipated, and present a simple method of preventing false tripping during a reversal. The method has been used successfully by PG&E for over ten years.

CAUSE OF ZERO SEQUENCE REVERSAL

Zero sequence voltage is a voltage drop which is produced by zero sequence current flowing through the zero sequence impedance network. The highest zero sequence voltage occurs at the fault location. Low zero sequence voltage is found at locations with low shunt impedance to the neutral bus, such as stations with large transformers and strong sources. This explains why large stations frequently have a very low zero sequence polarizing voltage available. See Figure 1.

Since the zero sequence voltage is primarily the result of a voltage drop in the network, a voltage rise must be induced in the network to cause a voltage reversal. The only source available to create a voltage rise through the zero sequence network is inductive coupling between a line carrying fault current and an adjacent line (mutual coupling), as shown in Figure 2. This occurs because the magnetic flux due to fault current in the faulted phase is not neutralized by the flux of the current return through earth. Some of this flux cuts through the conductors of the parallel transmission line causing zero sequence current to flow in that line.

The voltage produced by mutual coupling can add to the voltage drop in the coupled line or subtract from it, depending on the direction of current flow. If the mutual coupling produces a voltage rise greater than the $I_0 \times Z_0$ voltage drop through the network to a given location, the zero sequence voltage at that location can be reversed. If a shunt impedance such as a star-grounded power transformer is connected to the line at that location, the zero sequence current in the transformer neutral will also be reversed. Thus the zero sequence current polarizing from a bank neutral CT would be reversed at that location.

SUSCEPTIBLE SYSTEM CONFIGURATIONS

What system locations are likely to have problems with zero sequence polarizing? We will explore some examples of different system configurations using the same 230kv lines with mutual coupling (twin circuit tower construction) and without (separate rights-of-way). The lines consist of 40 miles of 954 MCM aluminum conductor on "standard" towers.

We will use an analog description of the sequence networks in our discussion. This will aid in visualizing the actual line configurations being investigated.

EXAMPLE 1: TRANSMISSION LINES BUSSED TOGETHER WITHOUT MUTUAL COUPLING

Figure 3 shows the zero sequence impedance network for the two lines, without mutual coupling, terminating on the same buses. Two faults are considered:

Figure 3A: A fault near one line terminal.
Figure 3B: The same fault with the adjacent circuit breaker open (line end fault).

Note that the zero sequence polarizing voltage E_p (E_p=3xE_0) decreases progressively from the fault location to the remote bus. The E_p values are all negative, thus showing no reversal.

EXAMPLE 2: TRANSMISSION LINES BUSSED TOGETHER WITH MUTUAL COUPLING

The system in Figure 4 is the same as in Figure 3 except that the two lines are mutually coupled. We will consider the same two faults as in Example 1:

Figure 4A: A fault near one line terminal.
Figure 4B: The same fault with the adjacent circuit breaker open (line end fault).

For the first fault condition (Figure 4A), note that the zero sequence polarizing voltages again decrease progressively from the fault location to the remote bus and they are quite similar in magnitude (compare Figure 4A with Figure 3A).

Now compare the polarizing voltages along the unfaulted line (the lower line) for the second fault condition (compare Figure 4B with Figure 3B). Note that the voltage difference between line ends is much smaller in Figure 4B. The voltage coupled into the unfaulted line by the faulted line current tends to cancel the voltage drop due to line current flow. The result in this case is a nearly flat voltage profile for the unfaulted line. Since the E_p voltages are negative, they still provide for correct polarizing.

EXAMPLE 3: TRANSMISSION LINES CONNECTED TO RADIAL SOURCES

Figure 5 represents the actual portion of the PG&E system that has provided the lines used to model our examples. The two lines are bussed together at the left end. Each is connected radially to a grounded wye/delta step-up transformer at its remote end hydro-electric generating station. The system exhibits the "classic" case of reversed zero sequence polarizing.

During the initial fault (Figure 5A) the voltages are all negative, have the correct polarity, and decrease with distance from the fault. Figure 5B shows the effect if the line's left end circuit breaker trips first, because of a nearby fault on the line. The faulted line E_p voltages are still normal, but two of the voltages shown on the unfaulted line are positive; they have reversed. Directional ground overcurrent relays at these locations will operate incorrectly.

At this stage of fault clearing we have two isolated systems, as can be seen in Figure 5C. The zero sequence voltage in the lower line is coupled in by fault current flow in the upper line. The resulting current in the lower line is small so it produces a small voltage drop. The voltage coupled in from the upper line predominates. As we shall see, the fault voltage and current in the lower line are zero sequence only. Positive and negative sequence fault quantities are not present in the lower line.

EXAMPLE 4: TRANSMISSION LINES TERMINATING AT DIFFERENT SUBSTATIONS

Zero sequence polarizing reversal also occurs when the lines are not bussed together at both ends, a far more common system connection than the radial line configuration of Example 3. Figure 6 represents the lines thus connected; bussed at the left end but terminating at different stations at their right ends. The polarizing voltages on the unfaulted line are again driven into reversal by induced voltage from current in the faulted line, but only for the line end fault condition. The lines during this condition are not bussed at either end; they are separate at one end and only weakly tied at the other end.

EXAMPLE 5: PARALLEL TRANSMISSION LINES AT DIFFERENT VOLTAGES

Another system configuration, somewhat rare, is a twin circuit tower line carrying circuits at different voltages, such as 230 KV and 115 KV. These lines are obviously not bussed at either end, and a ground fault on one circuit can induce zero sequence voltage into the other circuit causing a polarizing reversal.

FALSE TRIP PREVENTION

The polarizing problem and its causes should now be evident. How can relay systems be protected from the reversal and be made to operate correctly?

As can be seen in Figures 5B and 6B (line end faults), the ground fault current is much higher in the faulted line than in the unfaulted line on which the polarizing voltage has reversed. Inverse time overcurrent relays can usually be coordinated for correct operation under this condition if you are aware that the polarizing can reverse. Pilot protection, which has no appreciable time delay, is another matter. Some means other than time delay must be used to prevent false tripping.

Refer to Figure 7A, the line end fault with radial generation. Note that there is no negative sequence current in the unfaulted (lower) line. This occurs because we have two electrically separate systems for this particular condition. The only current flowing in the unfaulted system is zero sequence, coupled in from the faulted line.

Figures 7B and 7C show faults at each end of the lower line. In these cases negative sequence current (I_2) is present because the lower line is actually faulted.

Figure 8 shows the system with lines terminating at one end at different busses. In this case, faults on the lower line (Figures 8B and 8C) produce negative sequence currents of 245 and 809 amps. These currents are much higher than the 48 amps of I_2 that flow in the lower line during a line end fault on the upper line (Figure 8A).

The examples in Figures 7 and 8 show a means of determining whether a line has a ground fault with correct polarizing or has reversed polarizing while carrying current during a fault on another line. An instantaneous negative sequence overcurrent relay can be connected to supervise ground relay tripping. There will generally be plenty of margin to set the relay between the low I_2 in the line during faults on the adjacent line and the higher I_2 during faults on the protected line.

DOUBLE LINE TO GROUND FAULTS

So far our discussion has only considered single phase to ground faults. Two phase to ground faults must be investigated as well, although our experience has been that the zero and negative sequence currents are not too different for the two cases. This is shown in the example of the Table Mountain -Rio Oso system, Figure 9 (one phase to ground) and Figure 10 (two phases to ground).

The results of the Table Mountain - Rio Oso study are summarized below. The table shows the worst case must-trip and must-block currents in negative sequence primary amps.

	1 phase - gnd		2 phase - gnd	
Line name	Block	Trip	Block	Trip
Table Mtn - Rio Oso	74	733	99	738
Table Mtn - Palermo	78	824	119	830
Palermo - Colgate	13	1124	21	1116

The Table Mountain - Rio Oso line requires trip supervision at Rio Oso due to reversed E_p (actually a very low value) with incoming current during a line end fault on the Table Mountain -Palermo line (Figures 9A and 10A). The maximum negative sequence current in the unfaulted line is 99 amps.

The ground protection at Rio Oso must be able to clear a fault at the Table Mountain end of the line (worst case is with all breakers closed, Figures 9B and 10B). The minimum negative sequence current in this faulted line is 733 amps. This gives a 733/99 or over 7/1 spread in which to set the supervising relay. In practice, we have not seen this ratio go below 5/1, although it is possible. Each case should be studied to assure that this solution will work, and to determine the compatibility of available relay ranges with the current transformer ratio.

The protection engineer must establish his own rules for determining the setting of the negative sequence overcurrent relay. Our practice has been to set the pickup of the relay toward the low end of the trip/block range, at two times the block value determined by study. This setting can then accommodate trip values which might be lower than calculated due to high resistance ground faults. Incidentally, since these relays are tested by single-phase methods, we have found it beneficial to provide the technician with a test current value as well as the desired negative sequence value.

EXPERIENCE WITH SCHEME

When PG&E first started to use this scheme, the choice of available negative sequence relays was limited. The only "utility grade" relays available to us were electro-mechanical, which are slow to operate and have a high burden. We settled for an "industrial grade" solid state relay to which we added our own external surge protection and test facilities. We still use the same relay.

We started to apply negative sequence supervising relays to existing schemes that we found in trouble as a simple, reliable fix. We now include it in new installations where we expect to have a polarizing reversal problem. Our usual application is to directional comparison schemes using power line carrier blocking. We install the relay at both line terminals even though the polarizing reversal may only occur at one end of the line. A line terminal depends on blocking carrier from the remote line terminal to prevent tripping on out-of-section faults; carrier will not be transmitted if the remote terminal's polarizing reverses.

The relay is connected to supervise tripping of the pilot ground protection only. We want to retain maximum sensitivity of the backup ground relay to provide tripping for remote out-of-section faults that do not clear. The backup ground relay must then be coordinated for both normal and reversed polarizing conditions.

SUMMARY

Zero sequence polarizing reversal can be expected to occur on mutually coupled transmission lines that are not bussed together at both ends. A line end fault (due to one terminal clearing first) at the bussed end separates the two lines electrically, and mutual coupling from the faulted line can produce zero sequence voltage (and resulting current) reversal in the unfaulted line. The reversal should be expected if the lines are not bussed at either end, such as the case of lines operating at different voltages on the same towers or adjacent in the same right-of-way.

False tripping can be prevented by taking advantage of the fact that negative sequence current is high in a line when it is the faulted line , but much lower or nonexistent when the fault is on a parallel line. An instantaneous negative sequence overcurrent relay can be used to supervise tripping in pilot relaying schemes for these conditions, but it should not be used to block ground backup relaying or any phase protection.

This solution is more economical than replacing an entire relay terminal. It is a practical solution to relaying problems that are introduced by a transmission line configuration change, or by the addition of a new substation on a line. It has also been used on new installations since it is a simple, reliable scheme.

ACKNOWLEDGEMENT

Special recognition is given to Gerald B. Gilcrest, retired PG&E protection engineer, who recognized that this relaying problem existed in the PG&E system. He observed the principle presented in this paper while he was working with computer fault studies, and developed the solution that we use today.

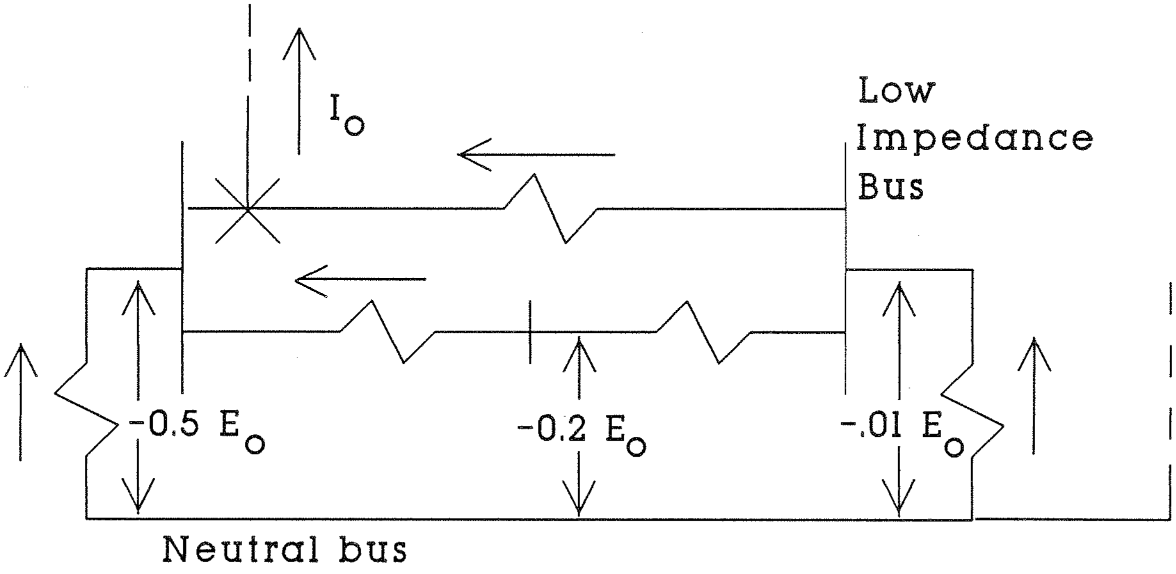


FIG 1: ZERO SEQUENCE VOLTAGE AND VOLTAGE DROP IN THE ZERO SEQUENCE IMPEDANCE NETWORK

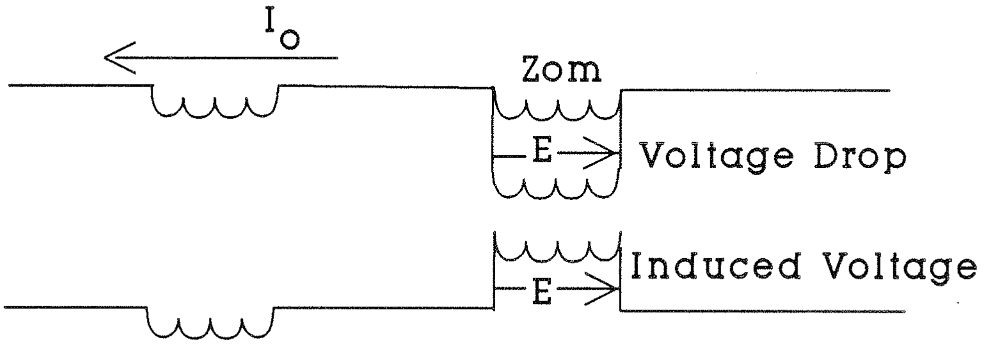


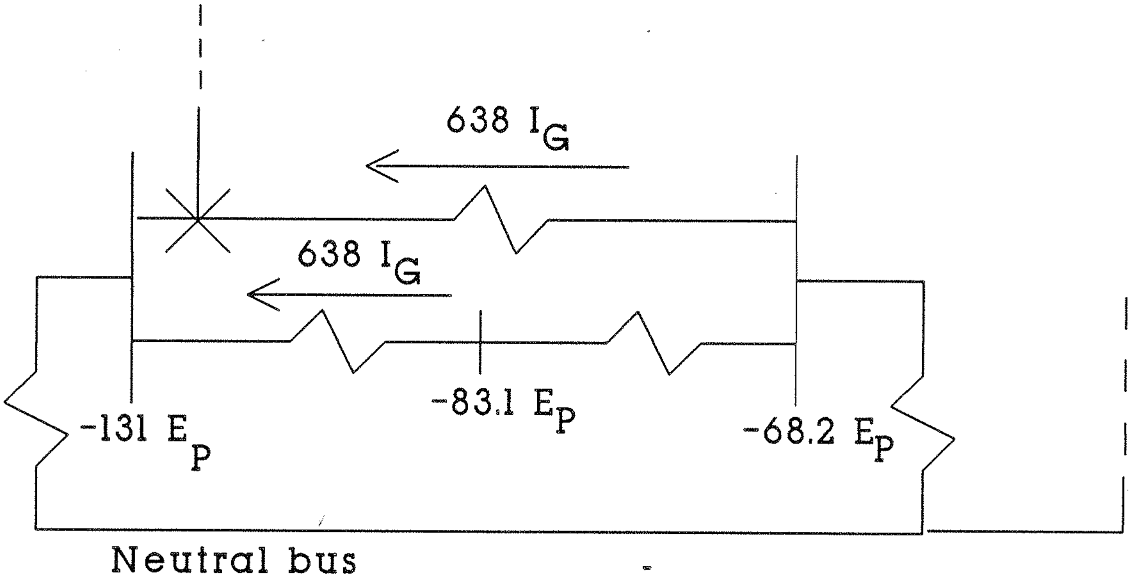
FIG 2: MUTUAL COUPLING IN ZERO SEQUENCE NETWORK

DIAGRAM NOTES IN THE FOLLOWING FIGURES 3 THRU 10:

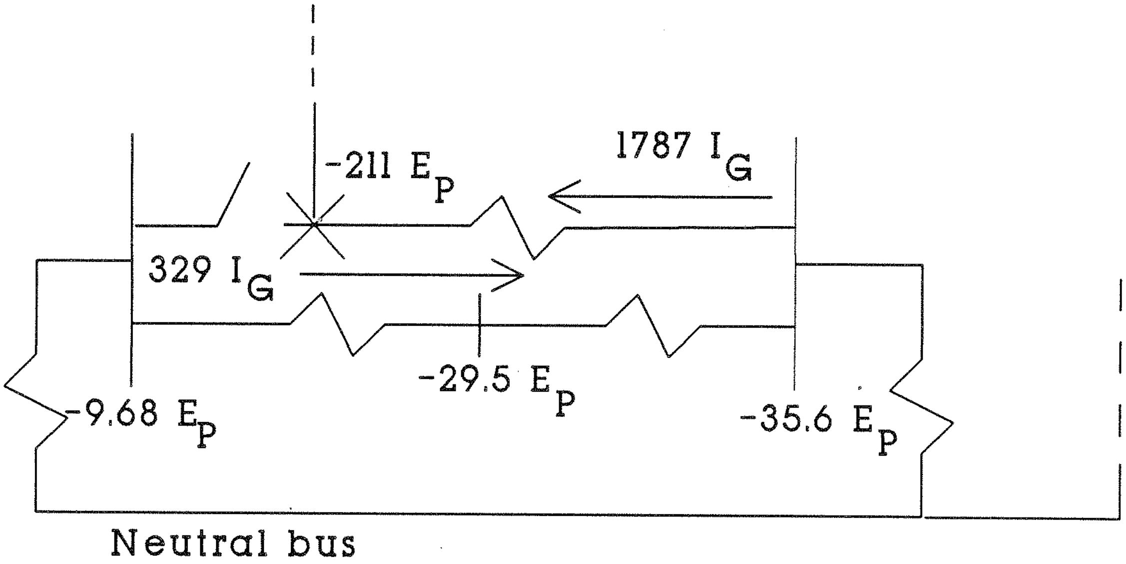
I_G = Ground Fault Current = 3xIo, in Amps.

I_2 = Negative Sequence Current, in Amps.

E_P = Zero Sequence Polarizing Voltage = 3xEo, in KV
Negative values are correct for polarizing
Positive values are reversed polarizing

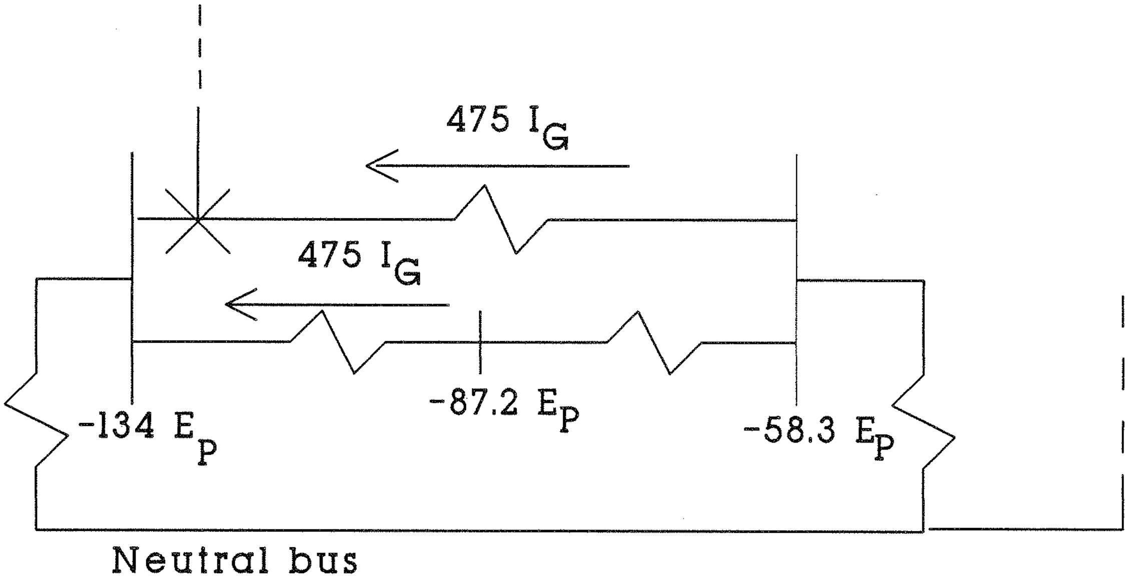


3A: BUS FAULT

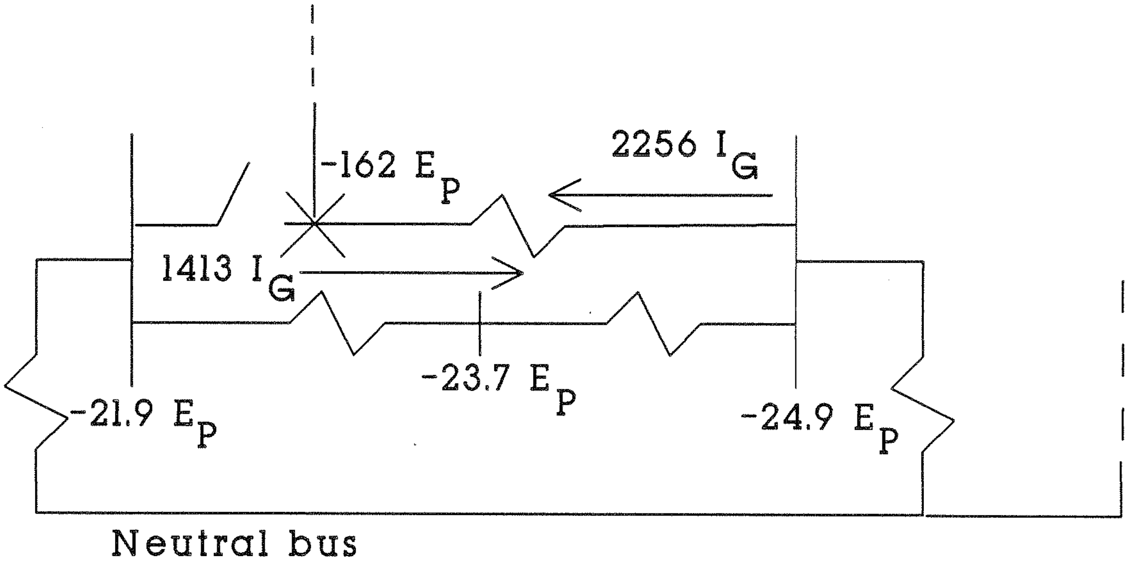


3B: LINE END FAULT

FIG 3: LINES WITHOUT MUTUAL COUPLING

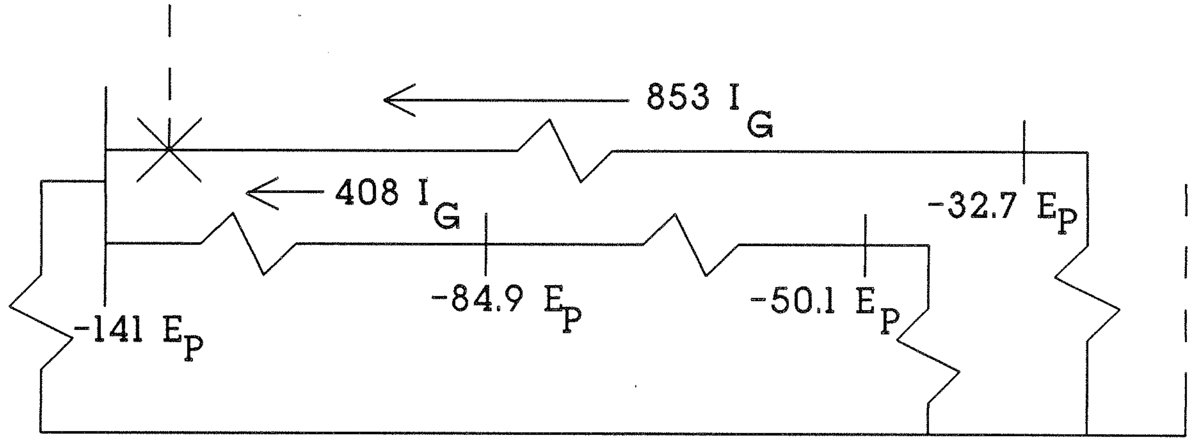


4A: BUS FAULT

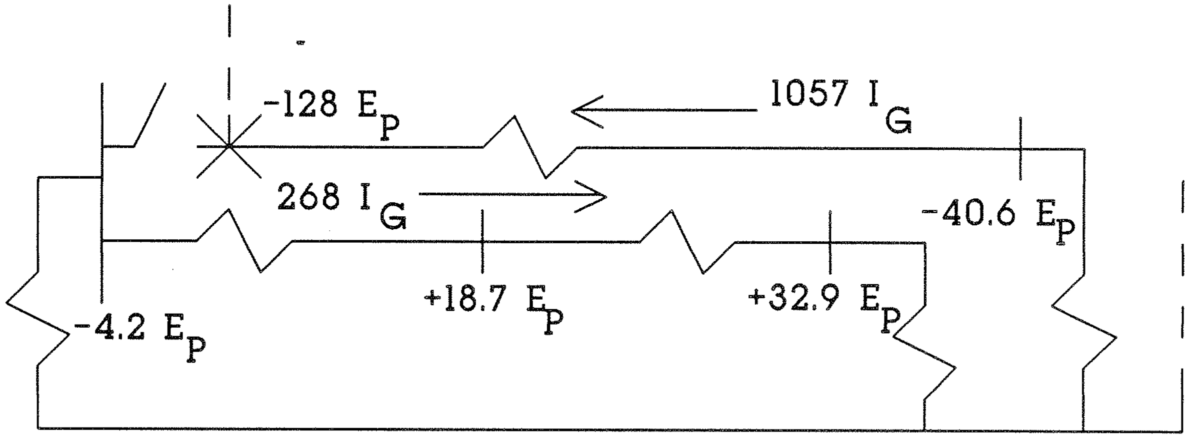


4B: LINE END FAULT

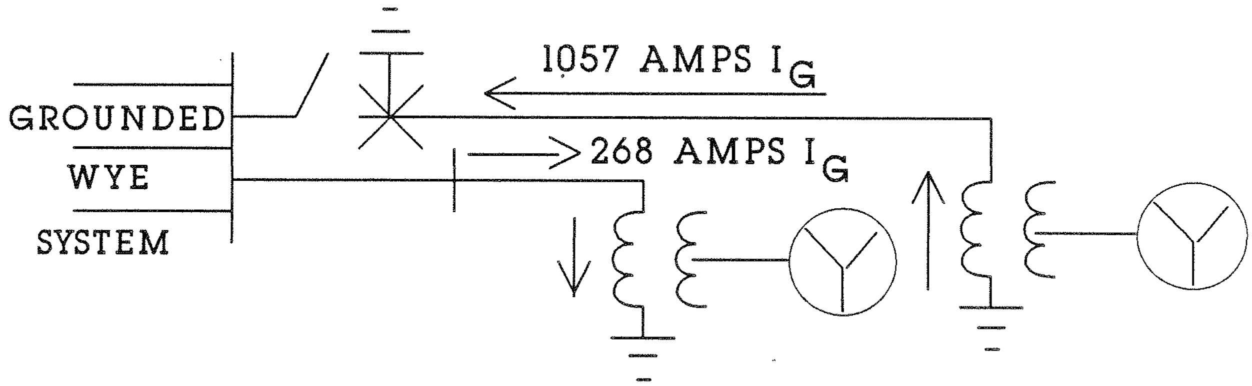
FIG 4: LINES WITH MUTUAL COUPLING, BUSSED AT BOTH ENDS



5A: BUS FAULT

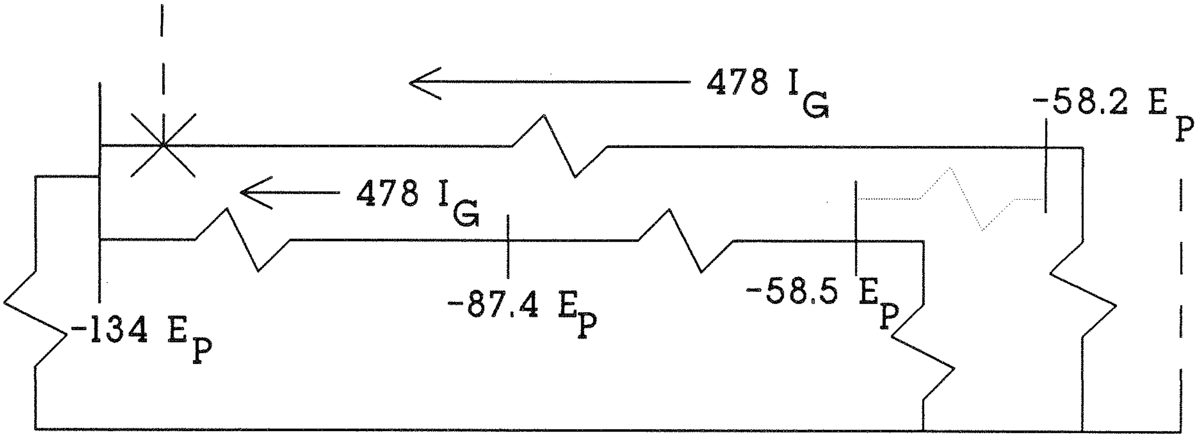


5B: LINE END FAULT

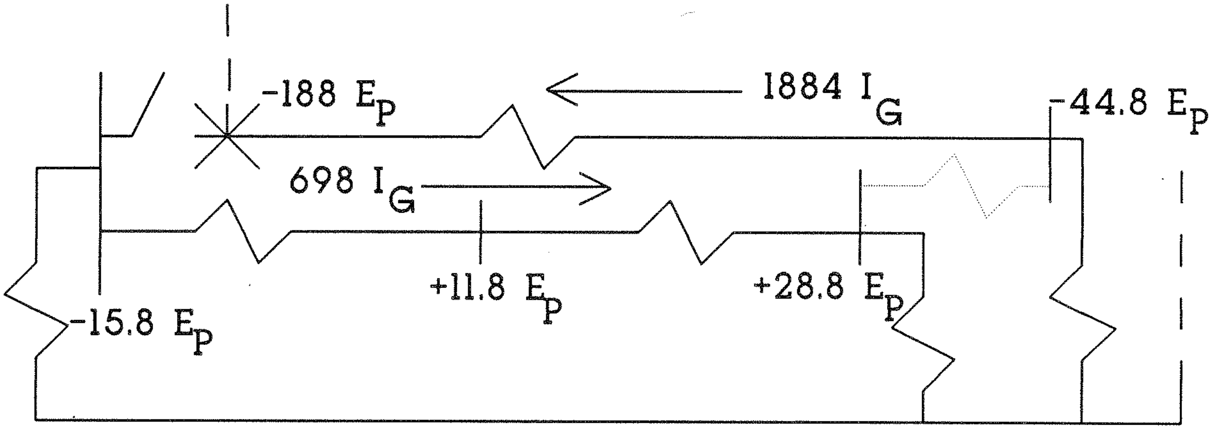


5C: LINE END FAULT

FIG 5: LINES WITH MUTUAL COUPLING,
BUSSED AT ONE END,
RADIAL GENERATION AT REMOTE ENDS

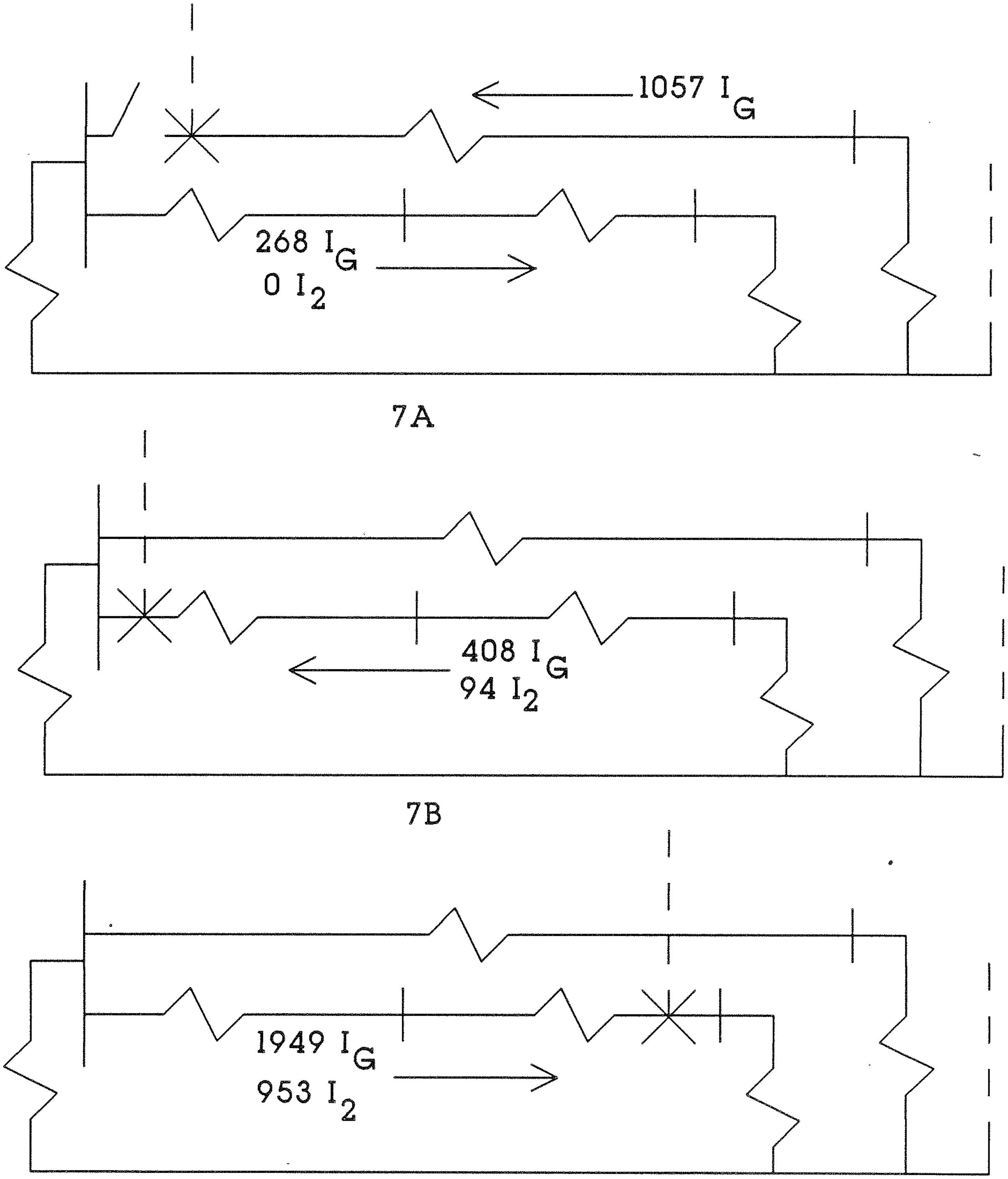


6A: BUS FAULT



6B: LINE END FAULT

FIG 6: LINES WITH MUTUAL COUPLING,
BUSSED AT ONE END,
WEAK SYSTEM TIES BETWEEN REMOTE ENDS



7A

7B

7C

FIG 7: LINES BUSSED AT ONE END, RADIAL GENERATION
(FROM FIG. 5)

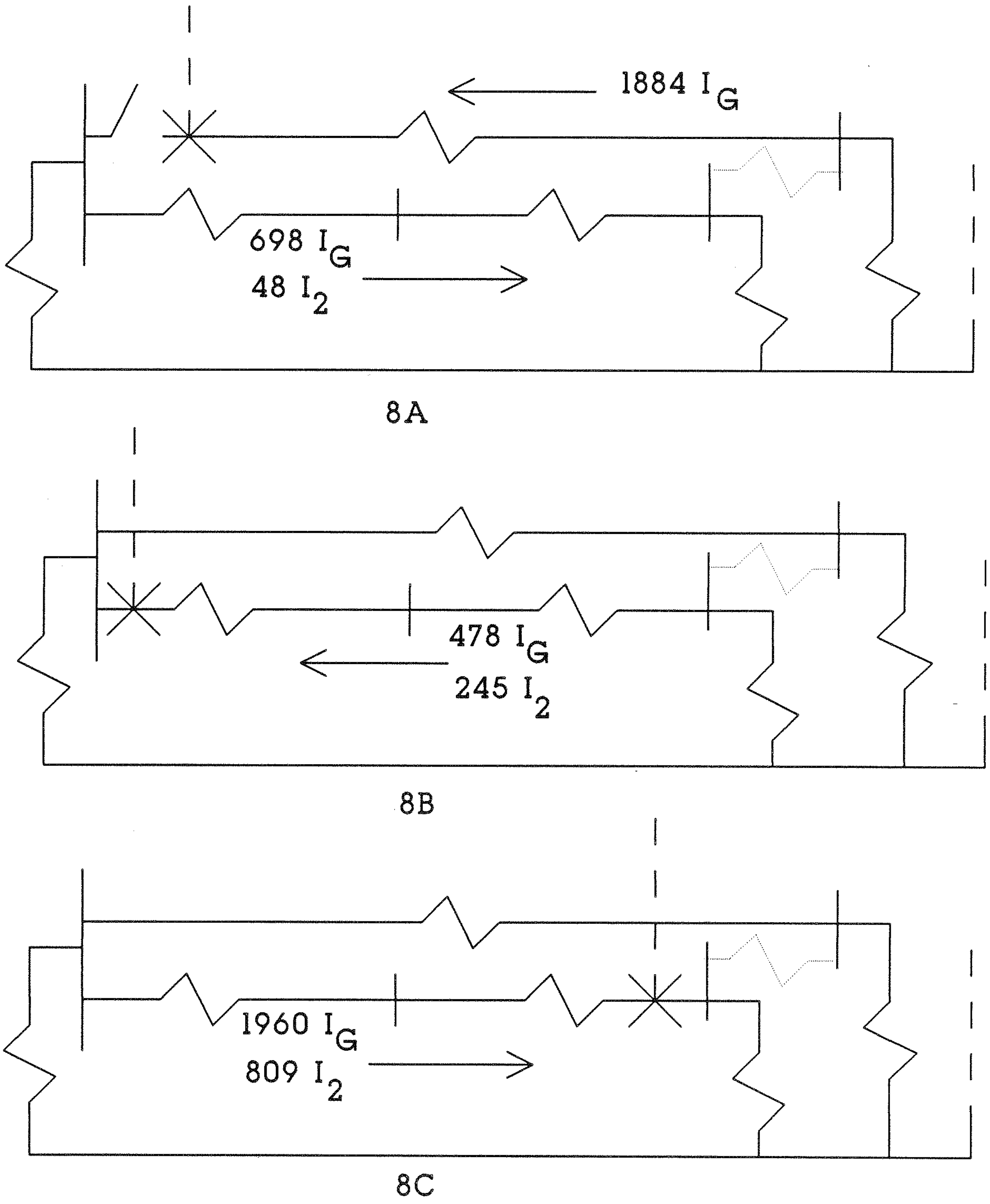


FIG 8: LINES BUSSED AT ONE END, WEAK SYSTEM TIES BETWEEN REMOTE ENDS (SEE FIG. 6)

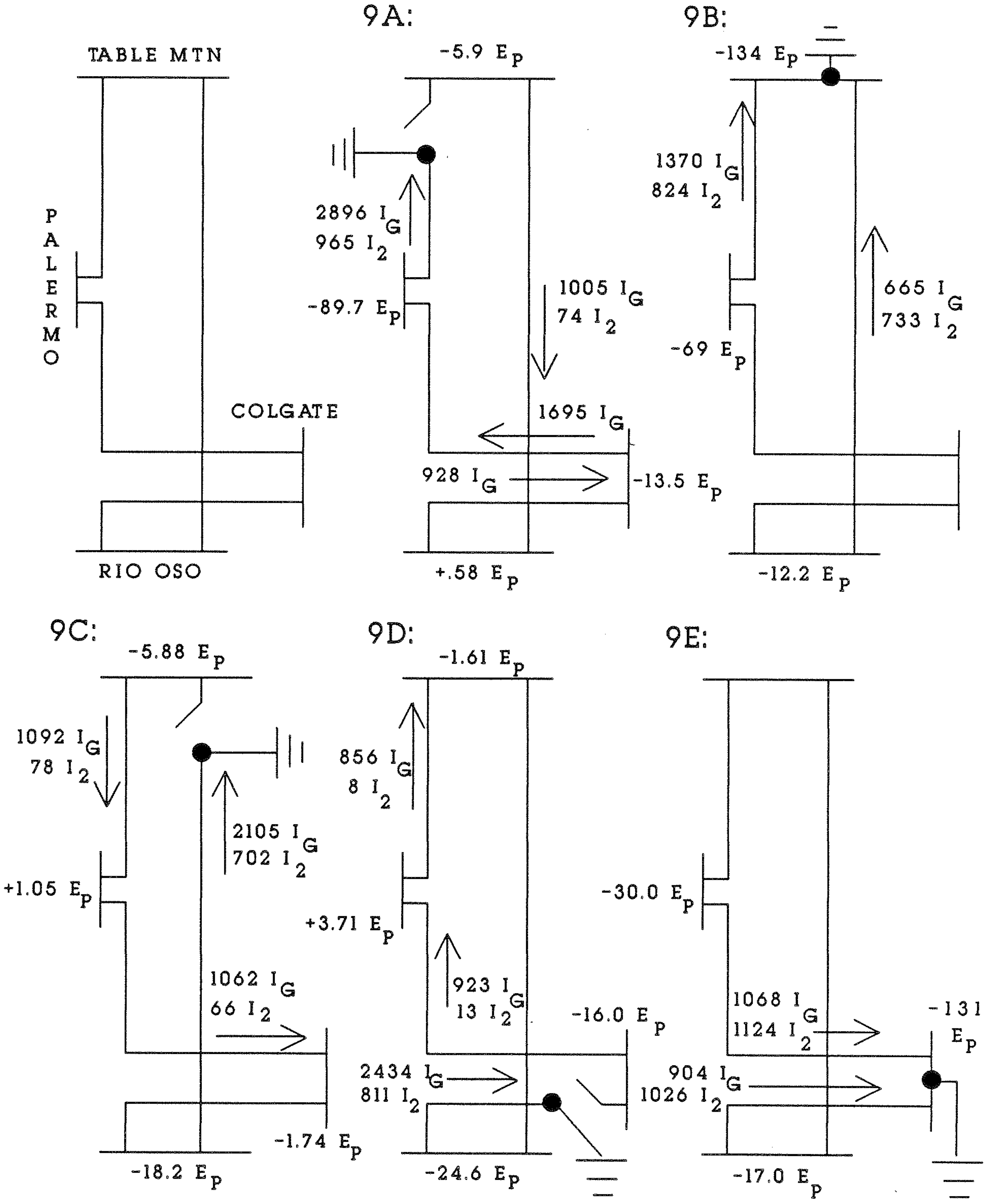


FIG 9: SINGLE-LINE-TO-GROUND FAULTS

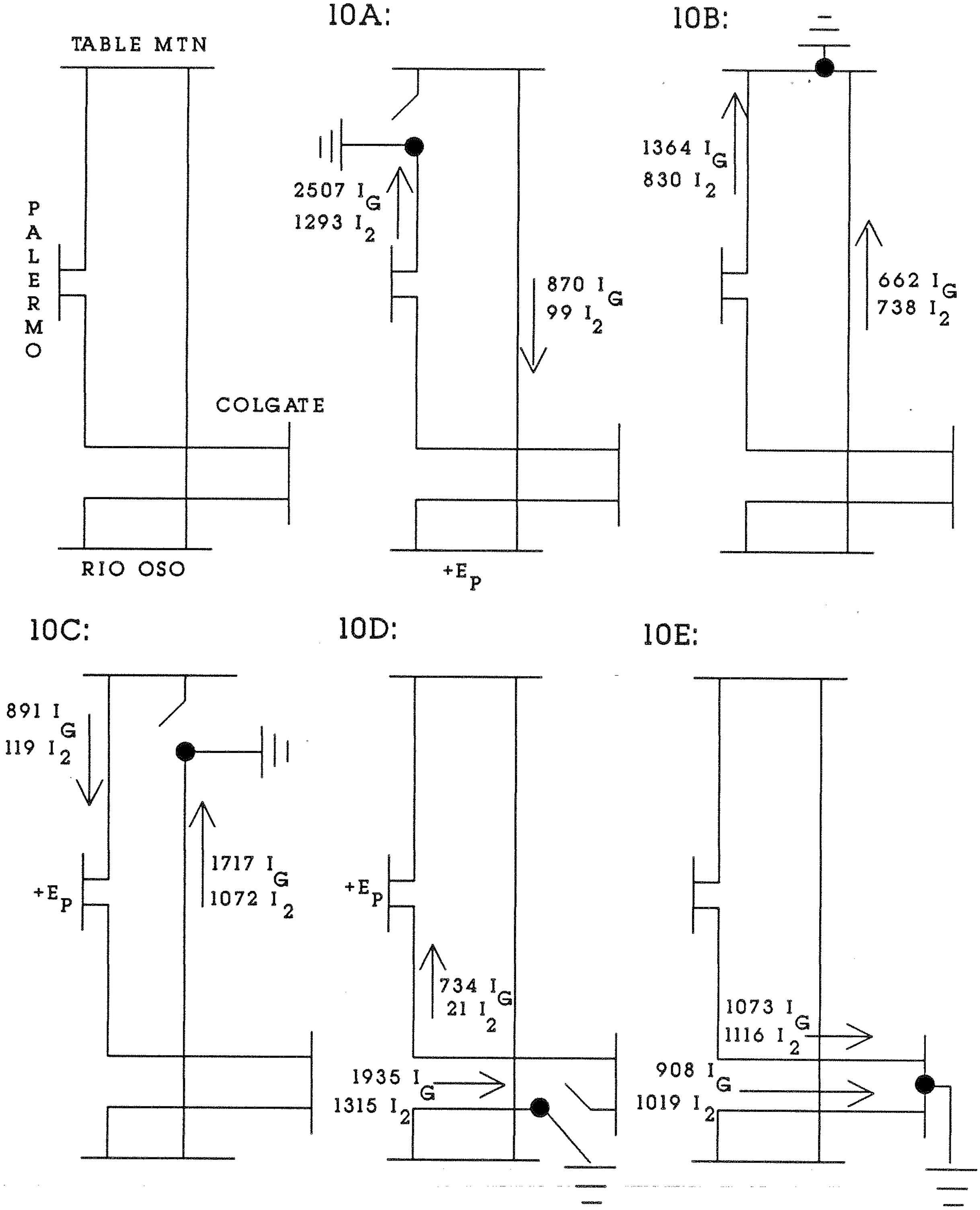


FIG 10: DOUBLE-PHASE-TO-GROUND FAULTS