Analysis of Recordings at Consumers Energy

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## Abstract

It is the intent of this paper to display some interesting and challenging fault records and discuss what happened and why, while keeping the discussion interesting for those with minimal experience analyzing system disturbances. This will be accomplished by starting with basic faults and continuing to build knowledge while progressing to more complex faults. These fault records are from various substations on the Consumers Energy High Voltage Distribution and Michigan Electric Transmission Company (METC), LLC Transmission system(s) and for the most part a fault record from a single exit will be used; when supporting fault records are needed, they will also be used. The first part of this paper will cover single breaker line exits and the associated fault record then breaker-and-a-half line exits will be covered.


## Introduction

The ability to read and understand a fault record is the basis for good system analysis. Once the fault record is deciphered, and the relationships between all the currents and voltages are understood (such as magnitude, phase angle, direction of flow etc.) the underlying cause of the fault and what caused the currents and voltages to behave as they did needs to be determined. Many times, this is straightforward because information from the field about the fault cause, system configuration, etc. is available, the fault record is also straightforward or the observed conditions are familiar from previous experience.

Sometimes, though, fault records are extremely difficult to decipher. Texts and other information on fault analysis, if available, are rare. Also the degree of difficulty in understanding these fault records is inversely proportional to the amount of experience that one has in reading these records. When the fault record is difficult to read the reasoning behind why the currents behaved as they did may be not be able to be definitively determined, but instead must be evaluated for plausible explanations. Additional data may need to be gathered, past fault records of similar events may need to be reviewed or you may need to plead your “plausible cause” case to coworkers because there might be something you have overlooked. Or, as often is the case, there is something about the event that you haven’t learned yet or don’t understand.

Such is the case for some of the fault records at the end of this paper. Current magnitudes and directions are exactly known. A plausible cause has been determined and the author needs to plead his case among peers. Hopefully in this process we all may learn more about analyzing fault records.

## Single Breaker Scheme

The first part of the discussion will include faults on single breaker exits. All digital records are from either a digital fault recorder (DFR) or a digital relay.

For the single breaker line exit where there is a DFR, the monitored current channels will consist of one of the following; a single phase and the residual, two phases and a residual or (rarely) all three phase and the residual. If two phases and a residual are monitored, the unmonitored phase is calculated by the analysis software from the available records. If the record is from a digital relay, three phases are monitored and the residual is calculated within the relay. (See FIGURE A.)

When CT secondary current circuits are displayed the currents will be shown on the illustrations in primary amps. Although all records are discussed in terms of A, B and C phases, all DFR records use X, Y and Z for the phases. The reader will have to make a mental translation when reading the DFR records. Additionally the residual current is often called ground current (IG), neutral current (IN) or residual current (IR). This current is referred to as residual current regardless of the descriptor on the relay or the DFR. All currents on the DFR and relay records are scaled to be readable and may not be relative to each other.

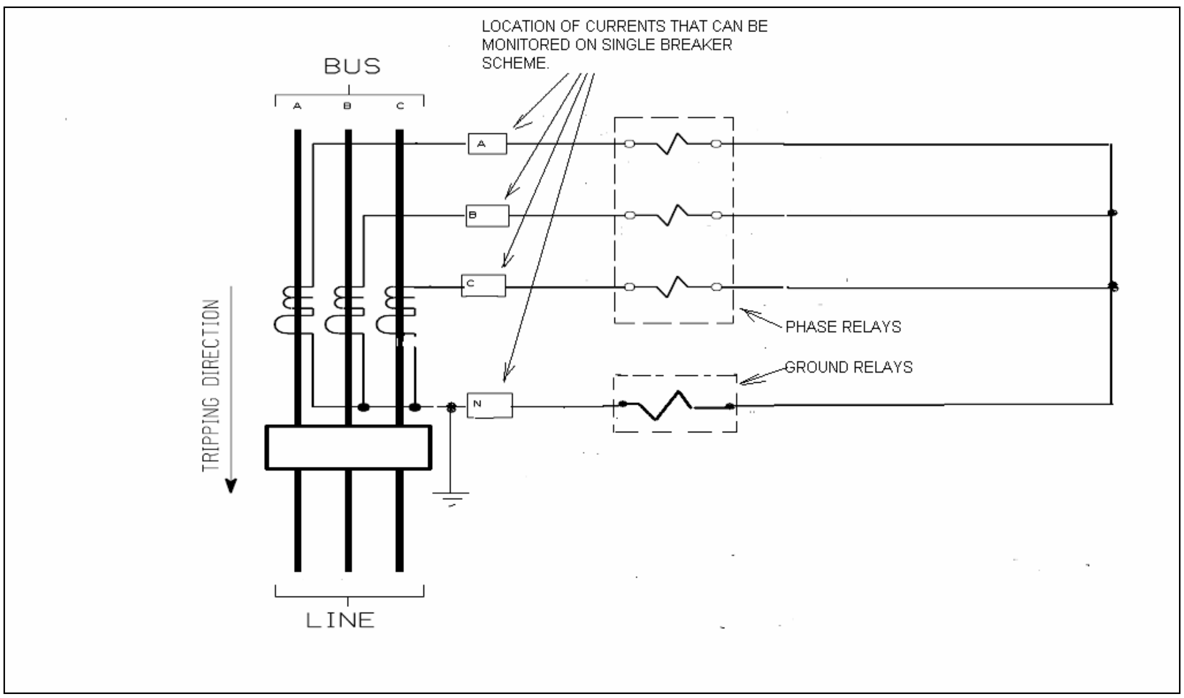


Figure A

## Breaker-and-a-Half Scheme

While the faults and fault records for the single breaker line exits are reviewed, experience is developed in recognizing the relationships between the residual and the faulted phase(s) in the single breaker schemes. Knowledge of this relationship will help in understanding the fault records when the breaker-and-a-half line exits are reviewed because the totalized currents and many times only a single phase and the residual of the middle breaker may be monitored. If the fault isn't on the same phase that is monitored on the middle breaker then the totalized currents and the residual of the middle breaker may be all that's available.

The secondary currents in the boxes are typical of what will be monitored on the breaker and a half scheme (figure B). Two totalized phases and the totalized residual, plus a single phase and the residual of the middle breaker are usually monitored. As previously mentioned, the residual of the bus side breaker may be monitored. Sometimes, a single phase of the bus side breaker may even be monitored.

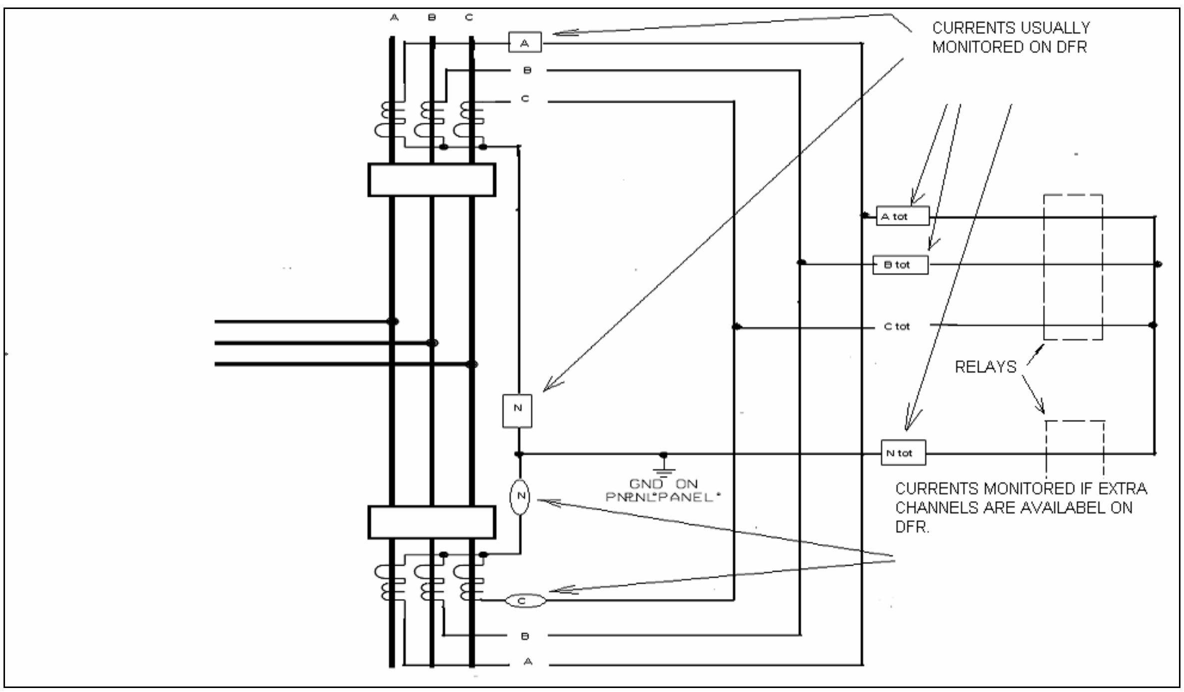


Figure B.

EXAMPLE FAULT #1

The following record (Figure 1-1) is from a single breaker line exit scheme. A single line-to-ground fault occurred on the A phase of this line due to a faulty insulator. The remote terminal breaker opened first as indicated. Next, the 388 GCB attempted to clear the fault but only opened its B and C phase poles. The line fault continued until the breaker faulted internally.

This record contains all the information needed to determine that there was a single line-to-ground fault on the line and that the A phase pole of the line breaker failed to open. This record will now be examined more closely to gain the experience needed to read and understand the more complex faults later in the paper.

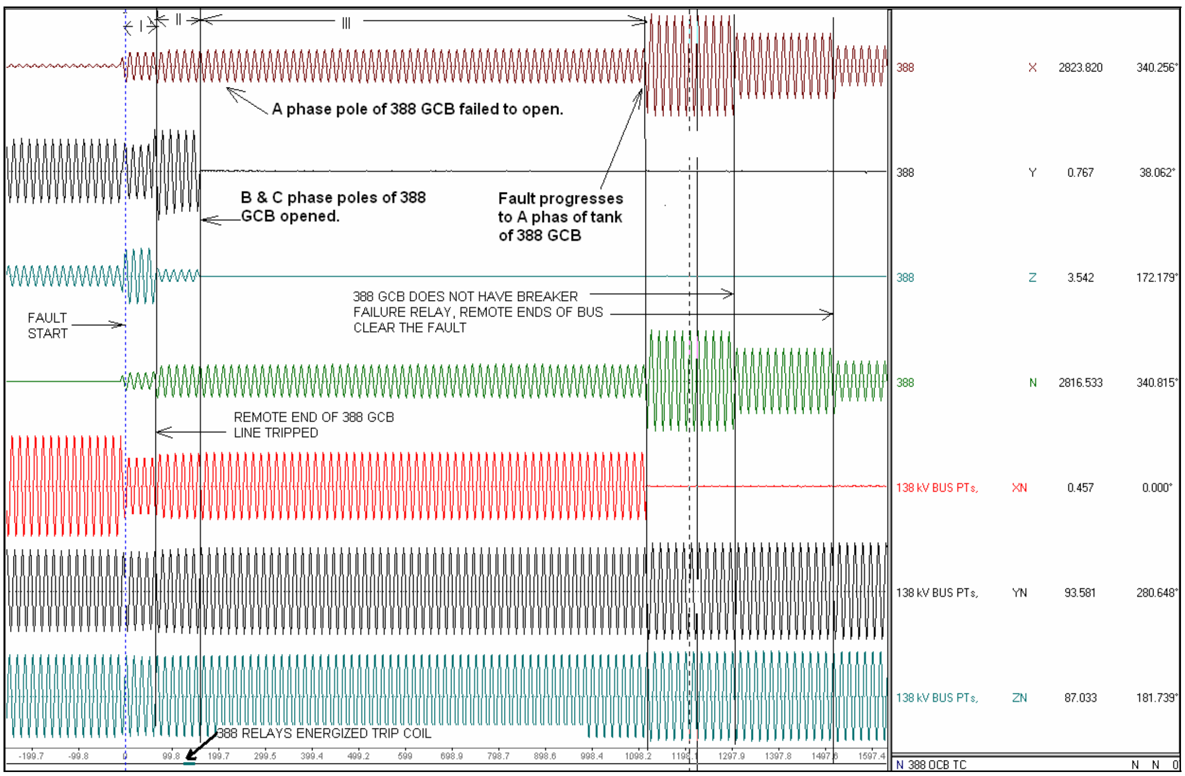

Figure 1-1

Figure 1-1 is broken down into three parts that are to be examined: "I", the initial part of the fault until the breaker at the remote terminal of this line opened. "II", the second part of the fault after remote breaker opened until the local (388 GCB line) breaker tripped and opened its B and C phase poles. "III", the AG fault continuing on the line until the A phase of the breaker tank is shorted to ground in the tank.

## "I" (INITIAL) PART OF FAULT

Figure 1-2 represents an ac schematic for the primary and secondary current circuits. This is the beginning of the fault and the remote terminal breaker of this line is closed as indicated. This first part of the fault has currents in both B and C phases in addition to the current in the faulted A phase.

To get a feel for the relationship between the faulted phase and the neutral current the following test can be quickly performed. The fault is on A phase and the currents in the un-faulted phases B & C shift as the fault ensues and are close to 180° out of phase with the faulted phase. They aren't exactly 180° out but because they are close to 180° a good estimate of the residual currents can be made by just summing the currents and ignoring the phase angle. Ir = Ia + Ib + Ic or Ir = 876 + (-95) + (-326) then Ir = 455. Because Ib and Ic were assumed to be 180º out of phase this is the lowest the residual current can possibly be. It is known that the currents were 215° and 190° out of phase, so the residual is actually slightly higher than the estimated 455 amperes. From Figure 1-2 it can be seen that Ir = 485 amperes.

In this case the residual equals only 55% of the faulted phase. This is typical of a fault where the relaying is looking into the stronger source but it wouldn't be considered a typical fault for all single line-to-ground faults on this system. For a good portion of single line-to-ground faults on this system, it is estimated that the residual is equal to 85-95% of the faulted phase. The residual can also be higher than the faulted phase. In Figure 2-2 the residual is slightly higher than the faulted phase and in Figure 6-2 the residual is 120% of the faulted phase.

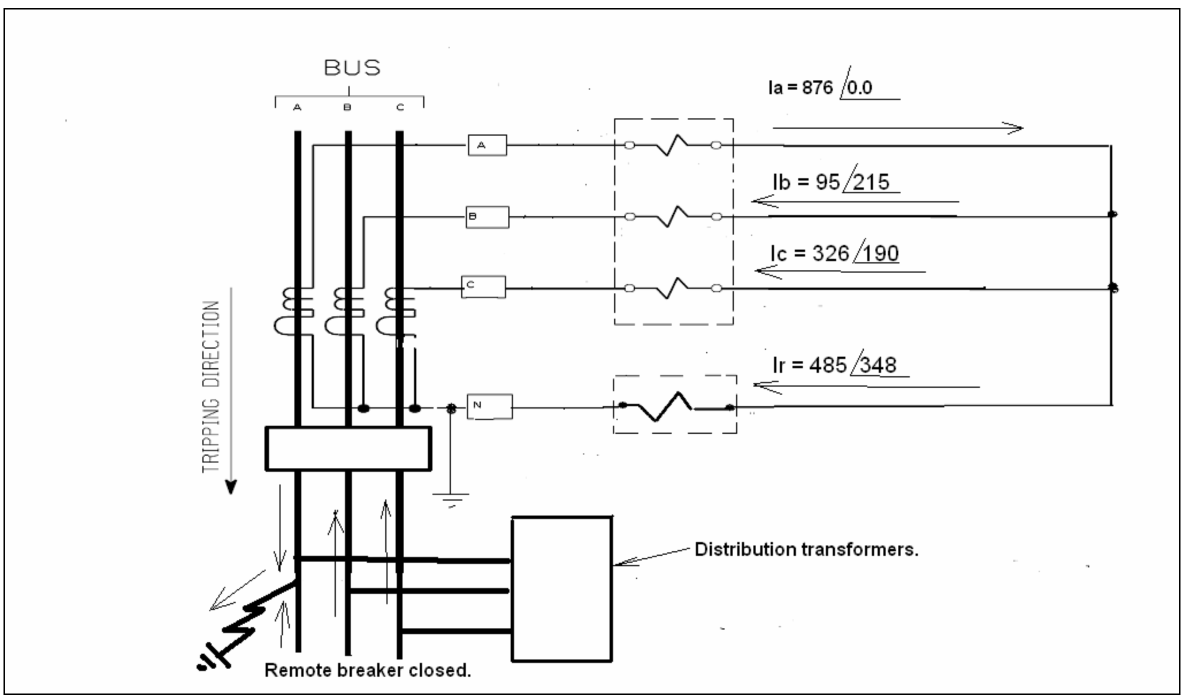


Figure 1-2

Understanding these relationships is important in learning the art of visually inspecting any fault record, but it is even more vital in order to analyze the individual currents in the breaker and a half line exit scheme due to the limited amount of data recorded for the individual breakers.

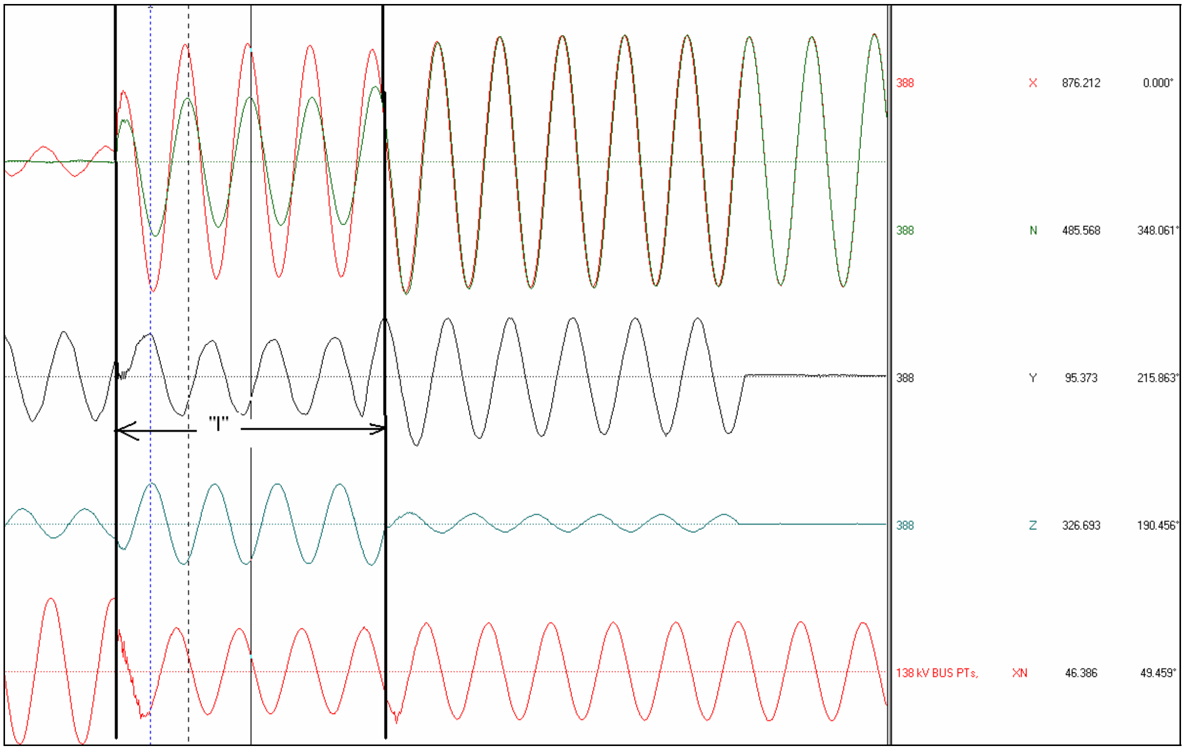

Figure 1-3

The faulted A phase currents (Ia) and the residual current (Ir) in Figure 1-3 are superimposed to get a better understanding of the relationships between the faulted phase and the residual current.

<u>"II" PART OF FAULT</u>

In this portion of the fault record labeled "II", the remote terminal of this line has opened. Now it can be seen that the currents in the un-faulted phases B and C shift around again. There is enough current in these un-faulted phases to affect the magnitude of the residual because there are two delta high side-grounded wye low side distribution transformers tapped on this line.

Figure 1-4 shows the magnitude and the phase angles of the currents in the 388 GCB after the remote terminal of the line opened. In the first part of this fault, the residual was estimated by looking at the secondary schematic and viewing the current magnitudes and angles. However, assume there has just been a severe lightning storm that tripped 56 lines on the system and all the associated fault records need to be reviewed. Drawing a schematic is essential for this paper but in the real world one needs to look at the fault record and process information quickly, so we will now review the fault record and determine the relationship between the faulted phase and the residual from that review alone (Figure 1-5).

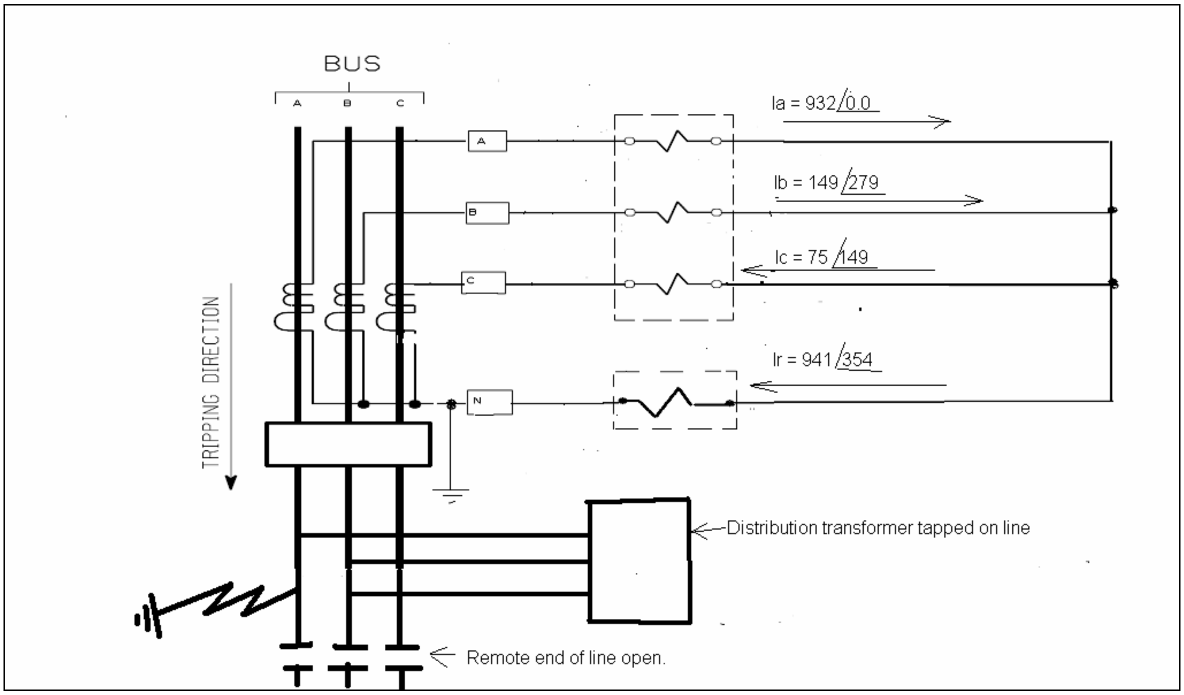


Figure 1-4

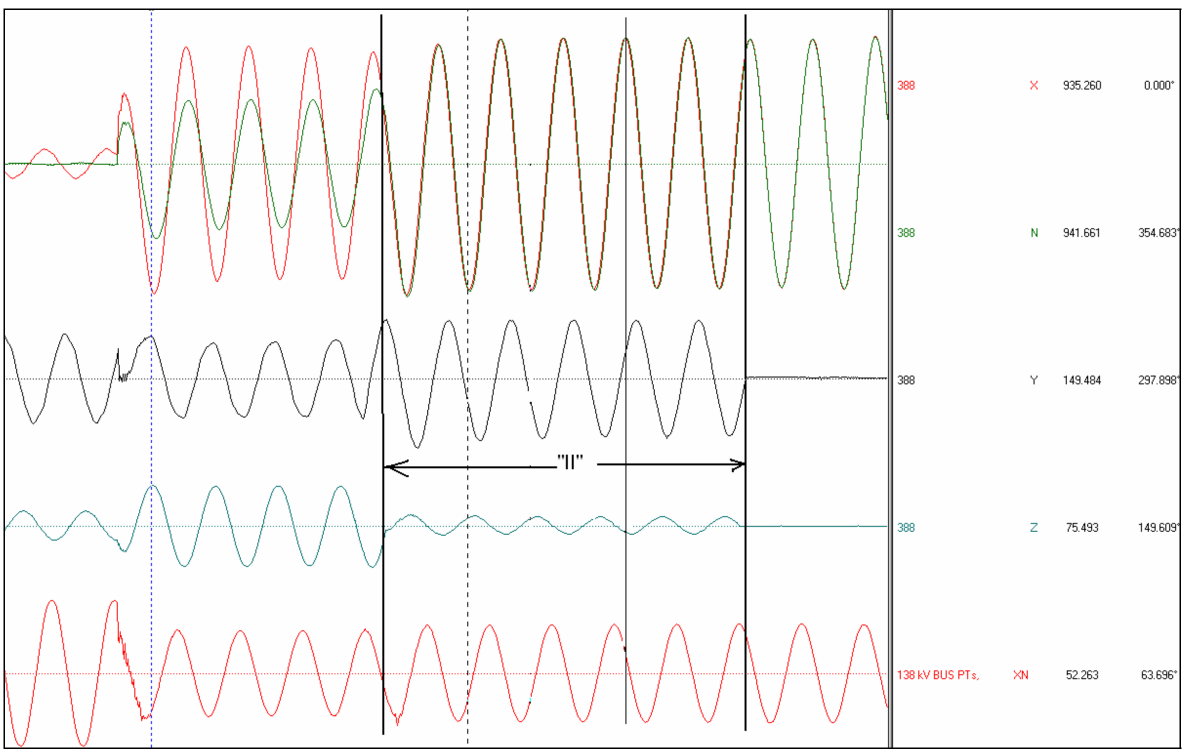


Figure 1-5

The faulted A phase and the residual are superimposed and the difference between the two is small but noticeable. To estimate the residual look at the line running through the peak of the superimposed Ia and Ir. Drop from the peak to Ib and notice that Ib is not in phase but it is in the positive direction as well. When compared to the Ia and Ir peaks the current Ib is about half way to peak of 149 amperes. A good estimation, then, is that 75 amperes needs to be added to Ia. Inspect Ic and note that at a max Ia, it is about 80% of its own (Ic) peak value and it isn't quite 180° out of phase with Ia. Therefore Ic is equal to 80% of -75 amperes at Ia peak or -60 amperes. If Ir = Ia + Ib + Ic or Ir = 935 + 75 – 60, then Ir = approximately 950 amperes. It is known that Ir = 941 amperes, so all looks good with the currents. If instantaneous RMS was available on the analysis program this estimation could be faster. Once one has enough experience, just a glance at the waveforms and magnitude is sufficient to determine approximate phase angles of the phase currents and the magnitude of the missing phase or residual.

Again the point of this exercise is to get a feel for the relationship between the faulted phase and the residual.

"III" PART OF FAULT

Now that both the remote terminal of this line as well as the B and C phases of the 388 GCB are open, the distribution transformers are no longer a factor. There is no current in either the B or the C phases; hence, Ir =Ia. This can easily be seen on both the secondary schematic (Figure 1-6) and the fault record (Figure 1-7). The slight differences are probably DFR calibration errors for the magnitude and differences in the DFR components for the phase angle.

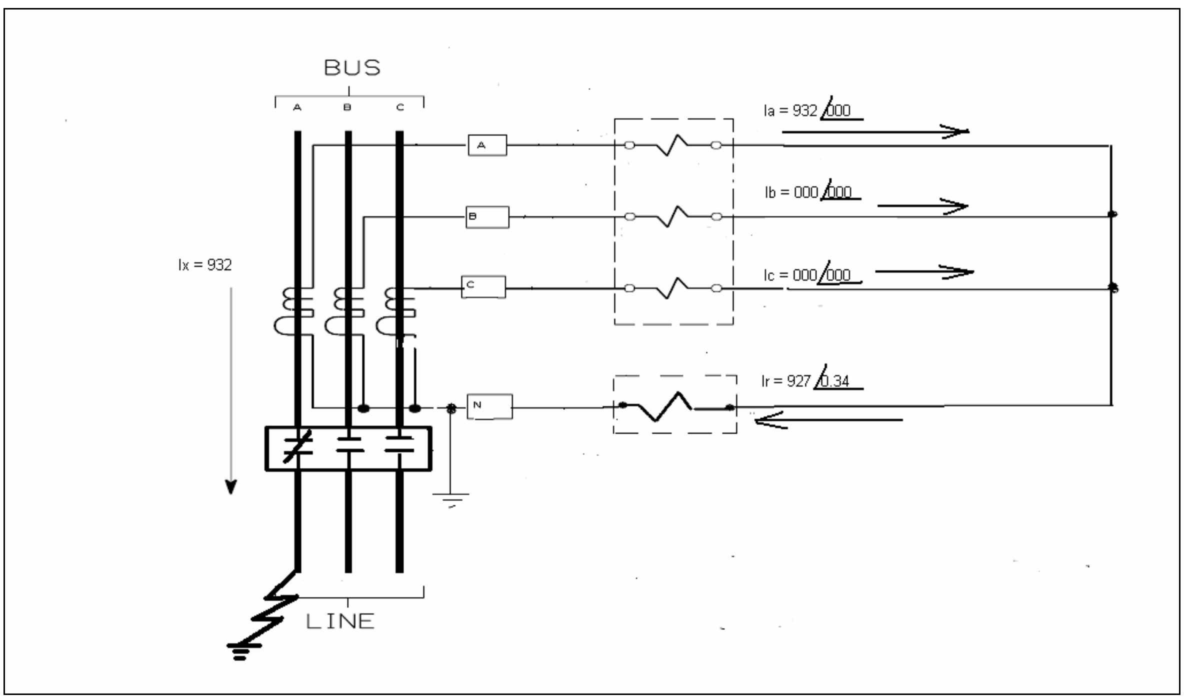


Figure 1-6

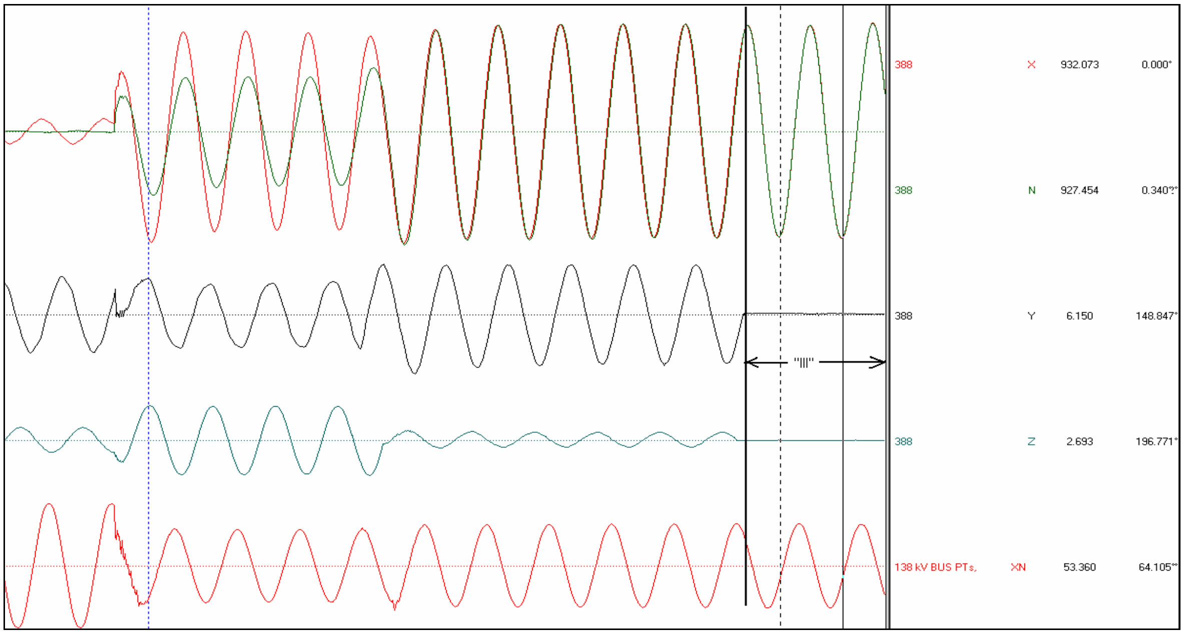

Figure 1-7

Part "III" of this fault is the simplest of circuits, but it is extremely important to recognize this relationship between faulted phase and residual because it will be the basis for understanding the fault records when the breaker-and-a-half scheme are discussed, again because of the limited data available.

The "III" part of this record could also be considered the long version of Ir=Ia (or Ir=$I_{\text{faulted phase}}$). The short version can be seen in the latter half of the "neutral kick" every time a breaker is opened on a balanced three phase load or a three phase fault. See figure 1-8.

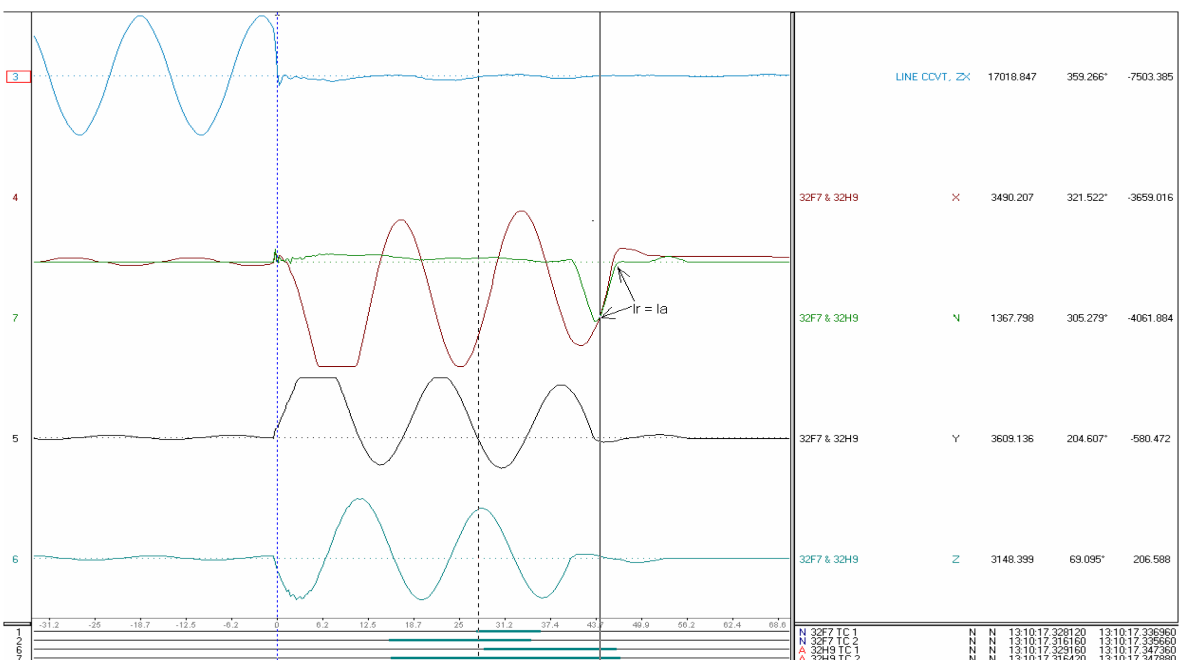

Figure 1-8

Figure 1-8 is a three phase fault on a line close to the station (the CA voltage is quite low during the fault). The C phase pole opened first as it crossed zero at which point Ic is almost equal to zero but not quite because of the breaker opening resistor. Now Ir = Ia + Ib + ≈0 and the resulting residual current can be seen rising from the zero crossing until the B phase pole is opened. Once the B phase pole is opened at zero crossing Ir = Ia + ≈0 + ≈0. Ia and Ir are superimposed to get a visual that Ir = Ia. Since this phenomenon lasts less than 1 cycle the RMS values displayed to the right of the traces in Figure 1-8 are not accurate. One has to look to the instantaneous values all the way to the right in the third column. Ia = -3,659 and Ir = -4,061. Again these values are not equal in this example because there is a small amount of current still in B and C phases because of breaker opening resistors.

EXAMPLE FAULT #2

In this example a single line to ground fault (BG) on an 85 mile 138 kV line was recorded at the exit at a generating plant. The CT ratio is 500/5 (or 100/1) and the fault is about 2 miles out on the line. This relay record (Figure 2-1) is filtered data from a 4 sample/cycle digital relay.

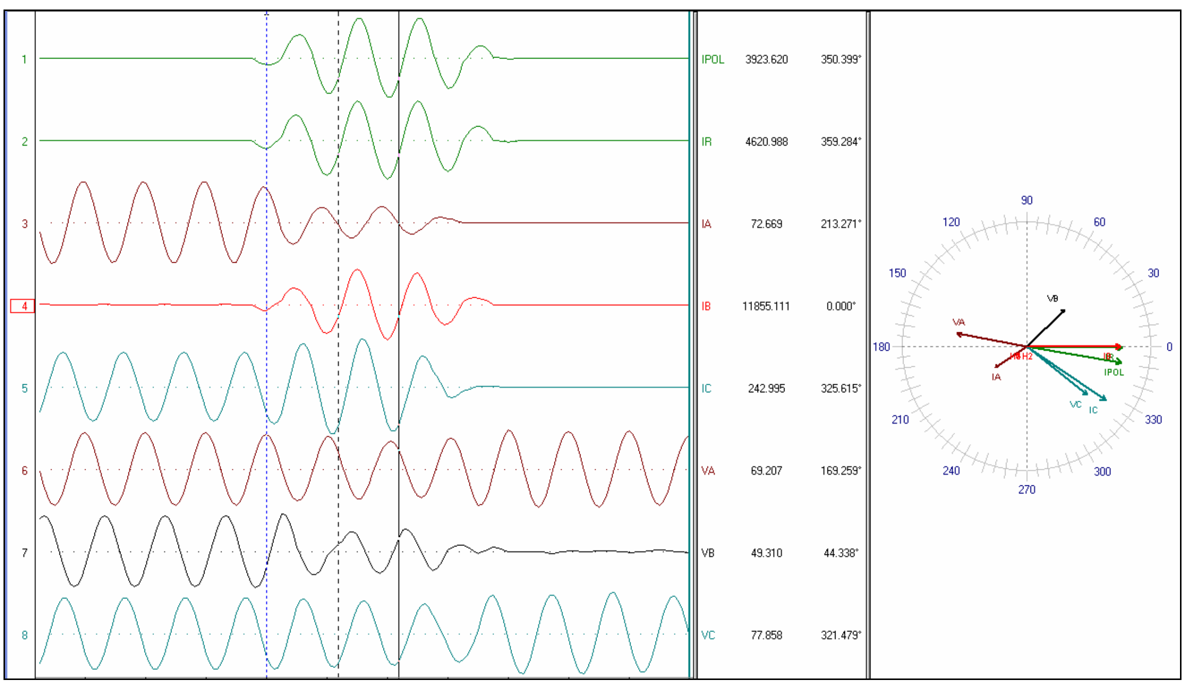


Figure 2-1

Examine this record using what was learned from the first example. The B phase voltage is sagged and B phase current is high, indicating a B phase to ground fault.

In Figure 2-1 the C phase currents aligns closely to the faulted phase (35° off) and A phase shifted toward the 180° out of phase position (33° off). Again since Ir=Ia + Ib + Ic then visually we can see that Ir is probably going to be close to if not slightly higher than Ib (the faulted phase). However, you will notice that Ir is disproportionately less than Ib (the faulted phase). Something is not correct with this record.

This digital relay record includes all three phase currents, so Ir will be calculated using the analysis software and Ir (calc) and will be displayed with the other waveforms. The program allows the equation Ir = Ia + Ib + Ic to be quickly programmed (See Figure 2-2 below.)

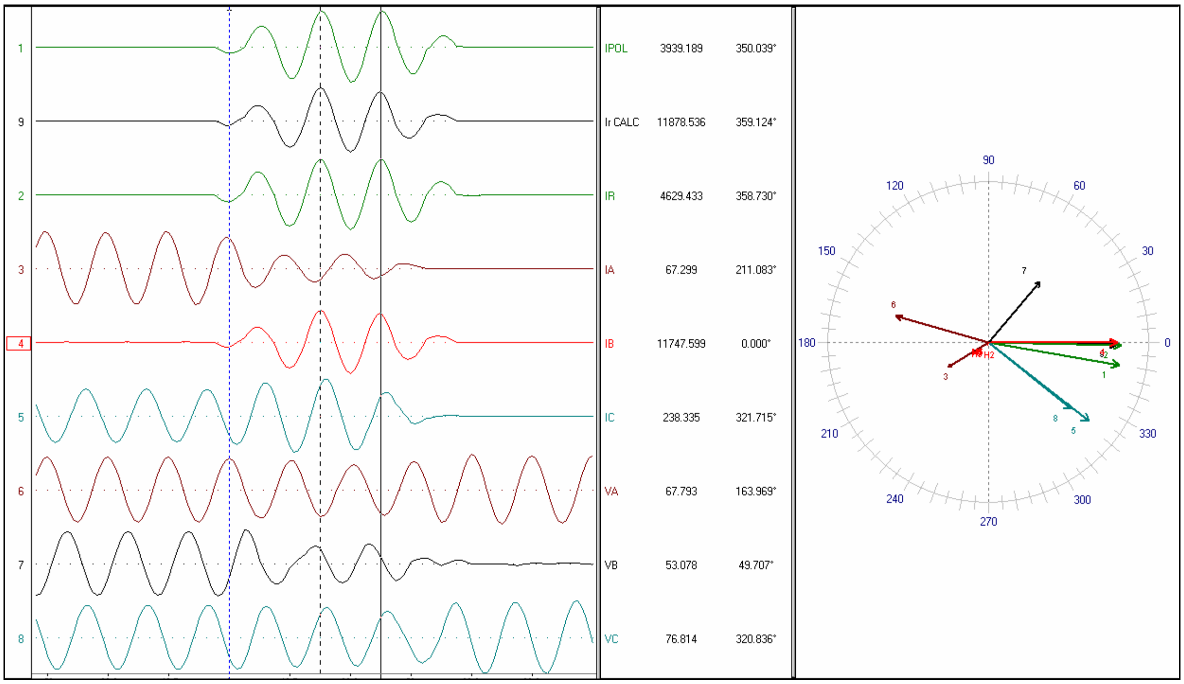

Figure 2-2

When examined, this record shows that when Ir was calculated, it is what would be expected, Ir is slightly higher than Ib. The Analog to Digital (A/D) converter in the relay saturated and Ir was incorrect.

It is usually a good idea to look at currents and voltages from line or transformer exits behind the relay to verify that the signature of the fault is the same from both locations. If it's not, the data should be reviewed further to determine why. Digital fault recorders are great for looking at data behind the line exit being analyzed, primarily because all the data is displayed on one graph and can quickly be digested.

Luckily, a digital fault recorder at this same station is monitoring some analog quantities, so an easy comparison can be made (see Figure 2-3 below).

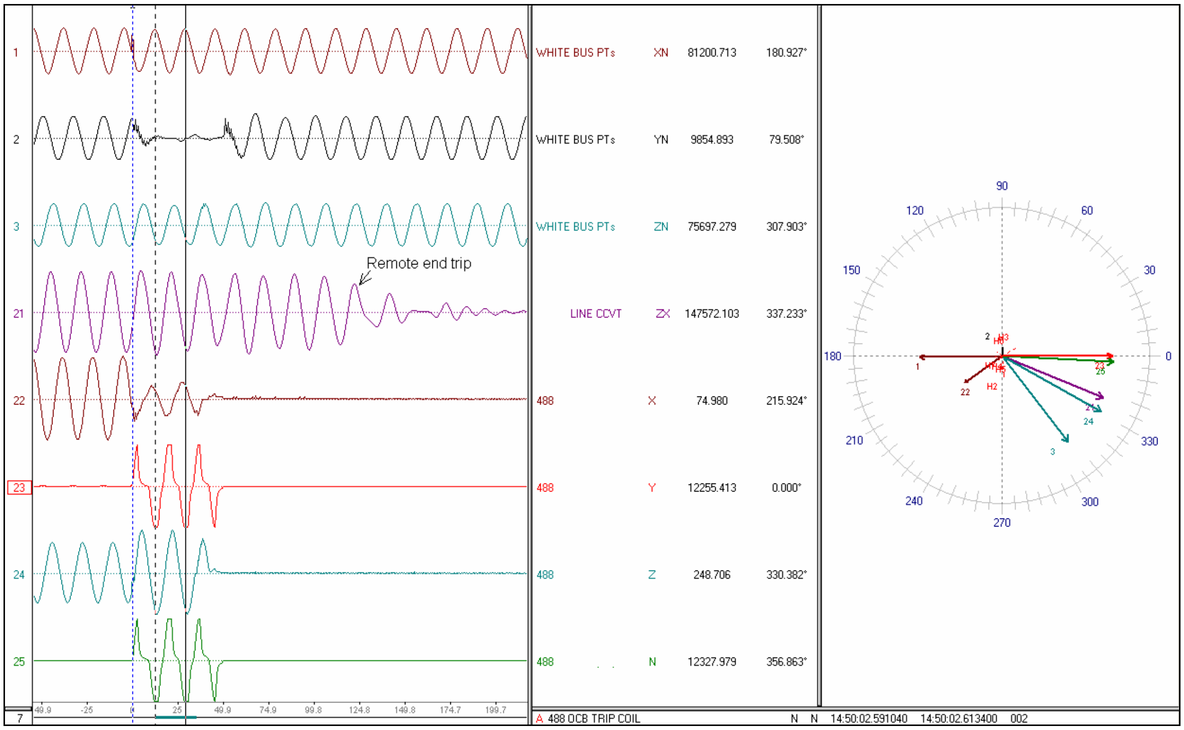


Figure 2-3

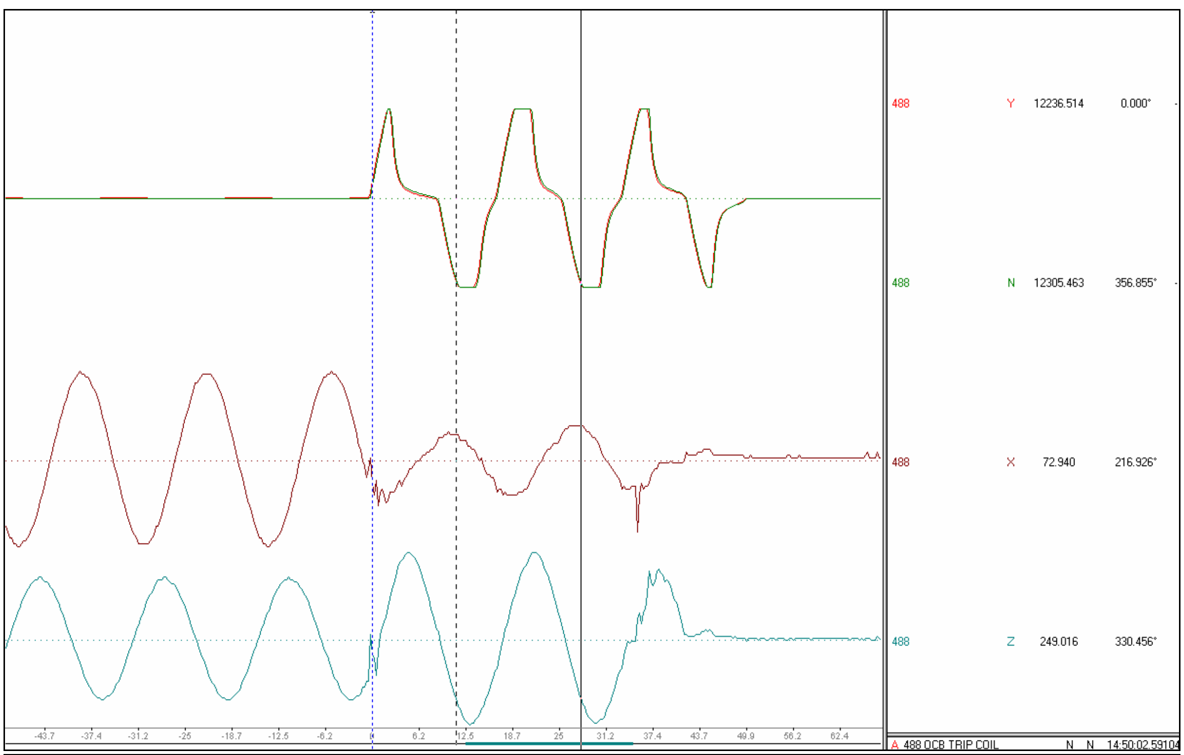


Figure 2-4

From figure 2-3 and 2-4 it can be seen that the Ib is saturated. Ib and Ir are superimposed in figure 2-4. This station has over 20,000 amps fault current available and employs a 500/5 CT ratio. For faults at the station, the CT is trying to produce 200 amperes secondary current. This fault is close to the station and the CT is trying to produce about 125 amperes. When this record is viewed it is an easy call to say that this B phase is saturated because it is expected to saturate.

Also the B phase on this record shows clipping. We don't calibrate the DFR for 200 amperes because the CT should not be able to produce 200 amperes. So these channels are calibrated for 123 amperes CT secondary current. Because the B phase current is both saturated in both the DFR and digital relay and clipped by the A/D converter in the DFR, the total reported by both those devices is suspect. All total incoming residual currents can be added together and displayed using the analysis software.

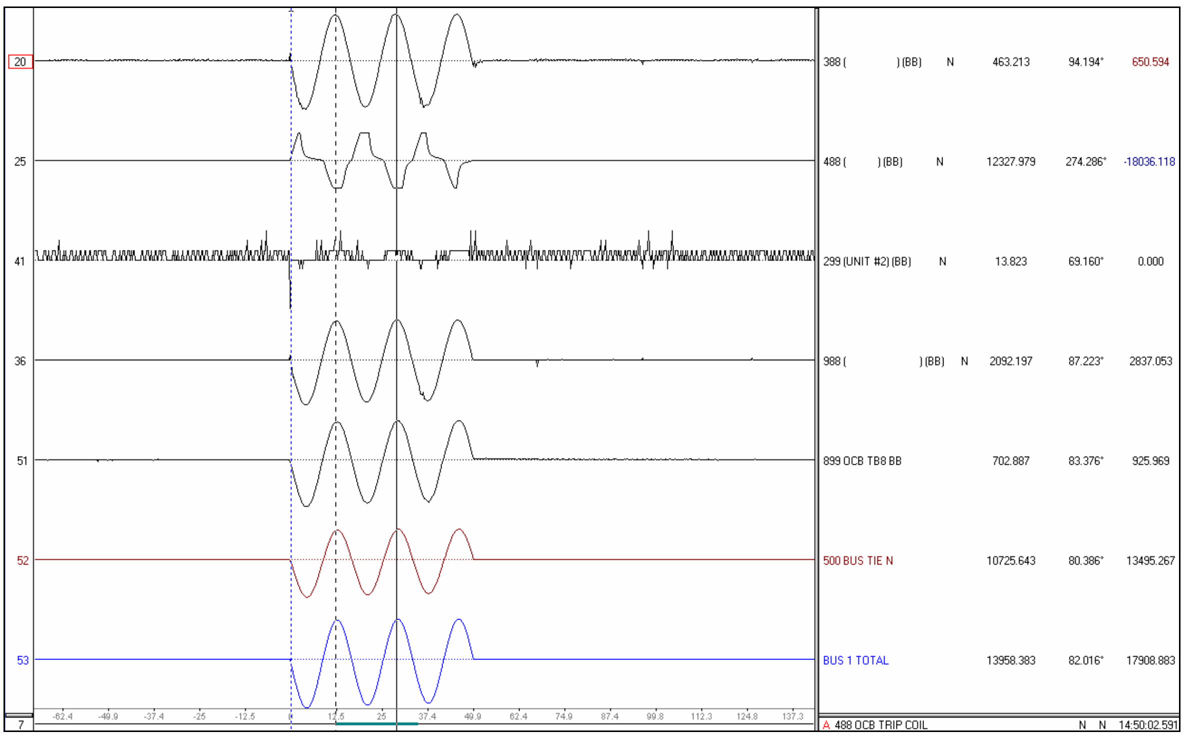


Figure 2-5

In Figure 2-5 all the incoming residual currents entering the bus were totaled to calculate the exiting residual currents on the line. This total fault current (BUS 1 TOTAL) is 13,958 amperes. Not all of the incoming B phase currents are monitored so the total B phase current is not available. However, if all incoming lines had either the B phase current or the A phase, C phase and residual currents monitored then the B phase current could be measured or calculated to get the total incoming B phase current. Unfortunately the two 138 to 46 kV transformers at this station have only 1 phase and the residual monitored. Another alternative to calculating the total incoming B phase current would be to total all incoming residual currents, flip the data 180° and subtract that value ( –Ir total incoming) from Ia and Ic of the line exit to calculate Ib. Based on what has been discussed thus far, Ib is probably slightly less than the residual by 100 - 200 amperes.

This is also a good example of filtered data from a relay verses unfiltered data from either a relay or a DFR. The relay in this example didn't have unfiltered data available and, although it doesn't affect the relays performance, at times it can be misleading when trying to analyze faults. This is especially true during quarter and half cycle changes such as current reversals. It is important to know your data type and be mindful of the differences when analyzing any fault records.

<u>EXAMPLE FAULT #3</u>

This was the first fault recorded on this DFR. Not all the channels were wired because the installation was not complete. Only the channels that were previously monitored on the old oscillograph had been completed. This example also shows the importance of looking at additional relay records behind your line exit.

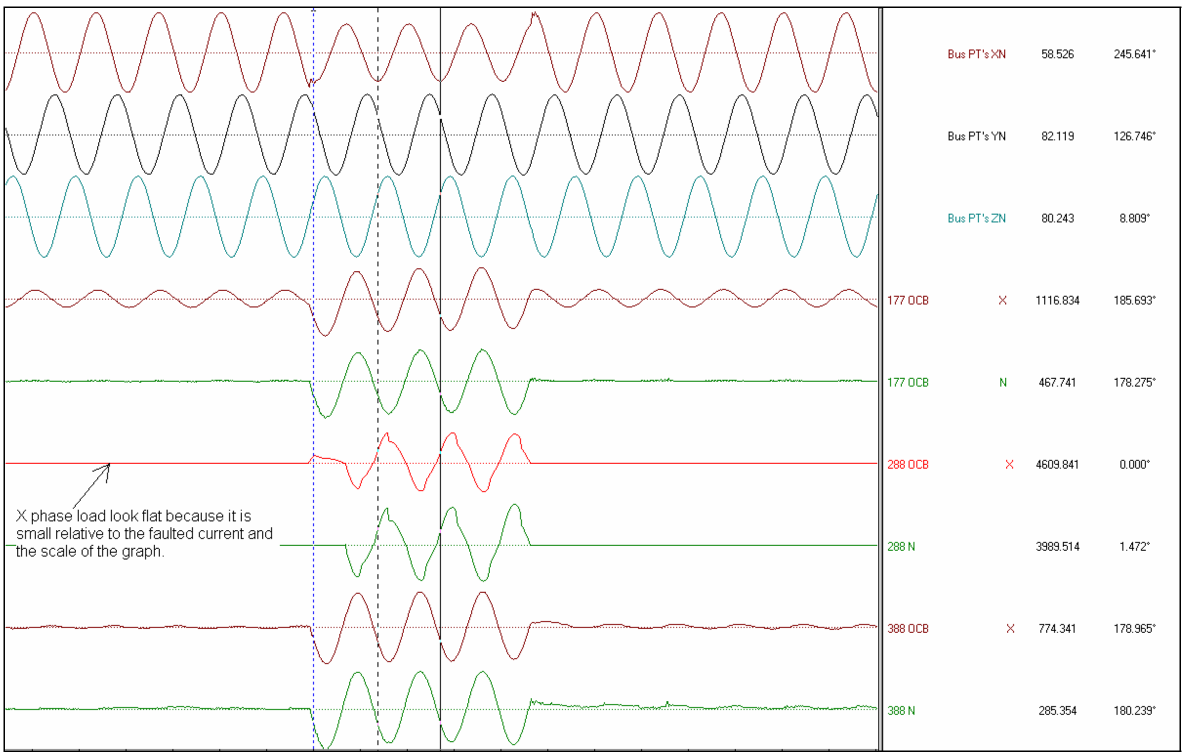

Figure 3-1

Looking at this digital record (Figure 3-1), the A phase and the residual current of 2 incoming lines (177 OCB and 388 OCB) are displayed along with the A phase and residual current of the faulted line exit (288 OCB). The A phase bus PT voltage is sagged and the B and C phase voltages don't show much change, indicating an A phase-to-ground fault. This fault is on the 288 OCB circuit and only A phase (Ia) and the residual (Ir) currents are monitored and displayed.

It initially appears that the observed current in the faulted A phase is affected by CT saturation. In the previous example it was easy to know it was saturation because the CT ratio was trying to produce over 100 amperes secondary current and saturation was expected. This circuit also has a 100/1 CT ratio but the CT is only trying to produce 46 amperes secondary. However, there is something even more disturbing about this record. Looking back at in example #2, Figure 2-5 it can be seen that all currents entering the bus look exactly like the current exiting the bus (with the exception of the magnitude and of course the saturation on the faulted exit). Figure 3-2 clearly shows that for the first half cycle the current in the faulted phase (Ia) of the 288 OCB is almost nonexistent and the residual current is zero for the first half cycle.

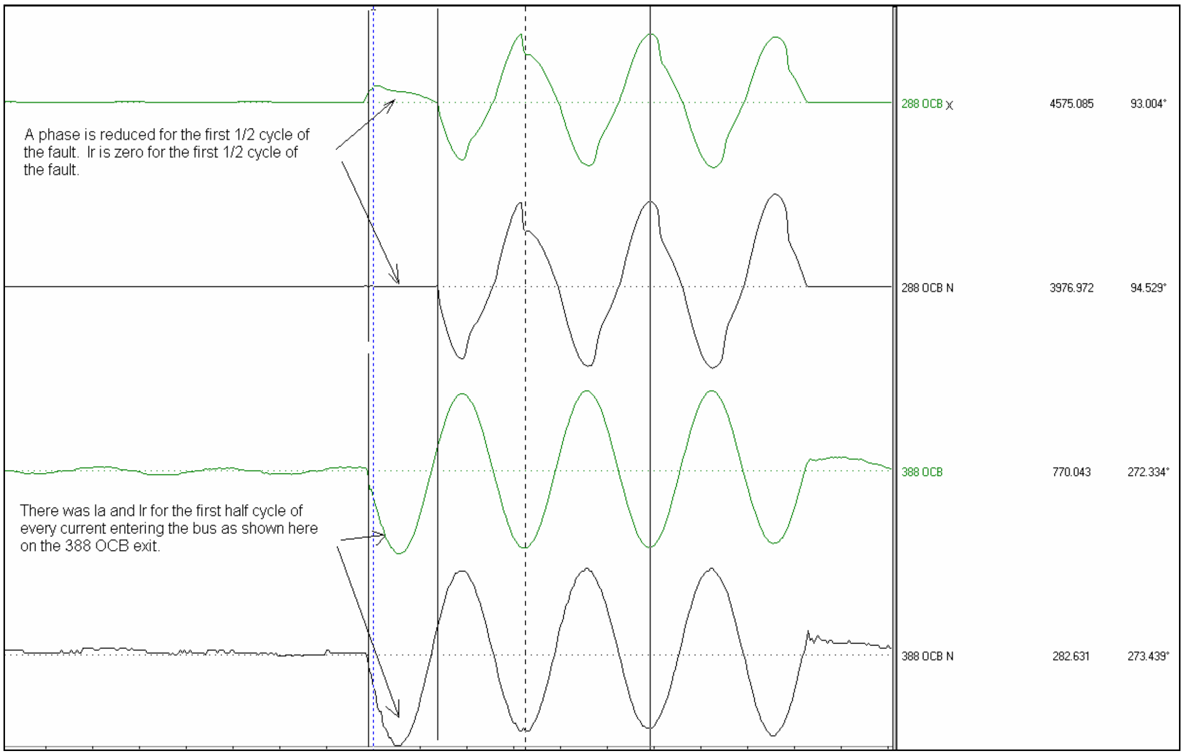

Figure 3-2

There certainly was current in the primary of the 288 OCB exit, as the fault was on that line. However, during the first half cycle, the exiting (288 OCB) A phase current doesn't look anything like the incoming (177 OCB or 388 OCB) A phase currents. From what was reviewed on the previous examples, Ir should be about in phase and reasonably close to the same magnitude as Ia, but Ir is zero for the first half cycle. An open link in the 388 backup relaying secondary circuit between the monitored A phase and where the phases are connected together to form the residual was found during a follow-up inspection. Figure 3-3 shows were the secondary current was flowing.

When the fault occurred there was enough voltage developed across the open secondary to flash somewhere between the A phase monitoring and ground for the first half cycle. After that, the presence of residual current shows that the open link arced over. Compared to the records reviewed thus far the relationship between the faulted phase and the residual looks in the ball park of what should be expected.

Note that this arc is now in series with the meters, relays, DFR, etc. and adds substantial burden to the CT circuit. This added burden from the arc resistance caused the CT to develop more secondary voltage then is expected for 46 amperes secondary current and caused the saturation. Since IR=V, the CT secondary voltage is also higher and this CT saturated at a lower current than would otherwise be expect.

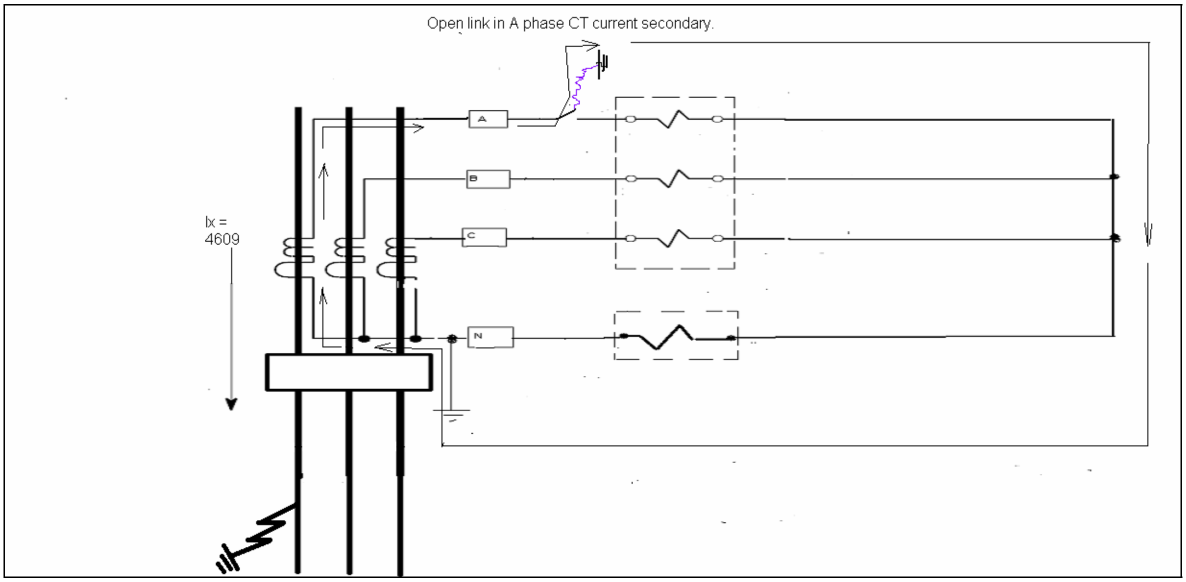


Figure 3-3.

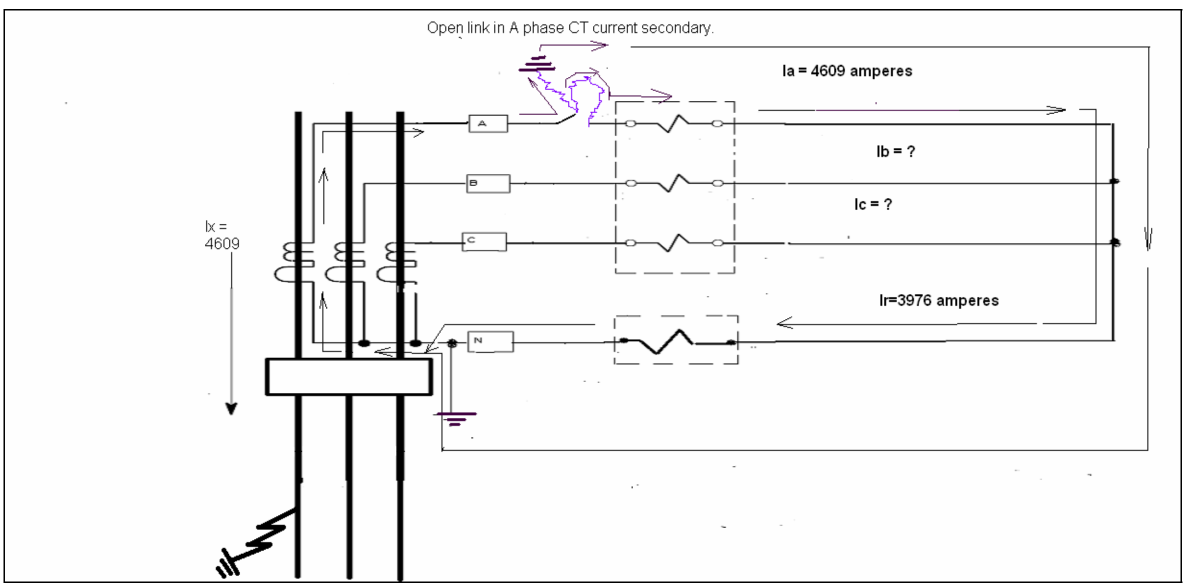


Figure 3-4

EXAMPLE FAULT #4

RELATIVE IMPEDANCE: When a short circuit model is built, line and transformer impedances are calculated and input into the program. Bus impedances are very low relative to the transformer and line impedances and are not modeled. This is because when added to the Thevenin impedance of a fault, they don't change the total fault current by any measurable significance. However, the following examples will explain why when analyzing faults, it helps to have an awareness of the relative impedance of buses, especially when parallel current paths are available around the bus in breaker and a half or ring bus schemes.

Figure 4-1 shows the voltage of a 138 kV bus during a single line-to-ground fault on that bus. The B phase voltage goes from 83 kV to 4.2 kV. The voltage at the point of any fault is zero and bus impedances are also zero, at least according to the short circuit model. However, buses do have impedance and the distance from the fault on the bus to the PT that is monitored has some impedance and this is reflected in the resultant voltage of 4.2 kV. Note the nice 60 hertz sine wave of the faulted BN voltage during the fault.

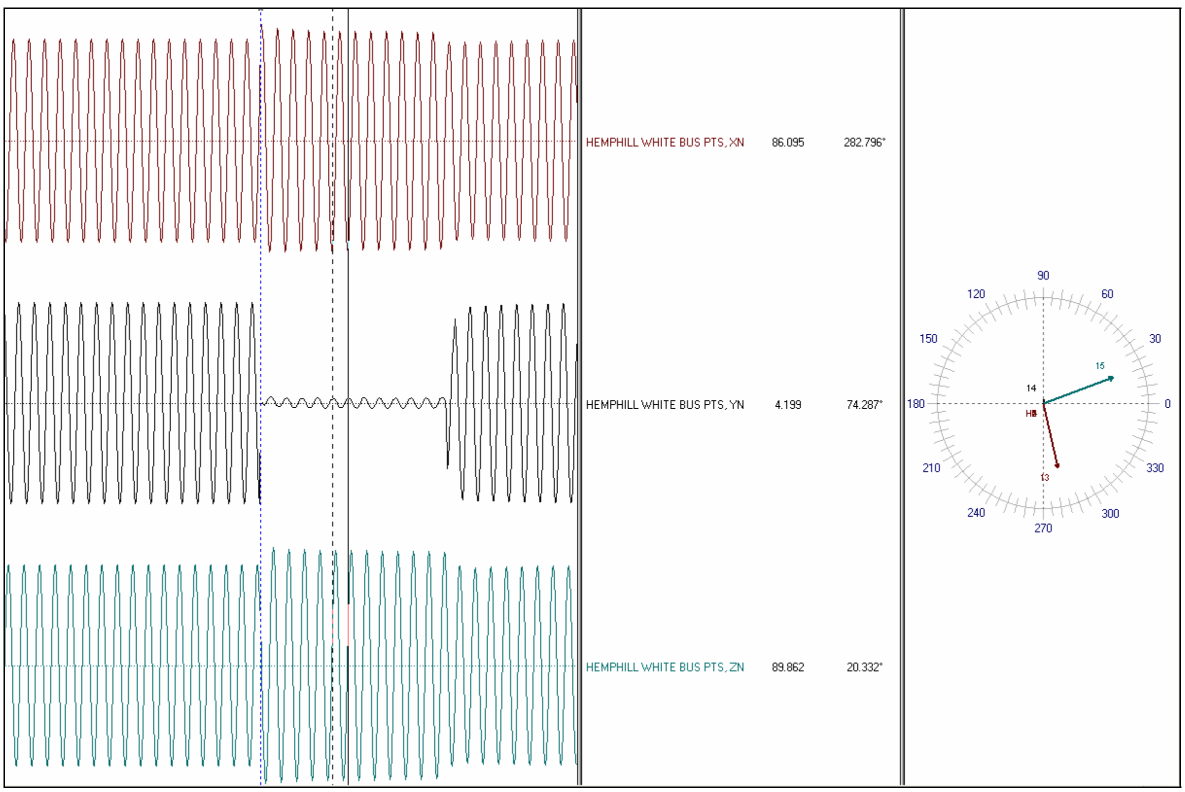


Figure 4-1

The one-line drawing in Figure 4-2 shows the fault location and the monitored PT.

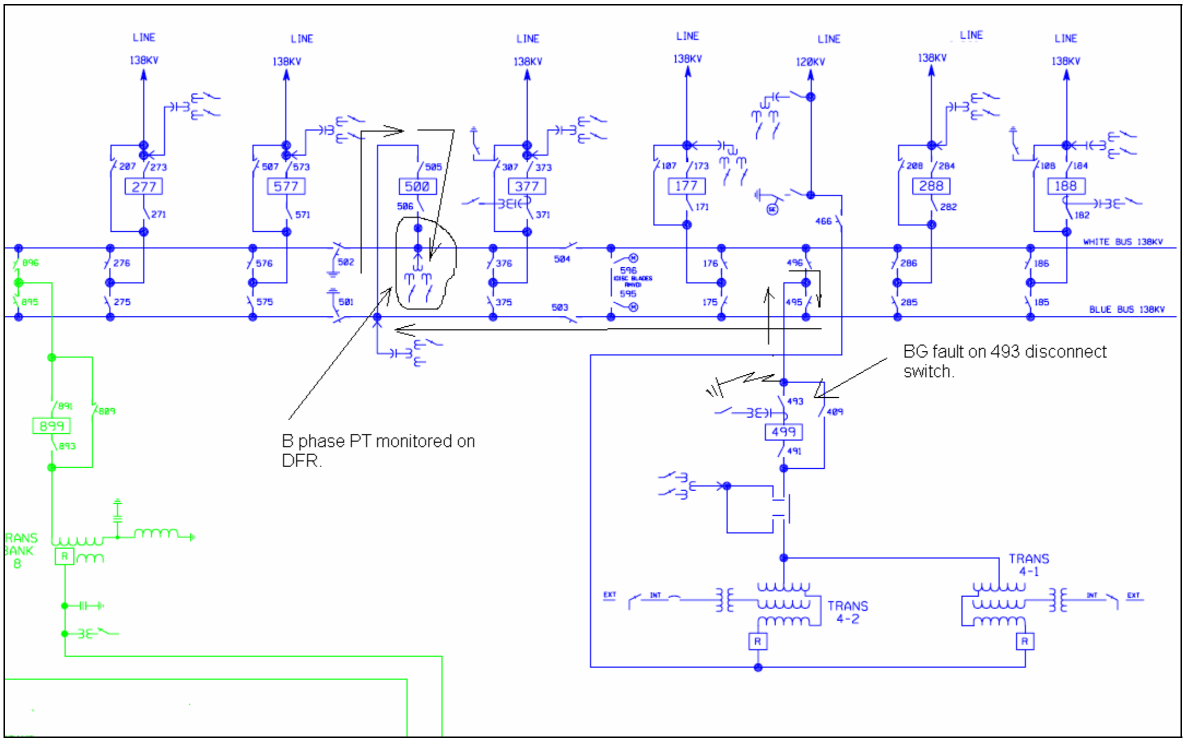


Figure 4-2

Figure 4-3 is also a 138 kV fault on the bus but the fault is very close to the monitored voltage source. Note that not only is the voltage lower than the previous fault but there isn't much of a sine wave.

When the operations department was looking for the fault location and this record was "casually reviewed", they were informed that the fault was very close to or right at the CCVT. The fault was found on the 9M6 disconnect switch just a few feet from the monitored CCVT.

Figure 4-4 shows the location of the 138 kV bus fault and the location of the 138 kV CCVT that is used to monitor the B phase voltage on the DFR.

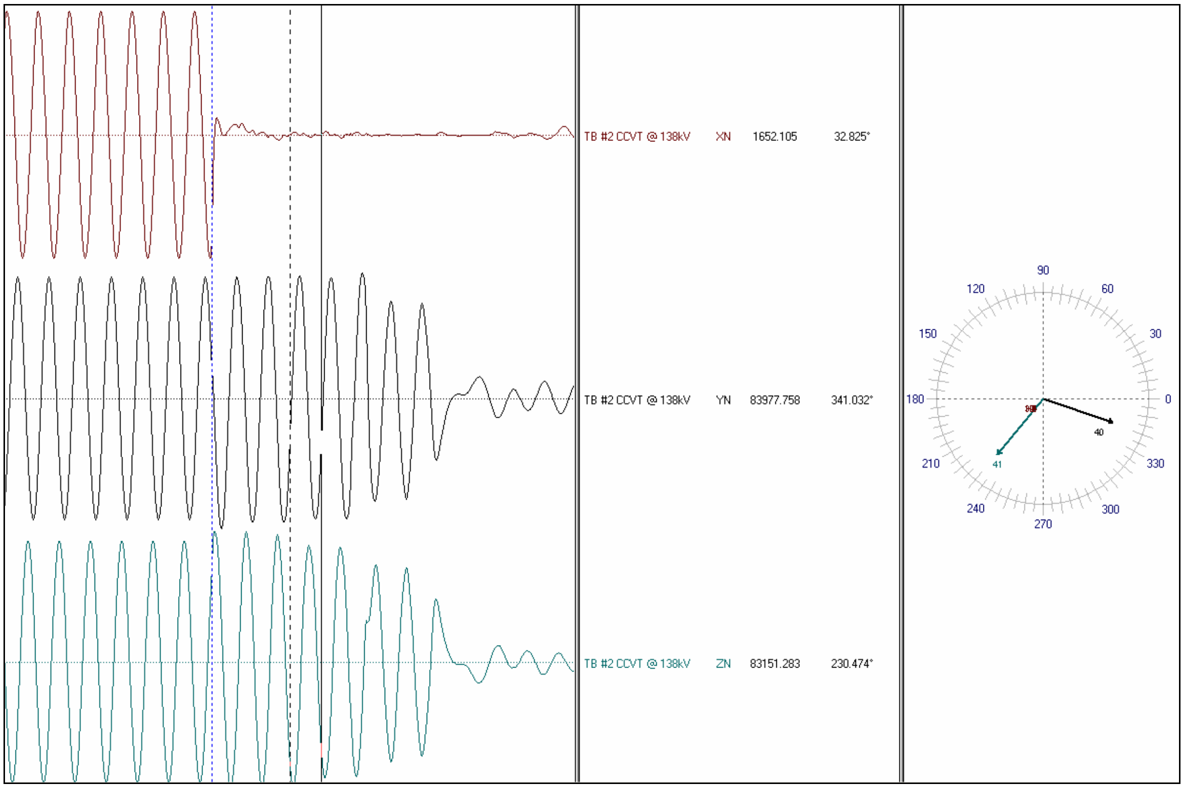


Figure 4-3

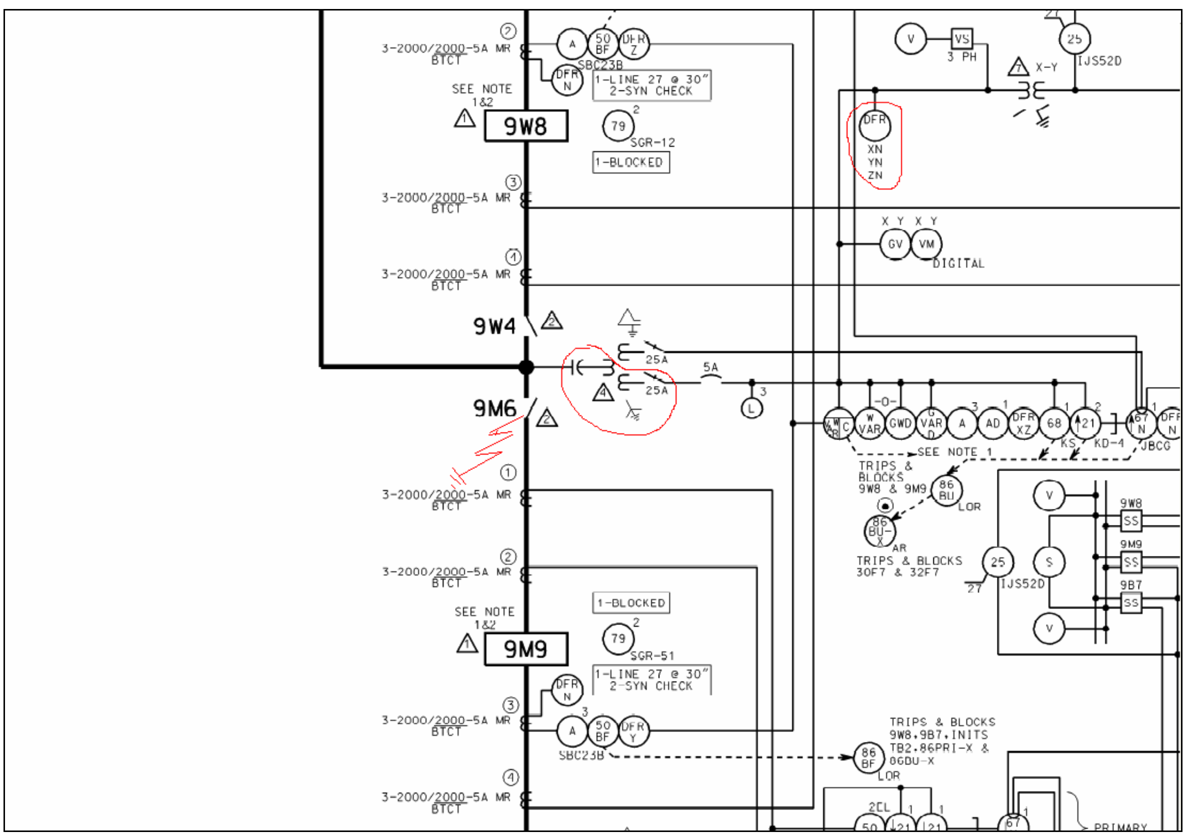


Figure 4-4

This next example of relative impedance is from a station that was built to accommodate a natural gas Independent Power Producer (IPP). Although built as a breaker and a half scheme the initial application is basically a ring bus. A 32 channel DFR did not have enough channels and the next available option was a 48 channel DFR. Since all 48 channels were going to be scanned and the data (with nothing on the unused channels) brought back over the phone line it was deemed prudent to monitor the individual breaker residual currents on the breakers adjacent to the bus.

This fault is on the RH26 line exit of this station. The totalized residual currents and the individual breaker residual currents are shown flowing around the bus. The faulted phase currents for the 26H9, 28H9 and 26F7 GCB are not available since only 1 phase and the residual is monitored, so only the total incoming and outgoing residual currents are shown. But it still makes the point that although bus work and disconnect switches have very little impedance, the currents still chooses the parallel path of least impedance. Figure 4-5 is a DFR record with all the residuals of the totalized line exits and residuals of the individual breaker currents. Figure 4-6 is a one-line showing those currents and their path of least impedance around this ring-bus.

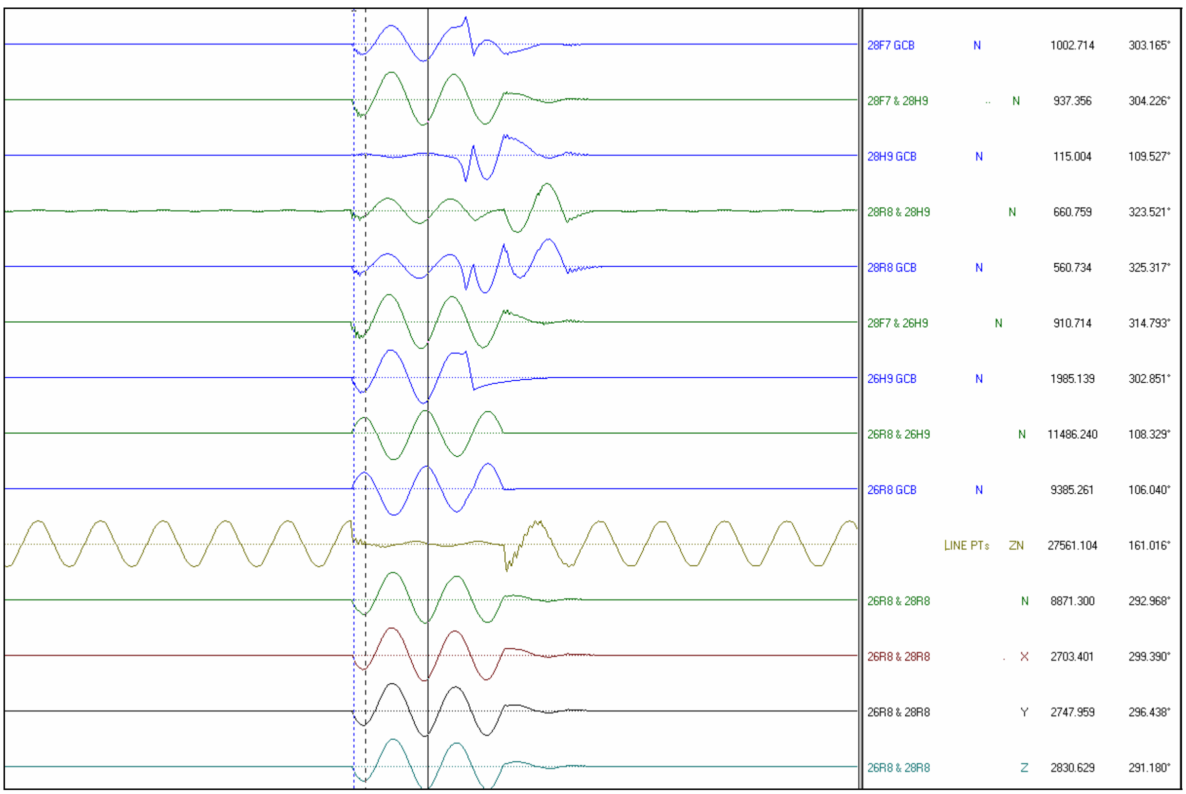

Figure 4-5

The 26R8 and 28R8 breaker exit is connected to a generator step-up transformer but the generator is not generating at this time. A, B and C phase current are equal in magnitude and are in phase with each other and if summed (without the phase angle) equal the residual current. Classic 3Io is flowing from a grounded wye-delta transformer with no source on the delta.

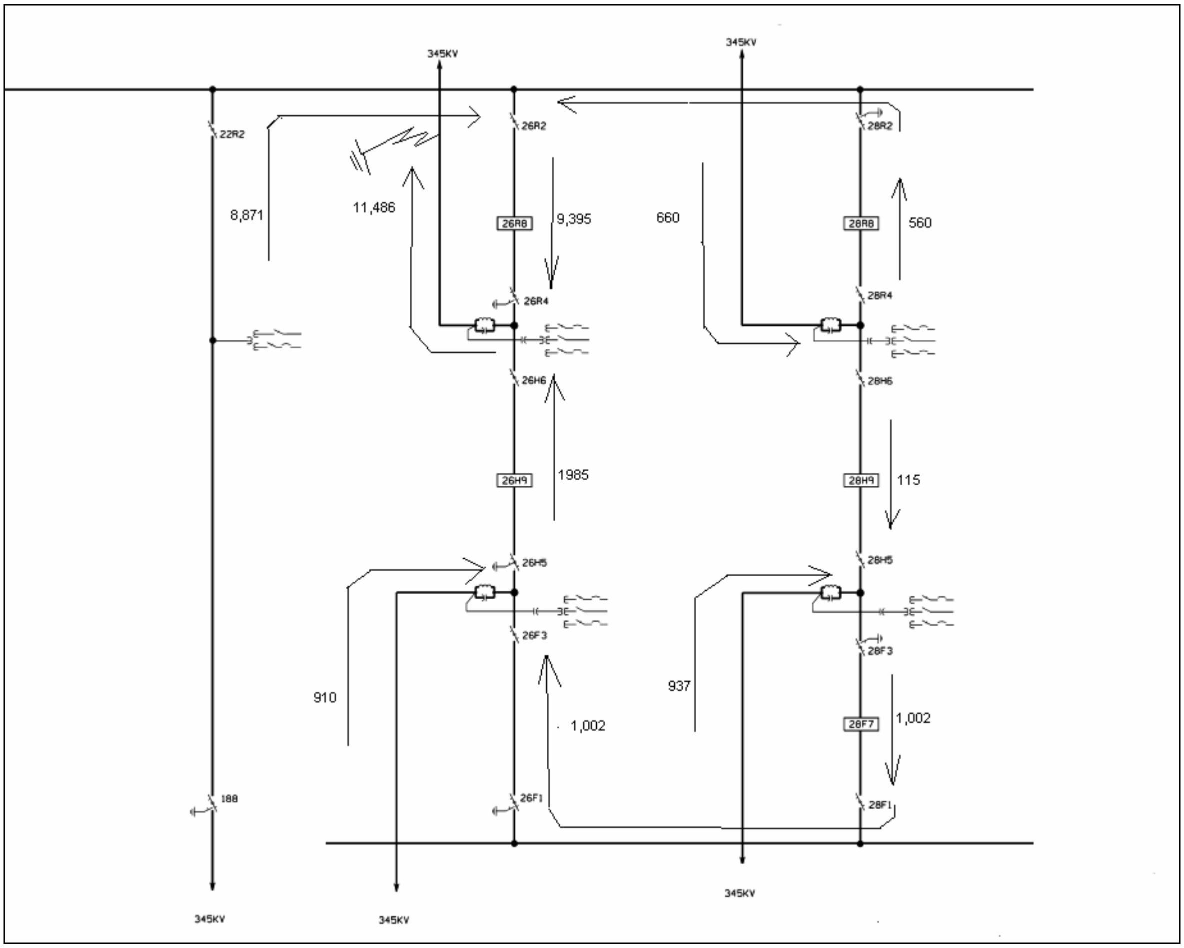


Figure 4-6

The difference between the two parallel paths from the FH28 exit and the RH26 exit (faulted line exit) is that one path has 3 breakers in series and one path has 2 breakers in series. Everything being equal it might make sense that the impedance from the FH28 node to the RH26 node is equal in either parallel path. However, the current flow indicates otherwise, all 937 amperes entering the FH28 node flow down one path.

Both parallel paths have the same amount of bus work and each have 5 disconnect switches in series. Is the impedance difference caused by the additional breaker? Maybe it's not the breaker itself but the connections to the breaker bushings and the connections to the disconnect switches that make the difference. Maybe it's the pitting on the disconnect switches where they make contact from the arcing during switching operations. The FH26 current comes into its node and all flows down only one path.

The point is that this is a situation where, however small the impedance of the bus may be, the relative impedance from one path to the other does make a difference how currents flow around the bus.

EXAMPLE FAULT #5

This fault is from a single breaker line exit at a 46 kV substation and the ground relay on this line exit was not working. Due to the relatively small spacing of the 46 kV conductors the single line-to-ground faults that were not cleared by this inoperative ground relay eventually changed to double line-to-ground faults (as more air was ionized) and the phase relays then cleared the fault.

The problem with the ground relay was that the neutral connection return from the phase relays back to the CTs through the ground relay was open. A knife switch was the problem, but when the technicians tested the relay and checked out the circuit, it was conducting the small amount of current used in the test. A digital relay was temporarily installed to monitor the circuit. Now normally this would guarantee that the line wouldn't be faulted for a long, long time, but in this case it happened within a month.

The fault was a single line-to-ground fault on the B phase. There are two 11 cycle records in Figure 5-1. The first record shows the BG fault and the second record shows the BG fault continuing and then changing to an ABG fault. Once the A phase was involved the breaker was tripped by the torque-controlled phase relays.

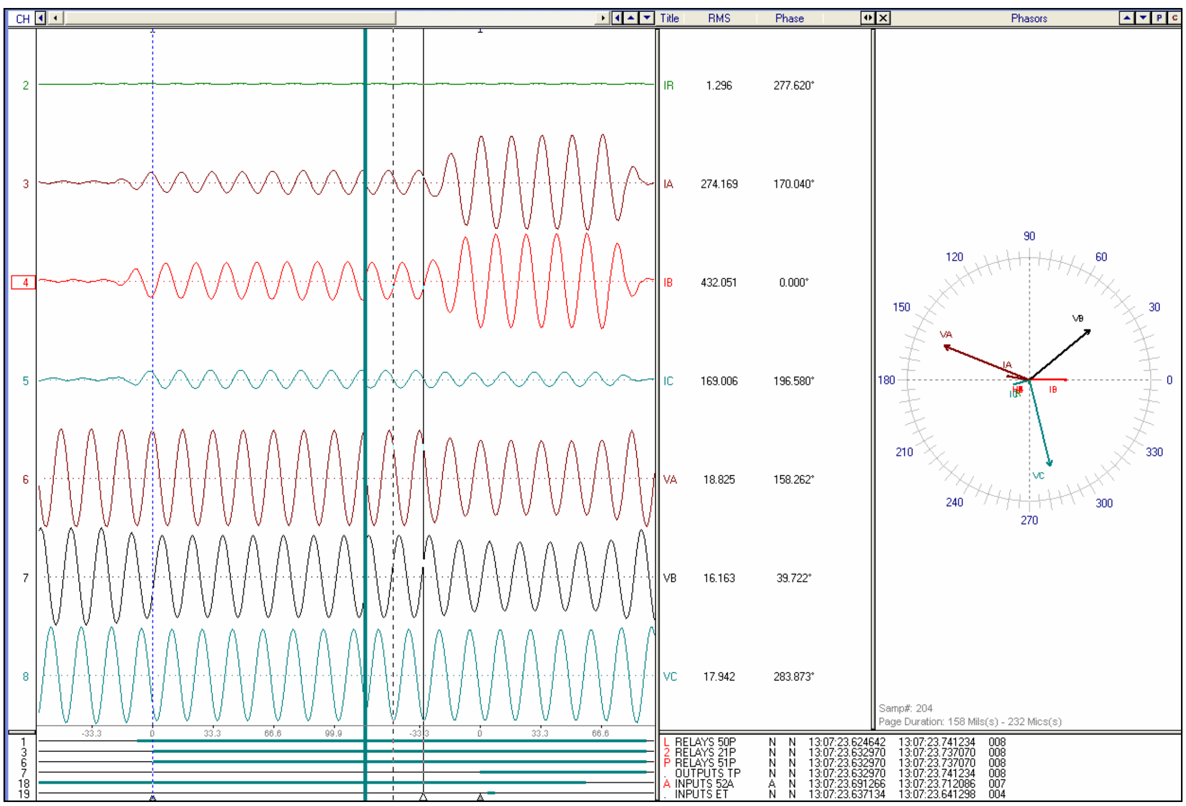


Figure 5-1

Because the neutral connection was open, the return path for the B phase current was back through the A and C phase CTs. The currents in the secondary of this circuit do not represent what was in the line as shown in Figure 5-2, instead, the B phase CT was driving current into the A and C phase CTs in the opposite direction of the actual A and C phase current flowing in the line (see Figure 5-2).

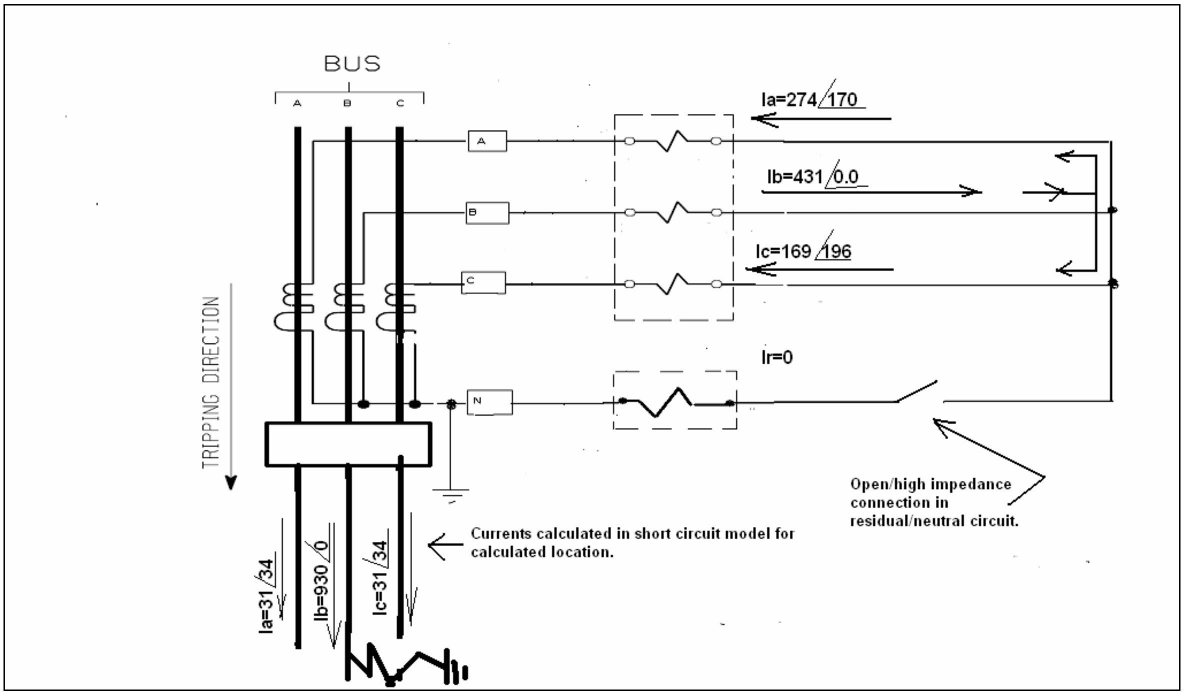


Figure 5-2

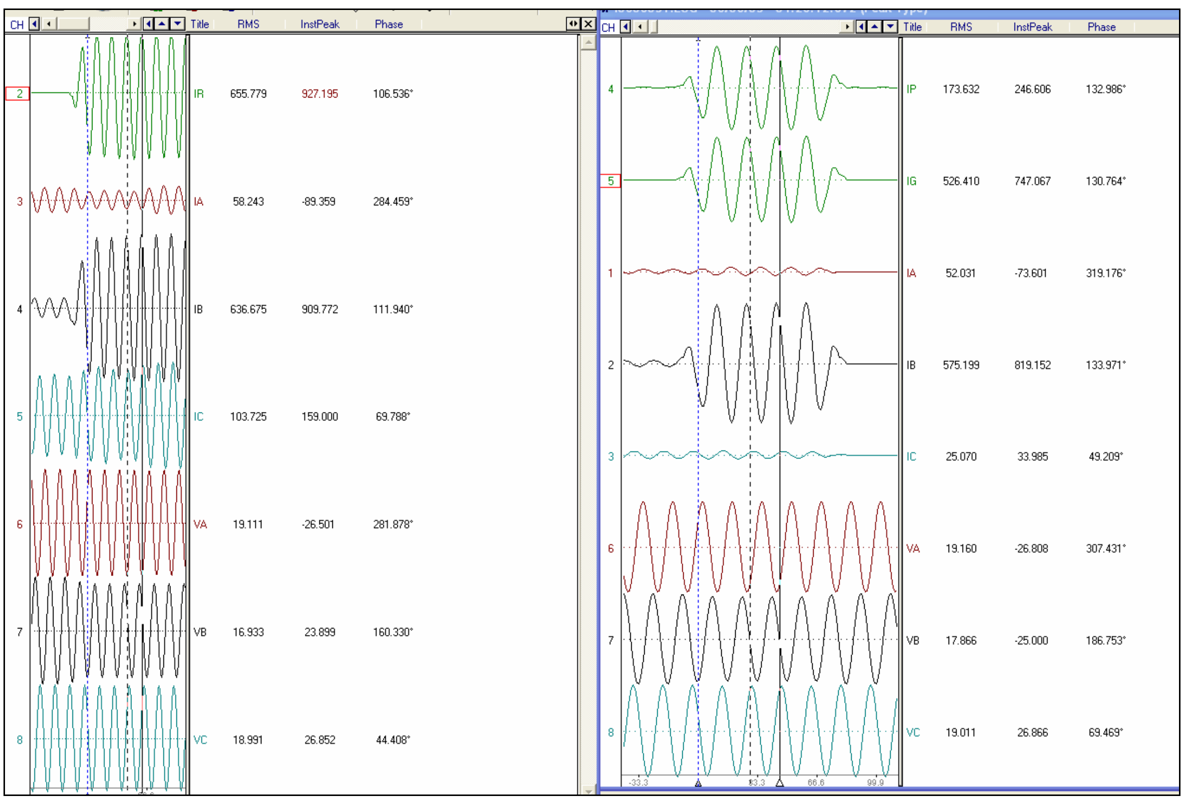


Figure 5-3

The first record in Figure 5-3 is from a relay one bus behind the failed relay and the second record is from the remote end of the line. These currents were used to locate the fault using the short circuit model. Note that there is more B phase current coming in from the node/line behind the relay (first record Figure 5-3) than is flowing down the faulted line (record #1 in Figure 5-1). Figure 5-4 shows the short circuit model used to calculate the fault location and contributions from the exit with failed relay.

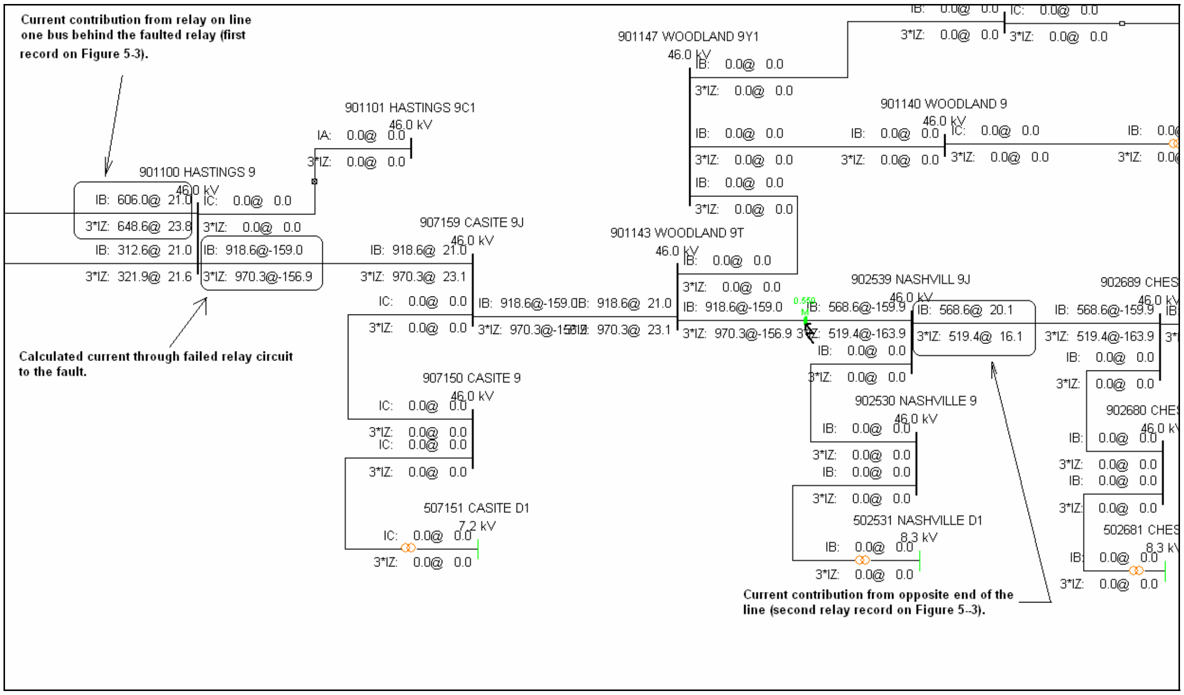

Figure 5-4

The digital relay from the remote end of this line calculated this fault to be 18.57 miles from the remote end. Using the short circuit model and currents gleaned from the available relays the fault was calculated to be 19.18 miles from the remote end with 8.2 ohms resistance in the fault.

## <u>EXAMPLE FAULT #6</u>

In this example, there was a single line-to-ground fault on the C phase of the RH25 line exit. There was 4,683 amperes recorded on the totalized C phase but only 215 amperes recorded on the totalized residual (Figure 6-1). The 215 amperes on the residual was probably the sum of Ia + Ib (the un-faulted phases). The C phase current was shorted to the case of an electromechanical phase relay used in this directional comparison blocking scheme. After the C phase current was monitored on the DFR it went into the electromechanical distance relay and then to ground (Figure 6-2). The current then returned to its source (the C phase CT) via the CT ground in the panel, bypassing the residual monitoring on the DFR.

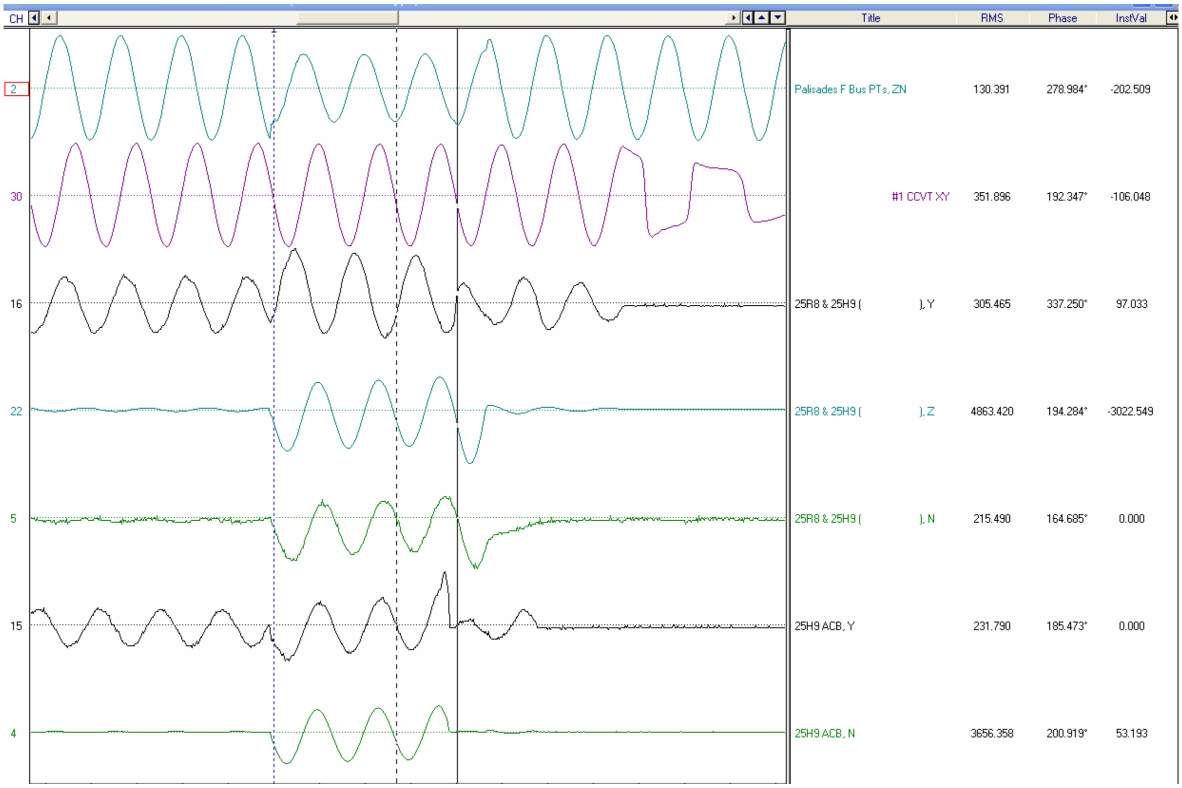

Figure 6-1

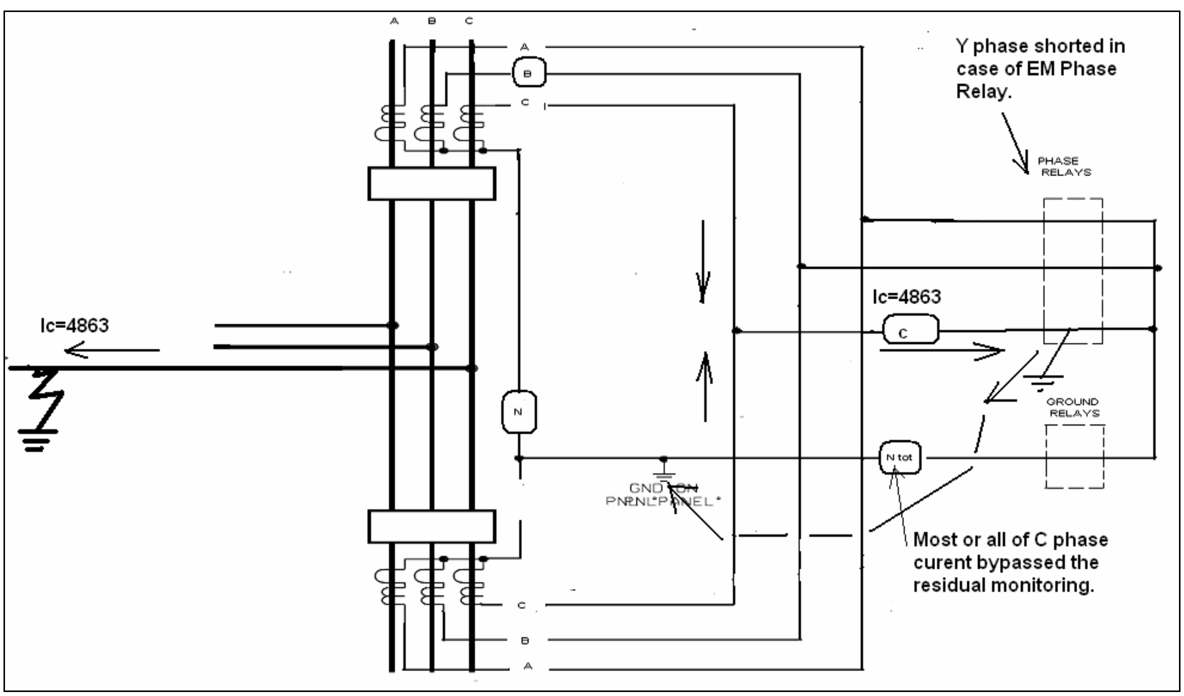

Figure 6-2

BREAKER-AND-A-HALF SCHEMES

Before delving deeper into the breaker and a half line exit schemes, we will review the secondary CT circuits to show where the currents are monitored.

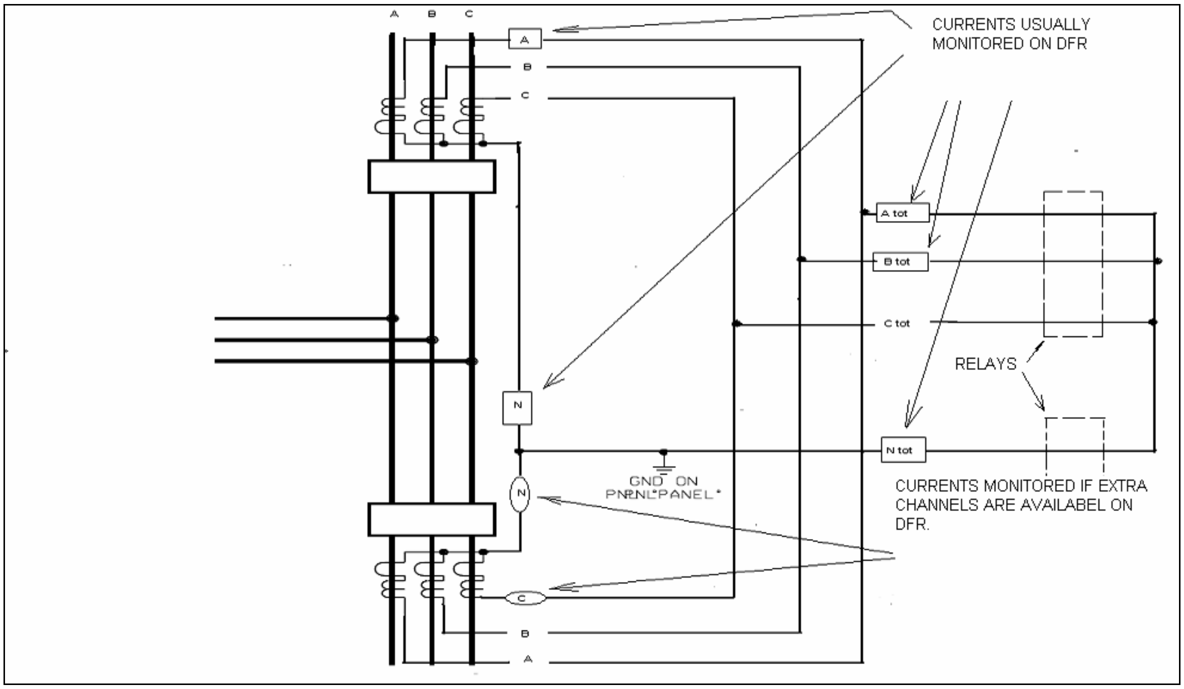


Figure B

Not every desired point is monitored due to cost constraints. The secondary currents in the boxes are typical of what will be monitored on the breaker and a half scheme. Two totalized phase currents and the totalized residual current, plus a single phase current and the residual current of the middle breaker are usually monitored. As previously mentioned, occasionally the residual current and/or a single phase current of the bus side breaker may also be monitored.

EXAMPLE FAULT #7

This first digital fault record is used to gain an understanding of how the breaker and a half schemes are monitored on the system and show the different breaker clearing times and currents through the breakers.

This is a BG fault on the RH32 exit.

The B phase of the 32R8 GCB and the B phase of the 32H9 ACB (in this breaker-and-a-half line exit scheme) are not monitored. However, in this case the residuals of both of these breakers are monitored. The faulted line currents are exiting the station via the parallel path of the 32R8 and 32H9 breakers. The total fault current values (32R8 + 32H9) are Ib=5,376 and Ir=6,449. Since the faulted phases of the individual breakers are not monitored it is assumed that Ib and Ir of the two individual breakers have the same ratio of faulted phase current to residual current as the totalized circuit. Like all the faults reviewed thus far the residual is close enough in magnitude and phase angle to the faulted phase that the residual current is a good indication for understanding the faulted phase current.

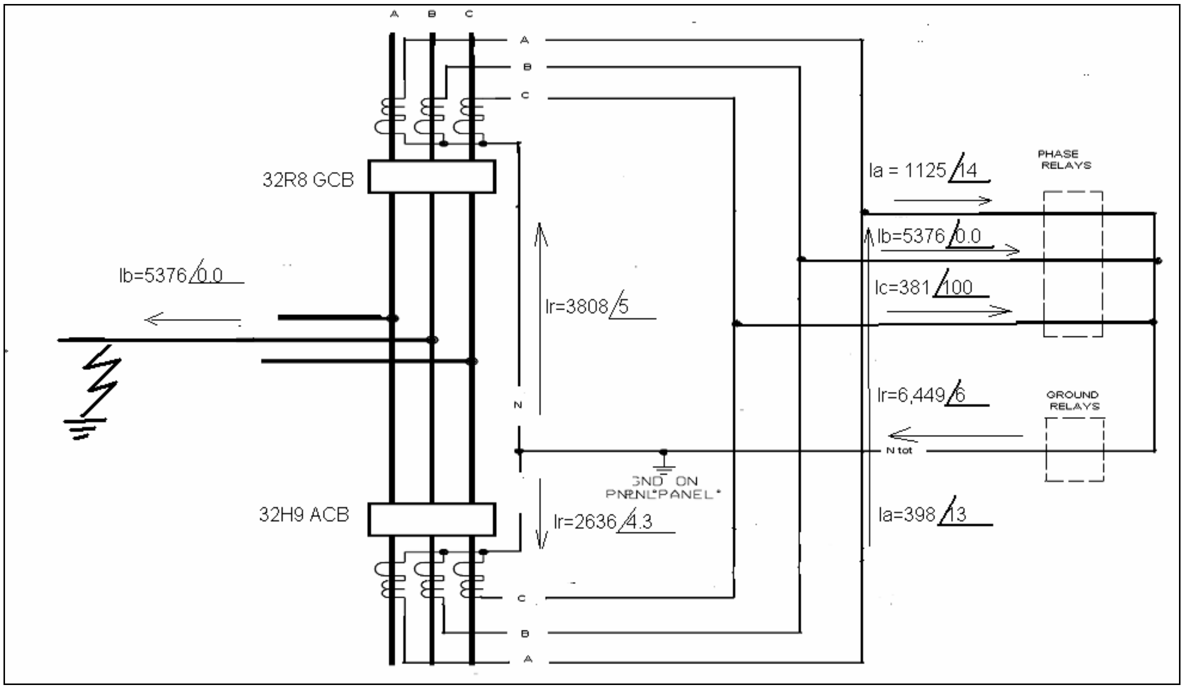


Figure 7-1

For this exit (figure 7-1), the fault residual current Ir totalized measured 6,449 amperes. Ir of the 32R8 GCB measured 3,808 amperes and Ir of the 32H9 ACB measured 2,636 amperes. The totalized residual current can be calculated by summing Ir of the 32R8 and Ir of the 32H9 or 3,808 + 2,636 = 6,443 amperes. The difference between this calculated total of 6,443 amperes and the measured totalized current of 6,449 amperes is from very slight calibration differences.

Two and one-half cycles into the fault, the 32R8 GCB opened at which time the A, B and C phase currents are transferred to the 32H9 ACB for the last half cycle. Now Ir 32H9 ACB is equal to Ir totalized for this exit.

A note of interest is that the current transformers on hub or middle breakers can only be polarized toward one adjacent line exit. So in this example the 32R8 breaker residual currents appear to be 180° out of phase from the 32H9 and the 32R8+32H9 totalized current.

The instantaneous values show that the 32R8+32H9 totalized residual values now equal the residual in the 32H9 breaker because the 32R8 has opened.

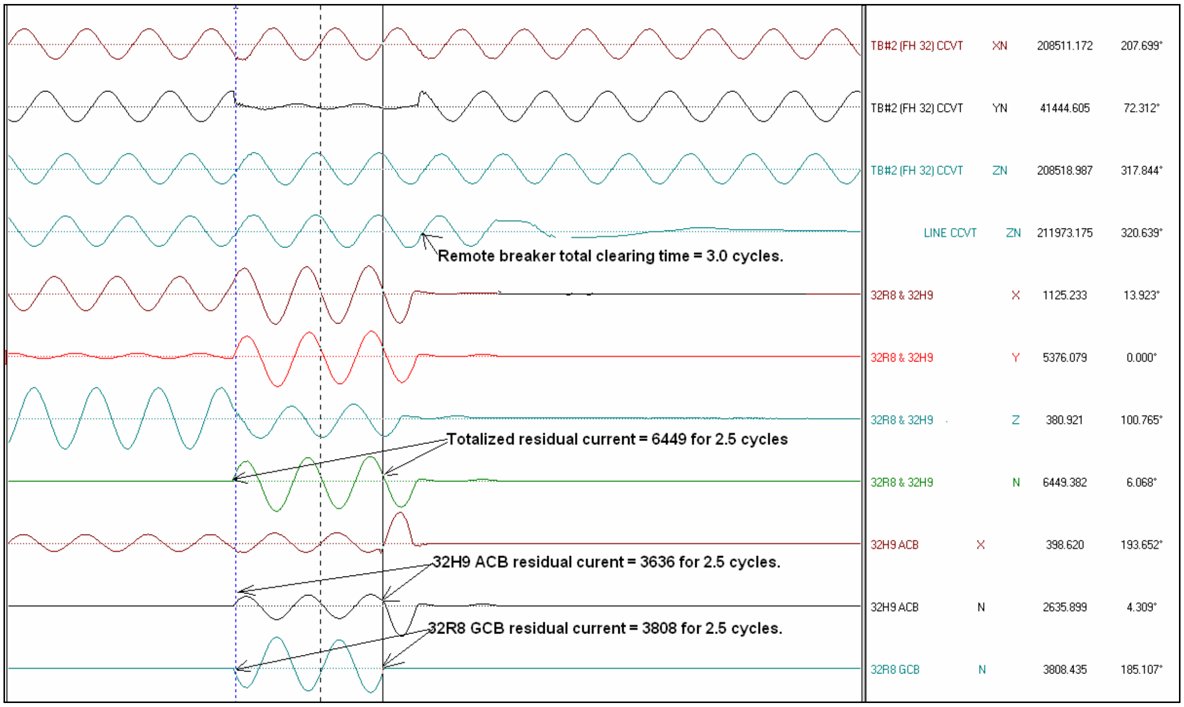


Figure 7-2

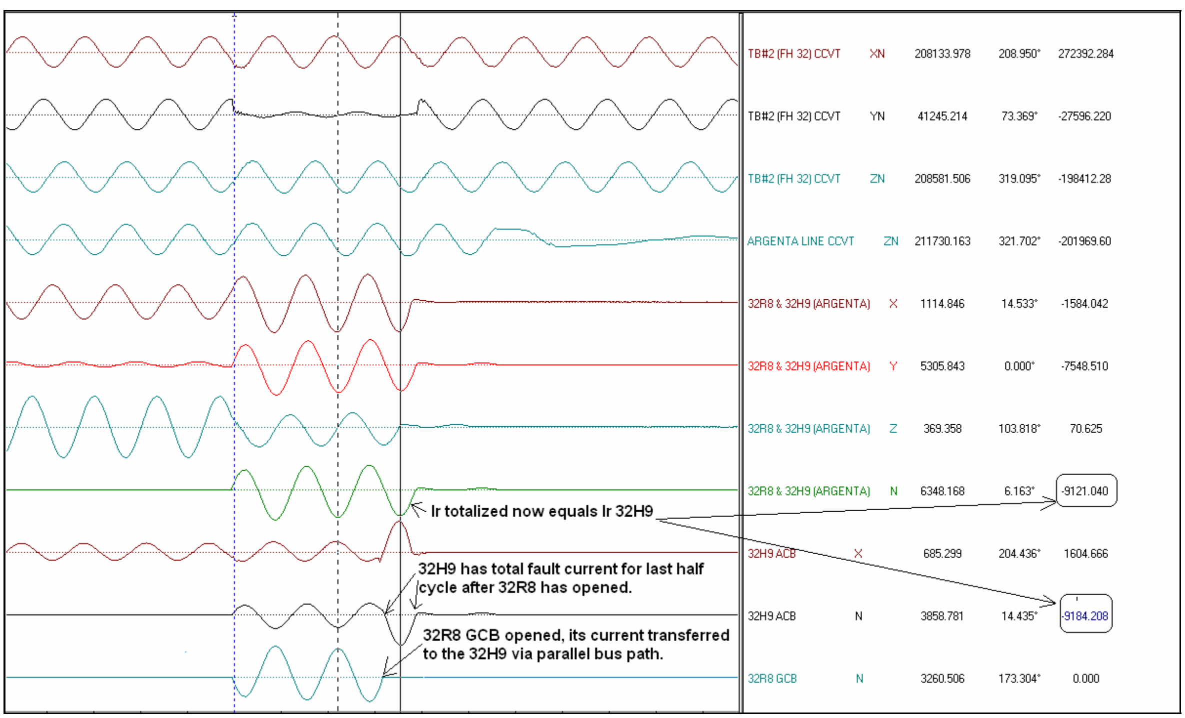


Figure 7-3

Figure 7-4 shows the faulted phase and residual currents before and after the 32H9 breaker is opened.

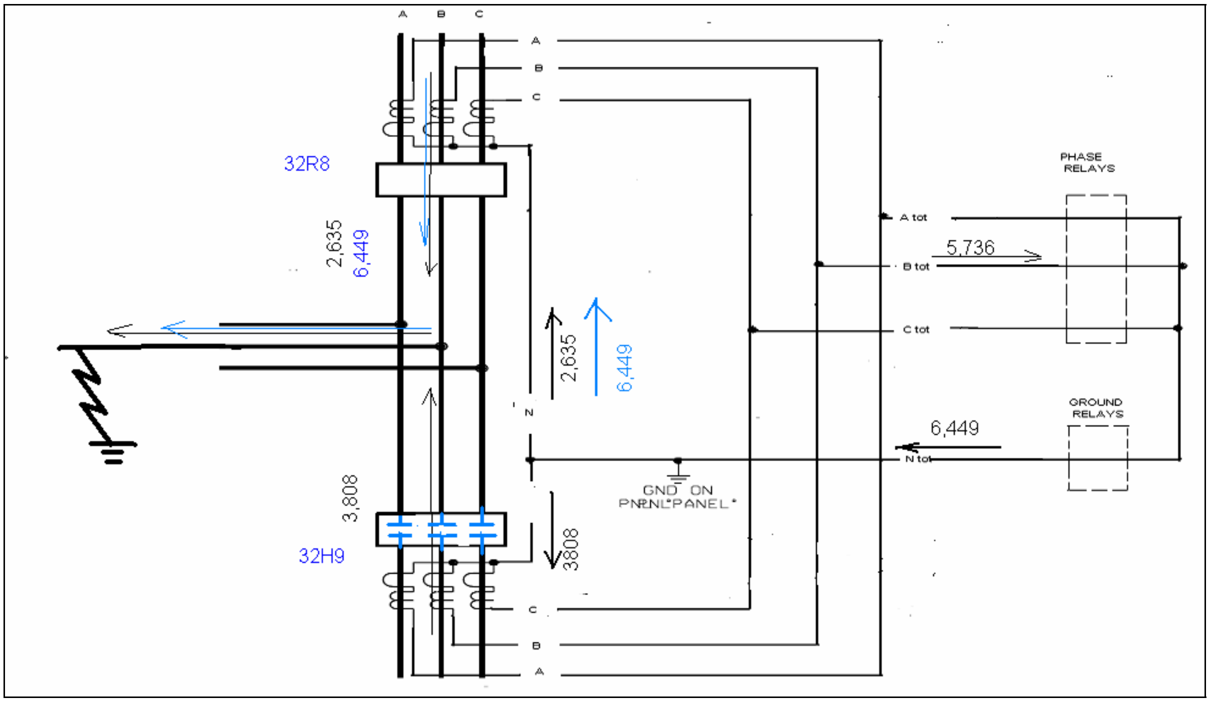


Figure 7-4

<u>EXAMPLE FAULT #8</u>

ARC RESISTANCE: In example #3 there was an arc in the breaker secondary current circuit and it had resistance, but how much resistance? When analyzing faults, it would be nice to know the resistance of the arc. When the arc can't be measured or calculated, the resistance of the arc relative to the impedances of the system being analyzed is always interesting to consider.

Example 8 is from a digital relay record that has 16 samples per cycle unfiltered. In this example, a B phase conductor broke on the line. The steel core of the conductor rusted and the aluminum strands could not support the weight of the conductor. The conductor broke and drew an arc; initially this arc was close to zero resistance. As the ends of the conductor dropped, they pulled apart increasing the length of the arc, and with it, the arc resistance. Although the resistance increase appears to be fairly linear as can be seen in the decrease of the B phase current and the resulting increase of the residual current, no conclusions were drawn as it is not known how rapidly the conductors pulled apart as they dropped (see Figure 8-1). At the end of the fault, just prior to the arc going out, the resistance of the arc appears to have increased rapidly in a non linear fashion.

Unfortunately, the relay didn't start recording until the arc had enough resistance that Ib (load on in the B phase) decreased to the point that Ir was high enough to trigger the relay. How long did this condition exist before the relay was triggered?

The lowest point of the conductor is at the bottom of the sag or 32 feet off the ground. Using the acceleration of gravity D= (.5) (32 feet/second/second) ($t^2$), the time it took the conductor to fall is represented by $t^2 = 32/ (32) (.5)$ which calculated to $t=\sqrt{2}$. It should take 1.41 seconds for the conductor to fall from the time it broke until it hit the ground. Again, it was not determined how rapidly the conductors were pulling apart as they fell to the ground. In the first 0.676 seconds (the time the relay did not record) the conductor fell only 2.9 feet.

This example is included because in many ways this conductor breaking is analogous to a breaker opening. The conductor broke and started to part, at this point an arc was established. At inception, the resistance of the arc was approaching zero but increased as the distance between the ends of the conductor increased. As the conductor fell and was pulled further apart, the resistance of the arc increased to the point that the arc could be perceived. That is, there was enough arc resistance to reduce the B phase current to the point that the residual/ground current was large enough to exceed the relay setting that triggered the record. In the pre-fault portion of the record, the neutral current was just getting noticeable after 0.6 seconds into the arc and increased as the conductor pulled farther apart. Also as the arc resistance increased, the B phase current was slowly transferred or loop-split to a parallel path until the resistance was large enough to break the current/arc. The resistance increased until finally when the current hit a zero crossing the arc could not be reestablished as the voltage started to rise on the subsequent half cycle.

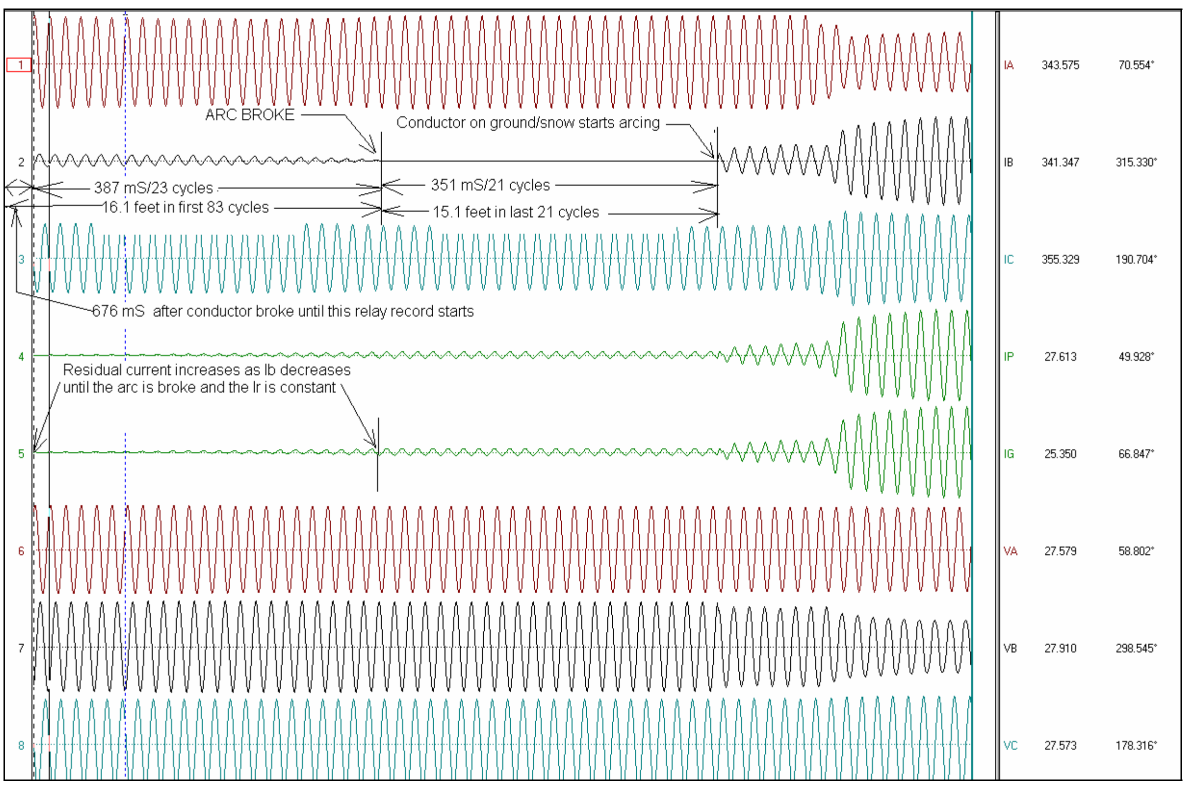


Figure 8-1

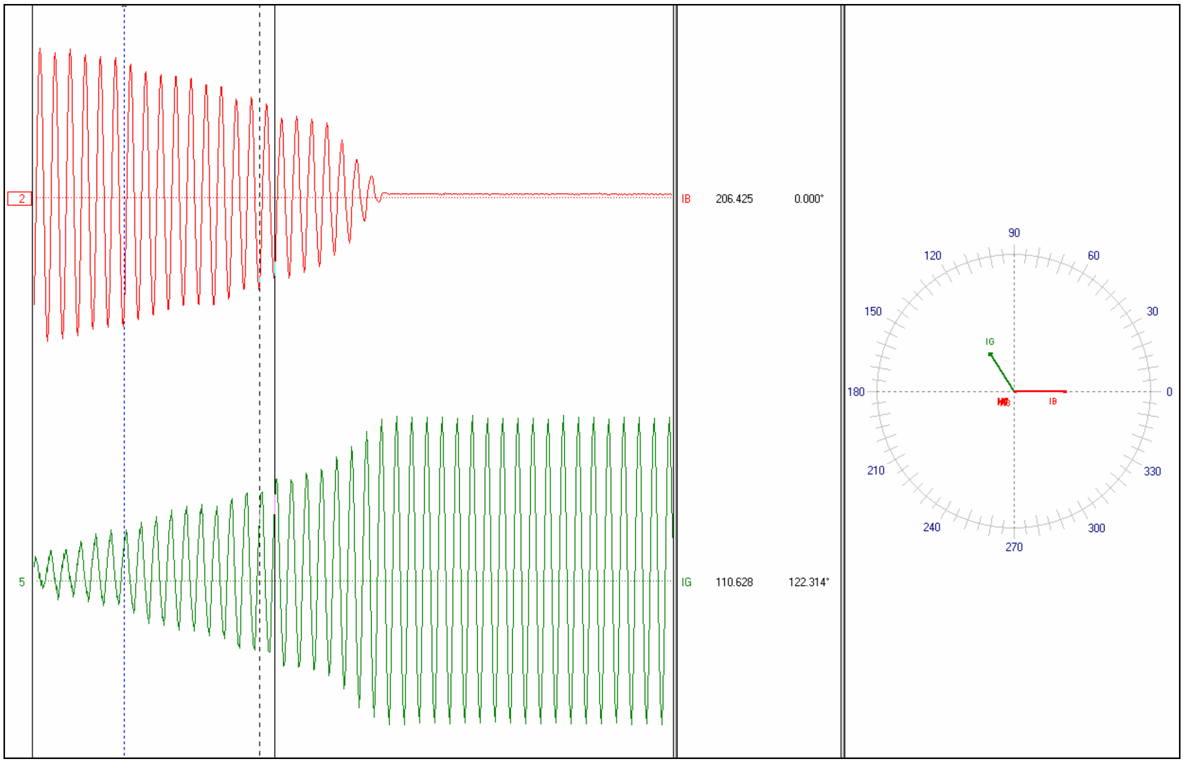


Figure 8-2

It took for this conductor arc twenty three cycles to go from perceptible to having enough resistance to loop-split and/or break the B phase current. In contrast, a three-cycle breaker may go from perceptible to clearing the current in less than 1/2 cycle and the actual time is probably less than a quarter of a cycle. The following digital fault records will show that as the breaker is opening it takes until the last half cycle before the currents are affected enough to be perceivable.

EXAMPLE FAULT #9

Figures 9-1 and 9-2 are the same fault. This is a single line to ground fault. There are no faulted phases monitored on either individual breaker or the totalized exit current. Only the individual breaker's residual and the totalized residual of the line exit are monitored. A casual review of this record as presented in figure 9-1 may glean the following information; both breakers were tripped in 1.0 cycle via the line relays connected to Trip Coil #2 and both breakers opened in 1.5 cycles, for at total fault time of 2.5 cycles. The Y phase on both the 26F7 ACB and the 26F7 & 26H9 totalized current was small relative to the faulted phase so it had to be scaled-up substantially to see a sine wave. This may be why it looks especially noisy. The 26F7 neutral appears to have some noise on it just past the peak on the last half cycle.

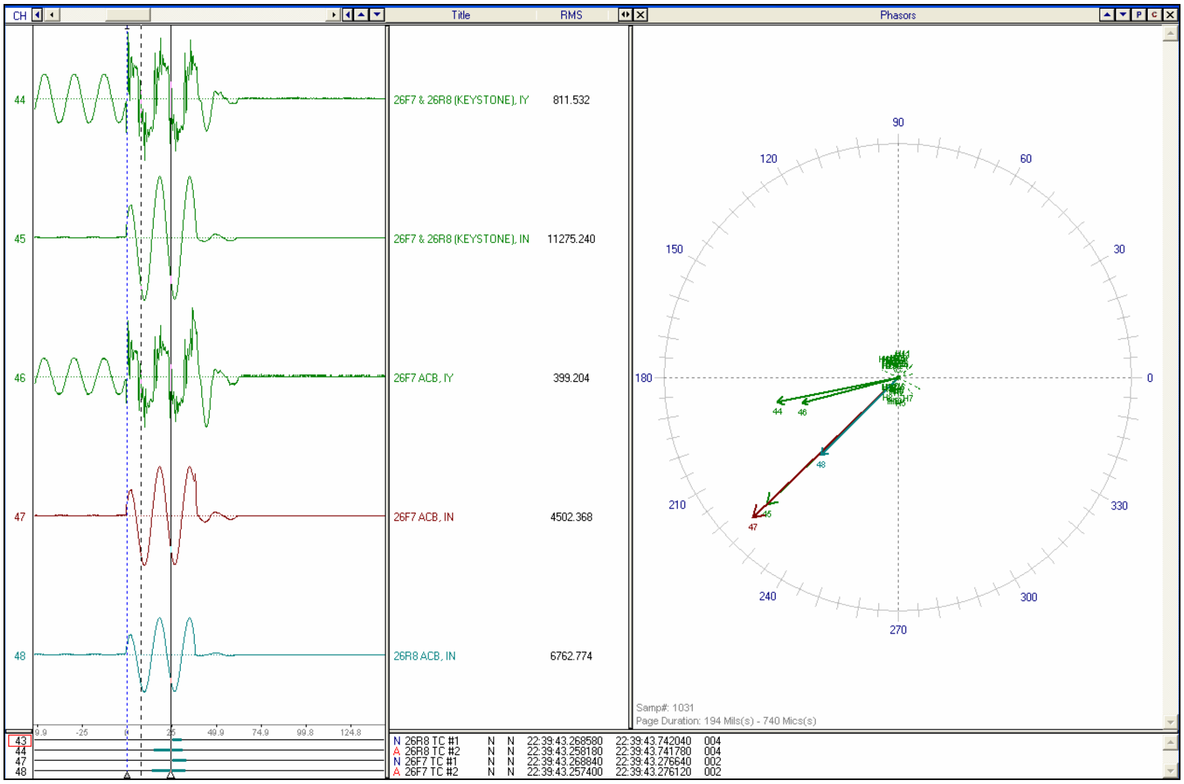


Figure 9-1

Analysis of this same record when presented in figure 9-2 tells a lot different story. This is the point in this discussion where the author needs to plead his case because the following conclusions were drawn from analyzing many fault records that all demonstrate the same phenomenon. When analyzing this DFR record as shown in Figure 9-2, it becomes apparent that when breakers are opening they have arc resistance.

To open a three-cycle breaker, voltage is applied to the breaker trip coil through the relay contact and depending on the breaker it then takes anywhere from 2-3 cycles to open/clear the fault. However, when opening this breaker some of this time is spent trying to instantaneously change the current on the breaker trip coil and this takes some time. A plunger in the trip coil then has to move to hit a trip mechanism, more time. Some form of spring has to then start moving and accelerate the breaker contacts, more time. When everything is added up, a three-cycle breaker that is clearing a fault in 2.5 cycles seems to be doing most of the work (moving its contacts to the point that an arc resistance is established and increasing its dielectric to the point that once the current crosses zero the arc cannot be reestablished) in about 9 milliseconds or less. As the breaker starts to open there is not a perceivable drop in the total fault current. If the arc resistance of the opening breaker does get large enough to change the total fault current then this resistance is achieved in the last quarter cycle (3-4 milliseconds) of the fault, when the current goes from peak to zero crossing. If this is the case then a large resistance would not be perceivable because the resistance would be reducing the total fault current when the current is moving from peak to zero-crossing on the sine wave.

Some interesting observations about breaker resistance can be gleaned from the DFR records for the three faults in this example. It appears that as the contacts of both breakers are parting and the arc resistance is getting established the relative resistance of the faster breaker to the slower breaker increases to the point that all or most of the current chooses the slower breaker as the path of least resistance.

After the trip coils of the breakers are energized, it seems that one breaker is faster to open than other. The faster breaker will establish arc resistance before the other breaker or establish resistance faster then the other breaker. A lot of the time this appears to be happening when the fault current is approaching peak or at peak. As can be seen on the digital fault records, the arc goes from having enough resistance to start the transfer of its current to the parallel breaker to enough resistance that all the current is transferred in 1-3 milliseconds. When the digital record is viewed it appears as if the current was cleared at or very near its peak instead of a zero crossing.

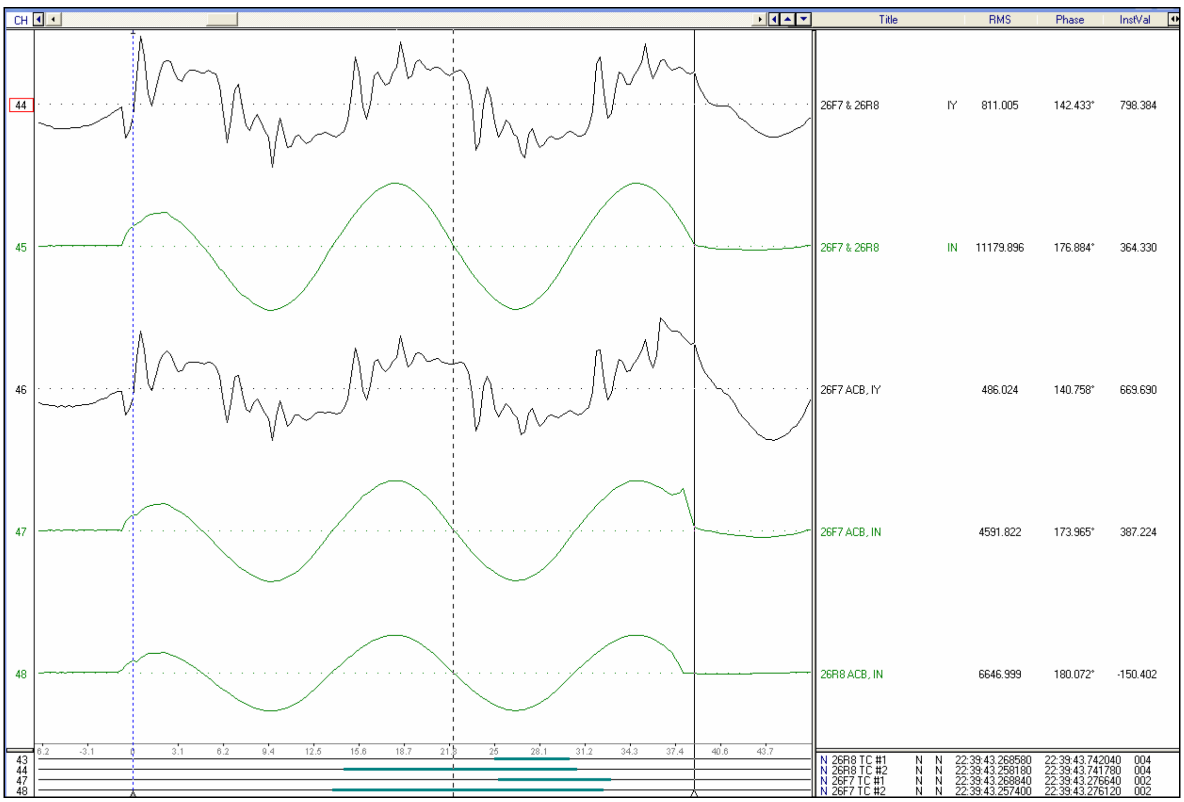

Figure 9-2

When Figure 9-2 is inspected closely, it becomes clear that what appeared to be some high frequency noise on the 26F7 neutral during the last quarter cycle is not what it appeared to be. The fault current from the 26R8 was transferred to the 26F7 by the increasing breaker arc resistance in just 0.78 milliseconds on the last quarter cycle due to the differences in the resistance of each breaker.

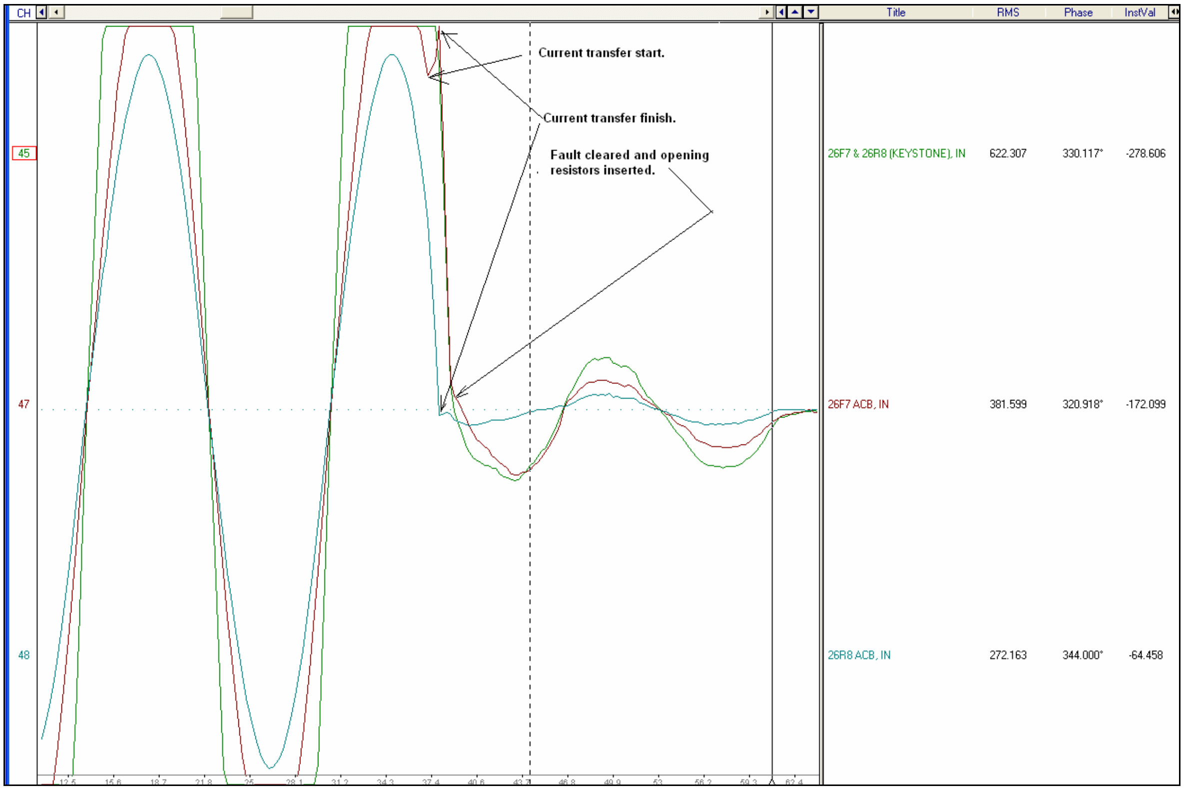

Figure 9-3

Only 0.65 milliseconds after the current is transferred out of the 26R8 and into the 26F7, the opening resistors of both breakers are inserted (Figure 9-3). After the opening resistors are inserted the relative impedance of the parallel paths is back to approximately equal and both breakers are again splitting the total current out of the line exit.

In Example Fault #7, the 32R8 current was transferred to the 32H9 at zero crossing (Figure 7-2). However, in the following fault examples (Figures 9-4 & 9-5 and 9-6 & 9-7) the arc impedance transferred the fault current in one breaker to the other breaker close to peak.

This first example (Figure 9-4 & 9-5) was chosen because this station has all new gas circuit breakers (GCBs). It is not as clean as the last record in this example (Figure 9-6 & 9-7) because in the last half cycle, not only is the current transferred from the 29H9 GCB to the 29F7 GCB near peak but there also is an increase in total fault current because the other end of the line has opened.

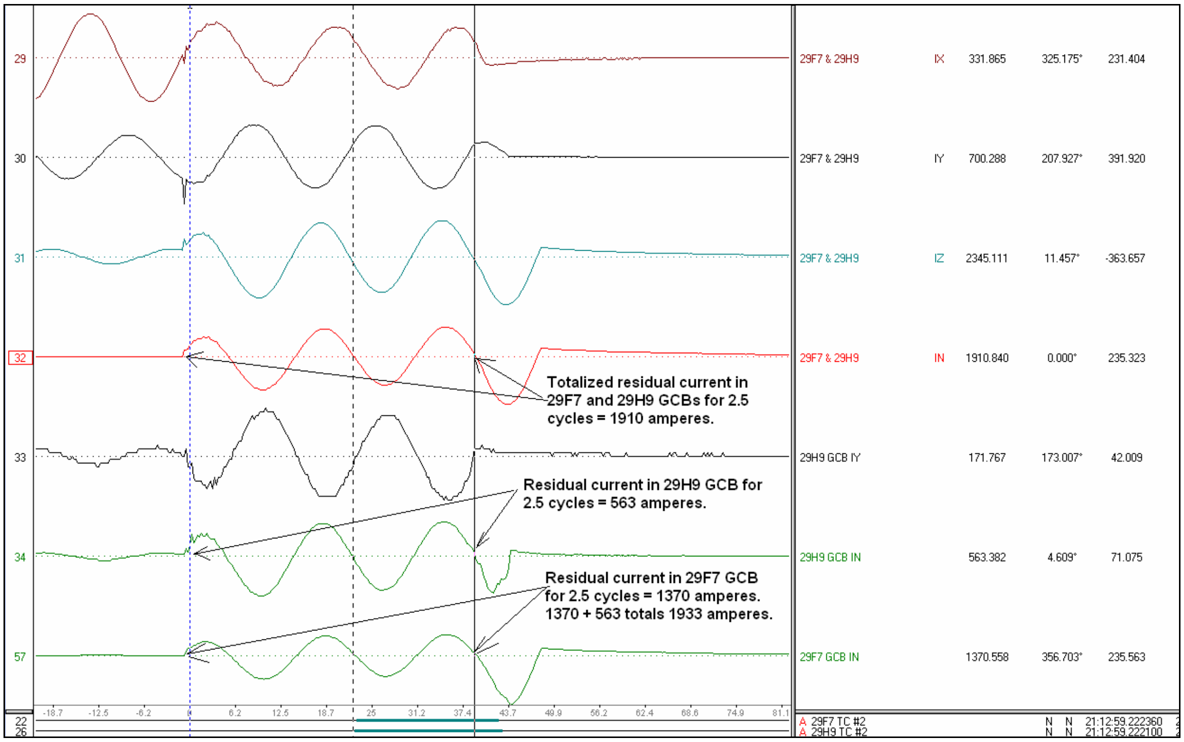


Figure 9-4

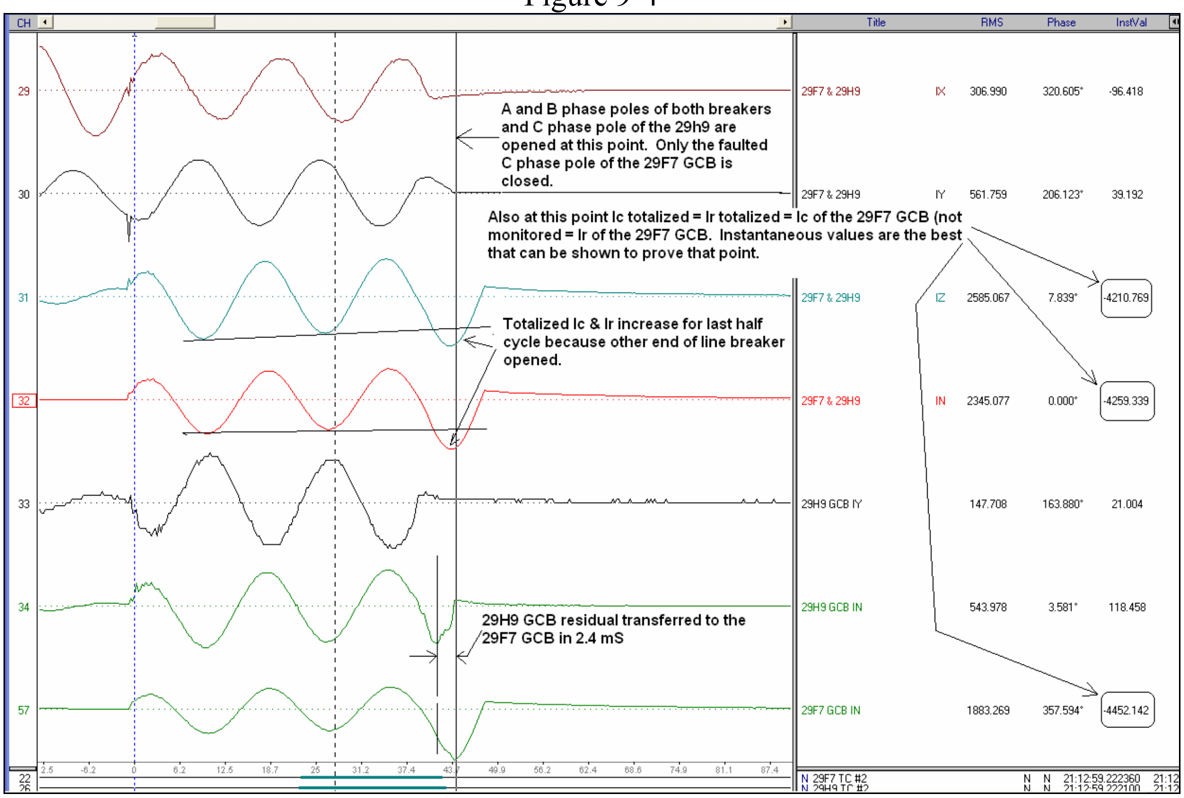


Figure 9-5

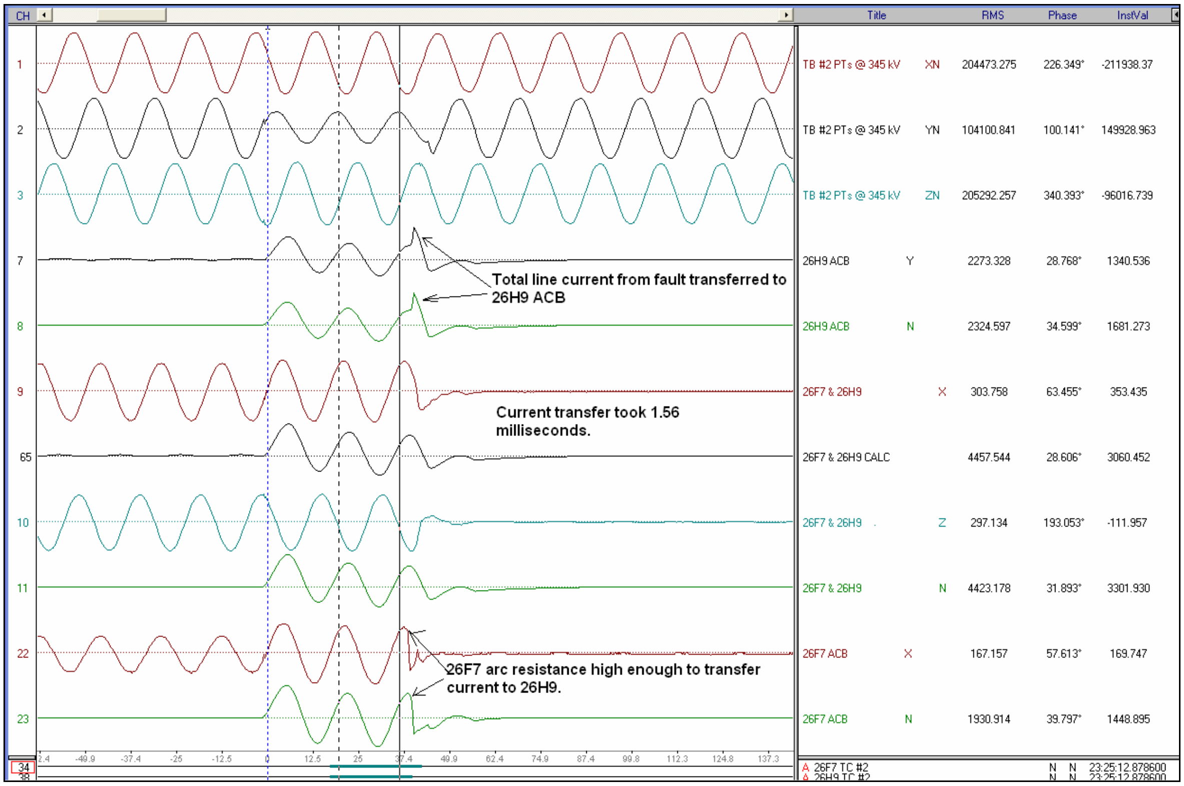


Figure 9-6

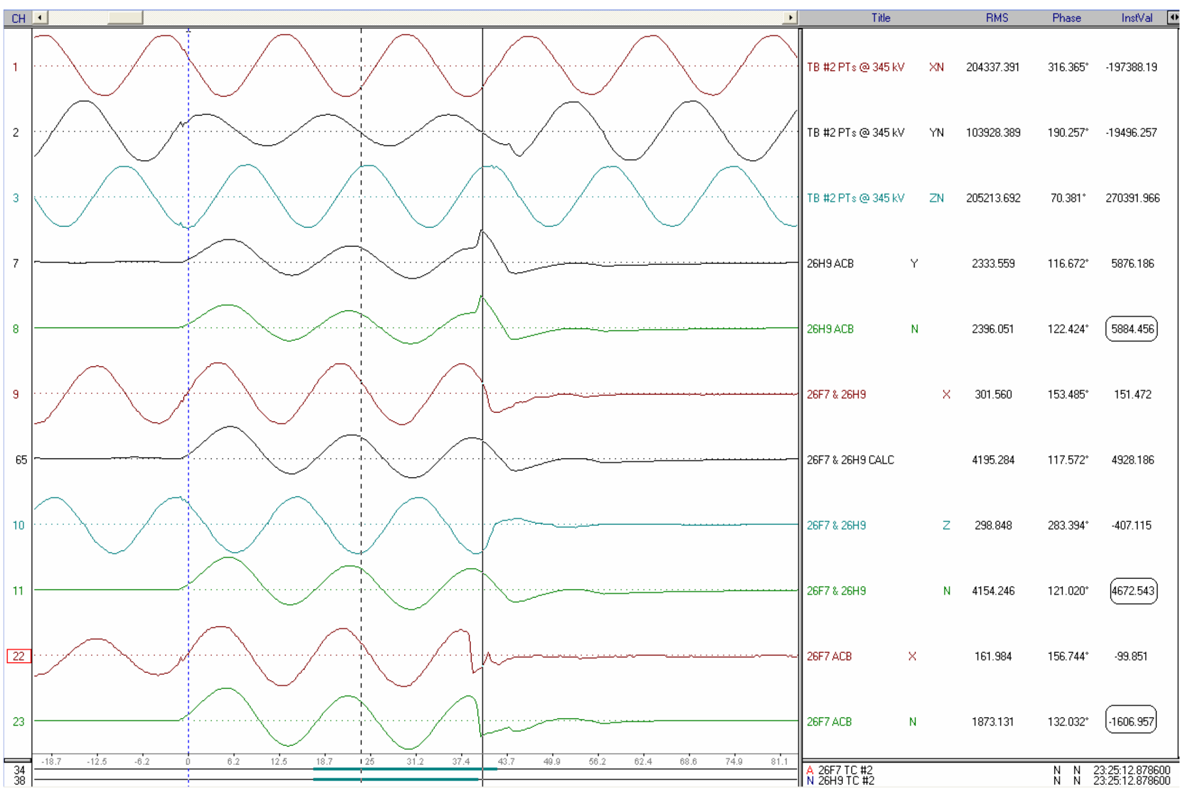


Figure 9-7

EXAMPLE FAULT #10

In the following example (Figure 10-1) there was a phase-to-phase fault on the B and C phases of a 138 kV line. This line uses a breaker-and-a-half scheme with five-cycle OCBs of the same model and vintage. The primary relay operated and energized both trip coils and both breakers started to open. The C phase of the 9B7 breaker established the arc impedance prior to the C phase of the 9M9 breaker but the B phase of the 9M9 breaker established the arc impedance prior to the B phase of the 9B7 breaker. The C phase fault current of the 9B7 then transferred to the 9M9 and the B phase fault current of the 9M9 transferred to the 9B7. See figure 10-1.

This fault has 1,977 amperes B phase and 1,882 amperes C phase totalized (9B7 + 9M9). The 9M9 C phase has 953 amperes of the 1,882 total. The 9B7 has 1,882 (totalized) – 953 (9M9) = 929 amperes C phase.

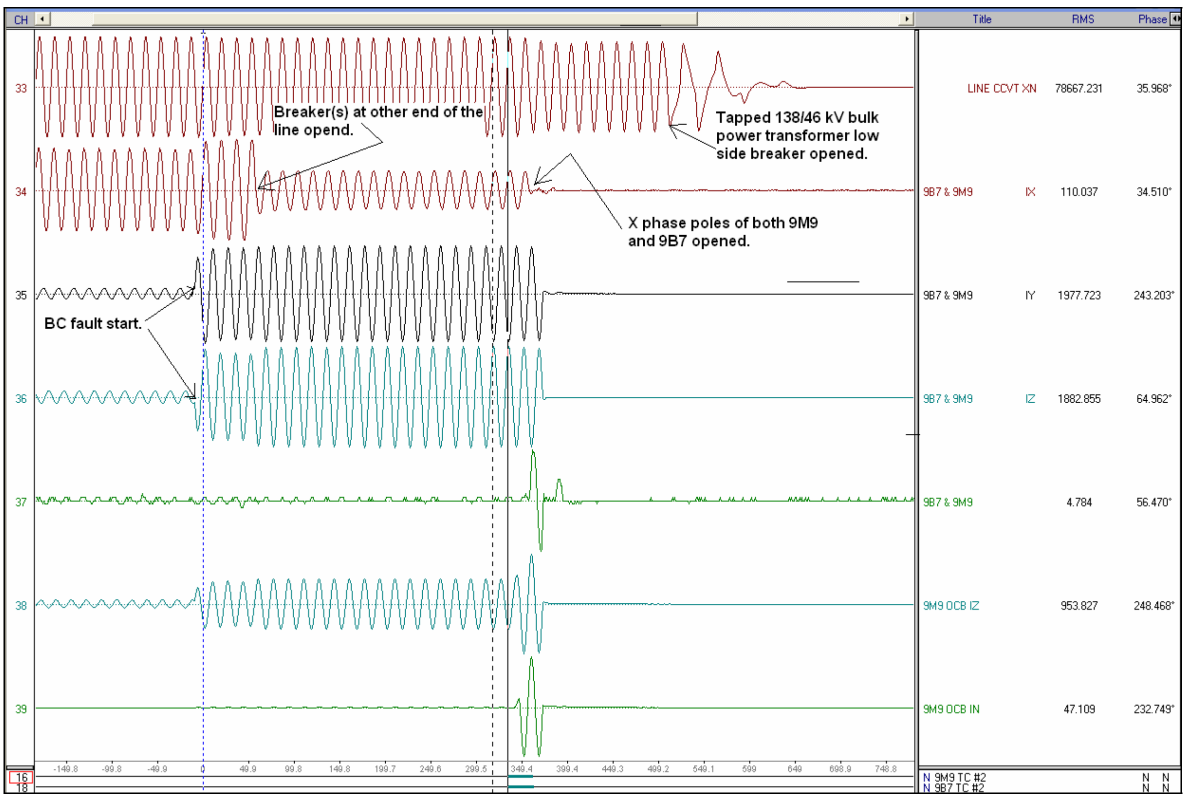

Figure 10-1

During the last 1.5 cycles of the opening of the breakers, observe that the 9M9 C phase current increased to 1,883 amperes. The 9M9 is now carrying all the Z phase current. Also notice that the 9M9 residual (In) has 1,885 amperes (Figure 10-2). Recall the fault in Example #1 when the A phase pole of the 388 didn't open and $I_{faulted\_phase} = I_r$ because there was no current in the other two phases. If Ic of the 9M9 is 1,833 /181º and Ir of the 9M9 is 1,835 /181º then Ia and Ib are zero. (Don't forget that the middle breaker (9M9) can only be polarized toward one line exit so the totalized current is 180° from the 9M9.) So if the totalized Ic is now equal to 1,830 /0º then the 9M9 breaker is carrying all the Z phase current.  If there is no B phase current in the 9M9 then the 9B7 has to have the total Ib for the fault.

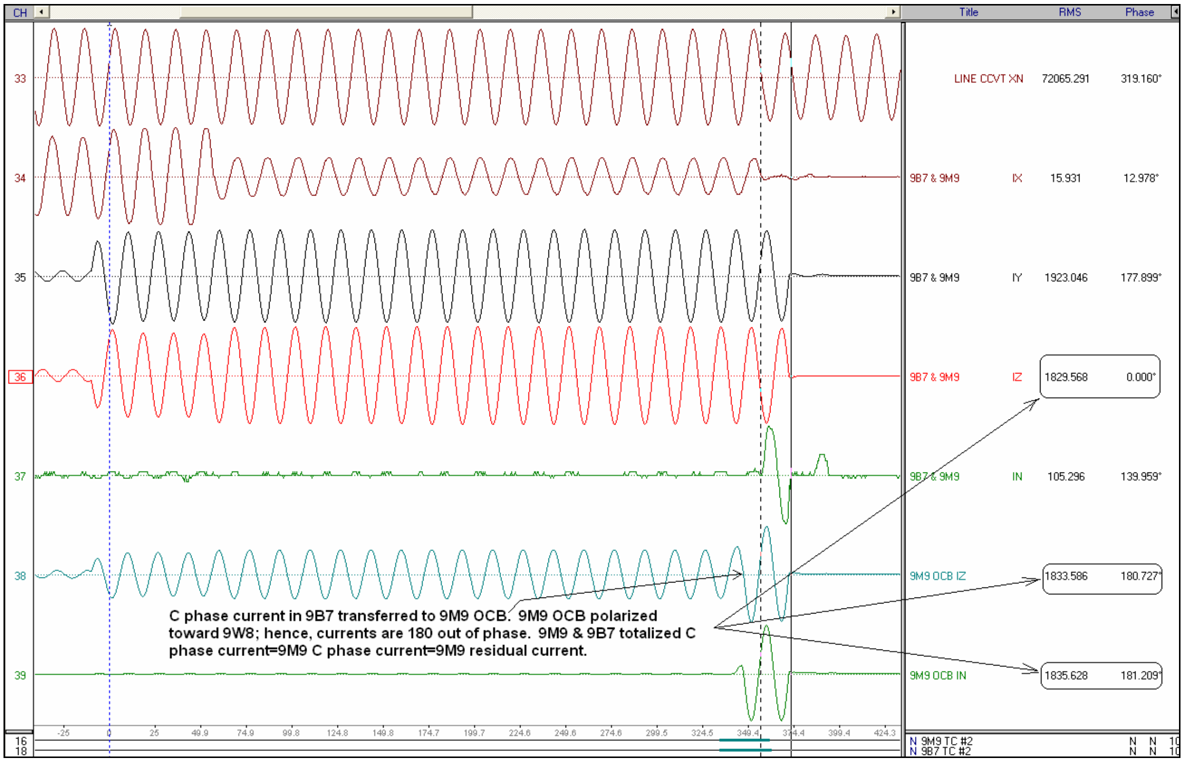


Figure 10-2

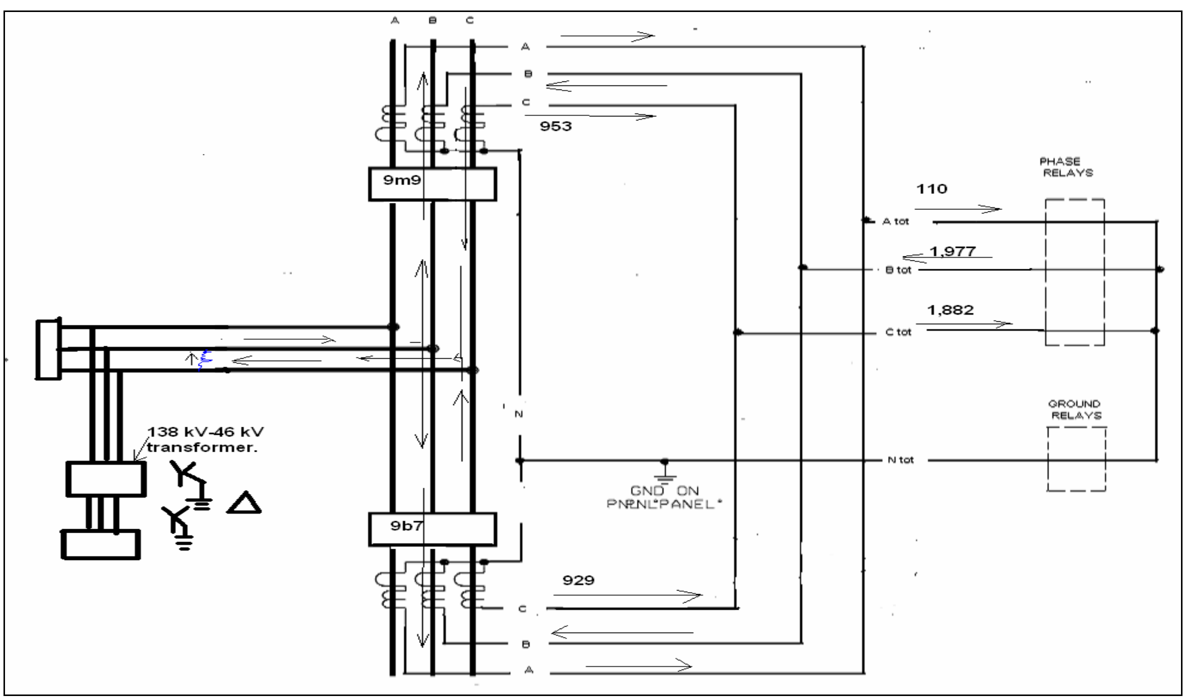


Figure 10-3

Figure 10-3 shows the distribution of currents for the initial BC fault.

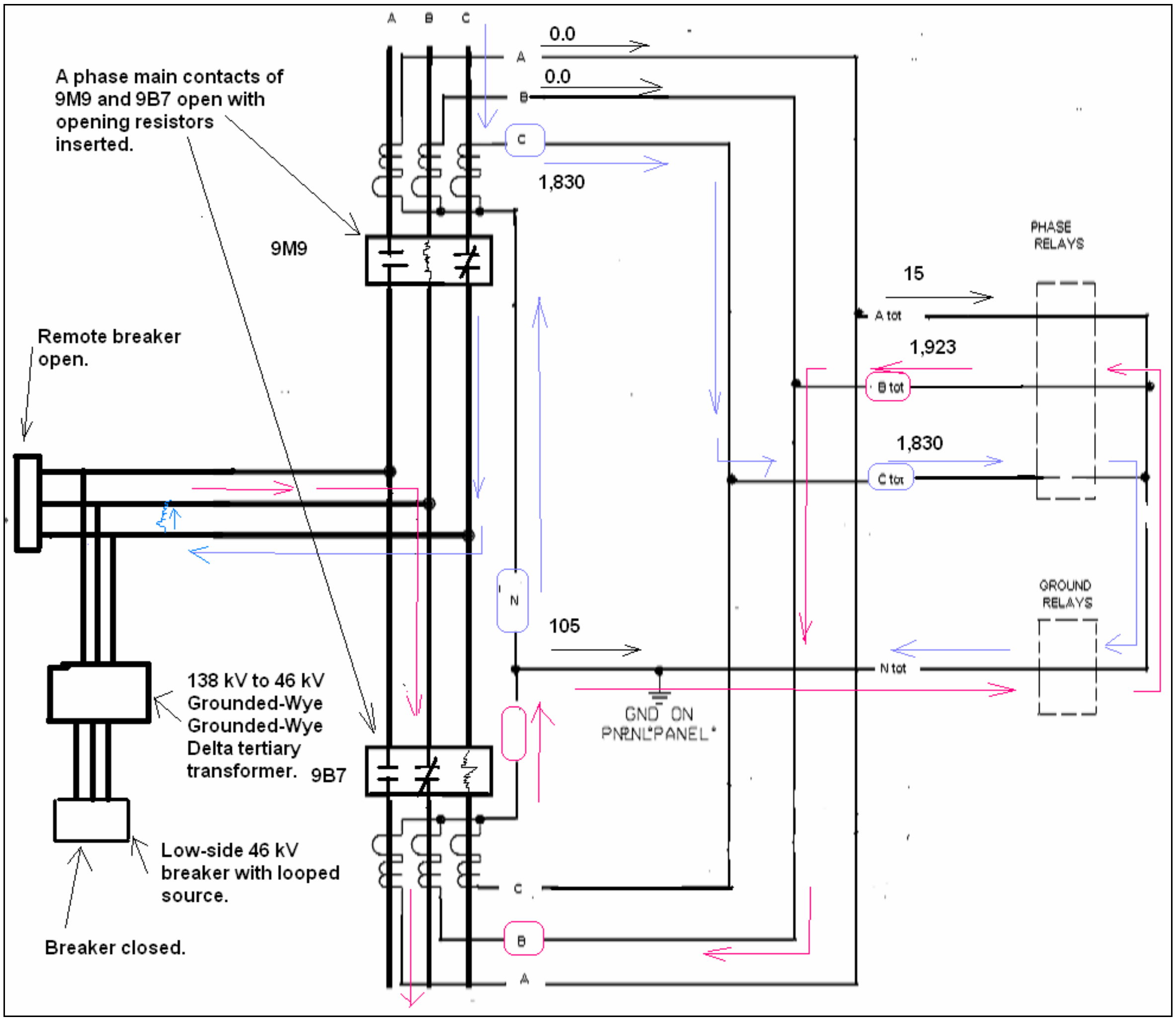


Figure 10-4

Figure 10-4 shows the current distribution after the transfer. The faulted C phase flows through the CT to the fault. The 1,830 amperes C phase current flows through the DFR (9M9 Iz), it flows to the node where the 9M9 and 9W8 are totalized, but there is no C phase current from the 9B7 so the 1,830 amperes flows through the DFR (9B7 & 9M9 Iz). It then flows through the DFR (9B7 & 9M9 In) but the DFR only measures 105 amperes because 1,923 B phase amperes are flowing in the opposite direction (1,923-1,830 = 93 amperes, but don't forget the 7.5 amperes A phase [current flow due to opening resistor] and now it's up to 100 amperes). The 1,830 amperes C phase then has to return to its CT so it flows through the DFR (9M9 In) and the DFR measures 1,830. Hence, as shown on the DFR record in Figure 10-2, the 9M9 Ic is equal to the 9B7 & 9M9 Ic is equal to the 9M9 Ir.

<u>EXAMPLE FAULT #11</u>

In this example, there is a three phase fault on a 138 kV line and the exit uses the breaker-and-a-half scheme. The breakers are identical 5 cycle trip time OCBs. The 15M9 trip coil got energized first and this breaker started to open and between 3 and 3.5 cycles into the fault and all three phase currents of the 15M9 were transferred to the 15B7. As the 15B7 opened, it transferred only the C phase current back into the 15M9 for the last half cycle. Hence, the 15B7 OCB cleared the A and B phase currents and the 15M9 cleared the C phase current. (See figures 11-1 and 11-2.)

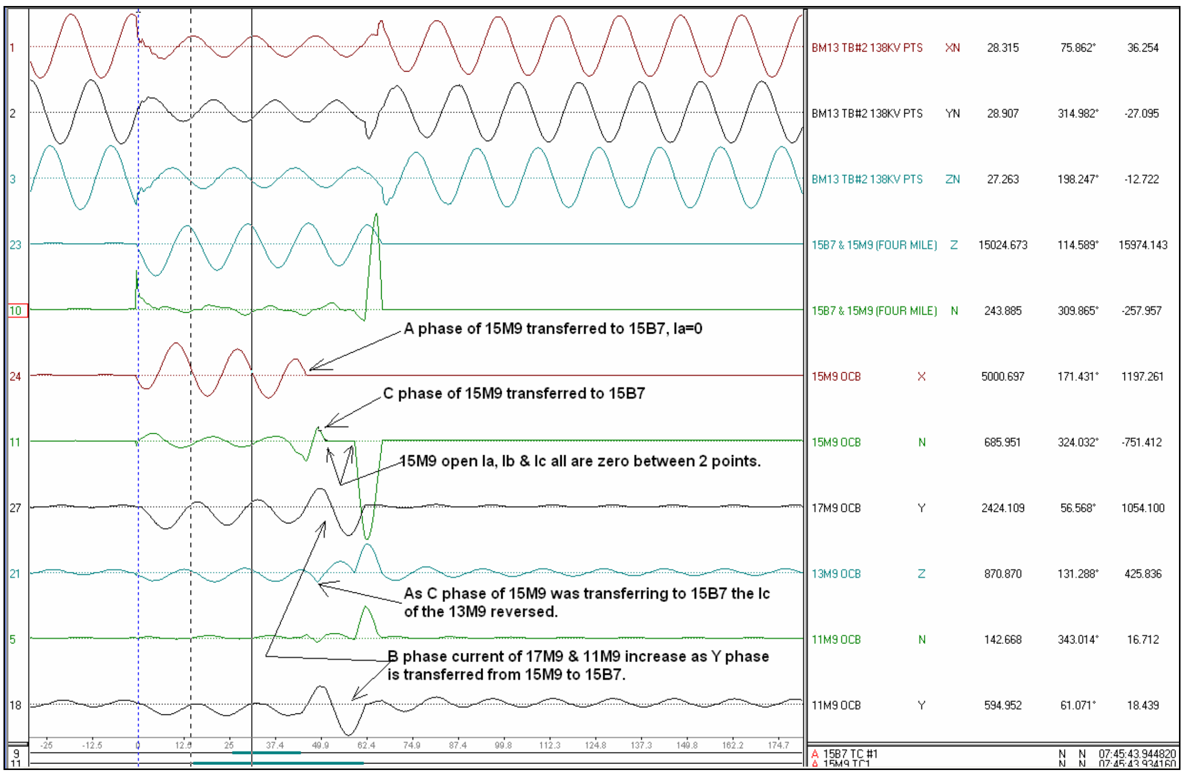


Figure 11-1

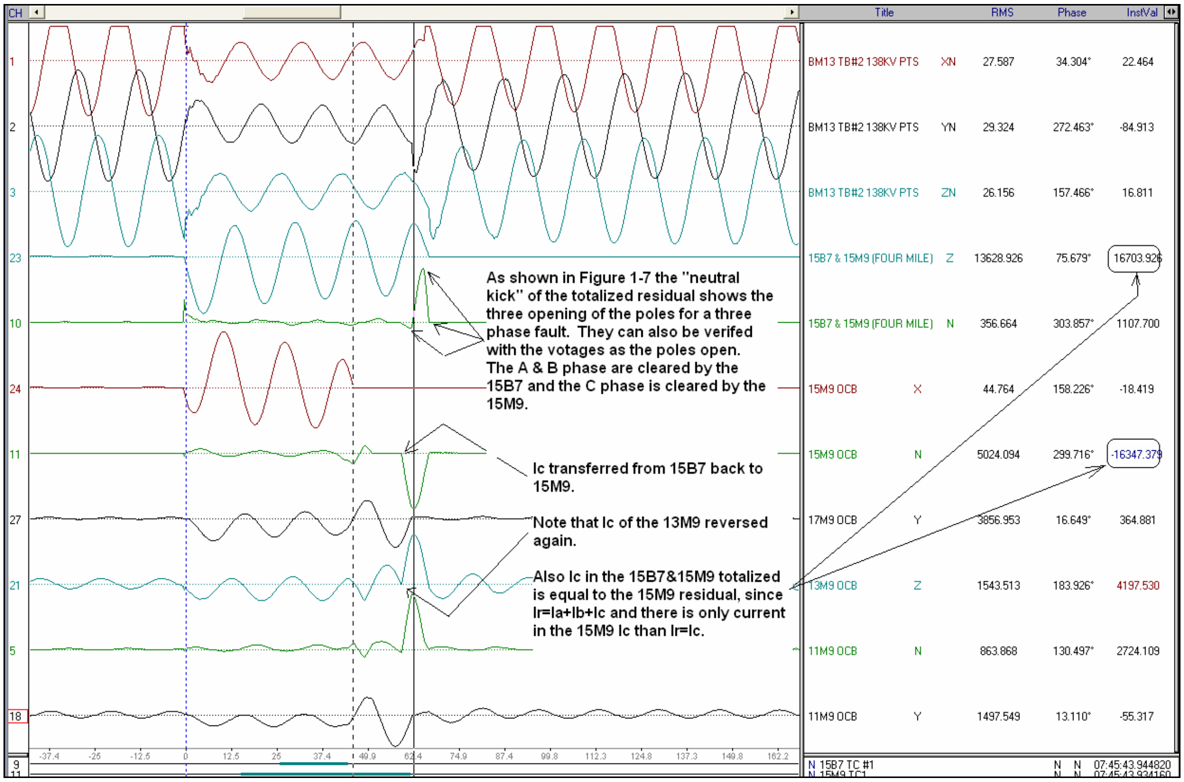


Figure 11-2

Would this be considered a re-strike? What is a re-strike? Papers written from oscillograph records in the 60s and 70s showed re-strikes and explained that the current was cleared for at least a half cycle but reestablished the arc in the breaker as the voltage rose a half cycle later. They never mentioned things like the breaker contacts were fully open when the arc reestablished. Whenever an arc re-strikes when a breaker is fully open, its contacts are fully parted and the breaker is at maximum dielectric strength there is probably something wrong with that breaker. In this case the fault was never cleared and the breaker was only a portion of the way through its travel when the current was transferred to the parallel breaker due to its high arc resistance relative to the parallel breaker. Therefore the breaker did not establish enough dielectric strength in the arc path to avoid re-ignition or re-striking of the arc. This phenomenon is observed approximately 2-4 times per year on the Consumers/METC system. Although it took a DFR to figure out what was going on here, once it was figured out it was abundantly clear that the old oscillogams showed us the same thing. Breakers were inspected when oscillograms led us down the path of thinking this phenomenon was a re-strike and nothing was ever found.

This phenomenon probably isn't just occurring on Consumers/METC breakers. If at least one individual breaker is not monitored it will never be observed. Hence, it's probably been occurring for years on other systems that don't monitor an individual breaker in the breaker-and-a half schemes and they haven't noticed it. Hopefully, if it were causing problems they would have investigated and discovered the cause. Consumers Energy has not encountered any problems with the breakers that exhibit this phenomenon.

EXAMPLE FAULT #12

This example is similar to the previous example except here there is a single line-to-ground fault on the C phase of the WM9 exit (See Figure 12-1). In this fault, the C phase fault current from the 9M9 OCB is transferred to the 9W8 OCB. Now the 9W8 is carrying the total C phase fault current. A half cycle later, the total C phase fault current from the 9W8 OCB is transferred back to the 9M9, so now the 9M9 is carrying the entire C phase fault current. In one more half cycle the total C phase current from the 9M9 is again transferred to the 9W8 OCB. (See figures 12-2 trough 12-4.)

Here a problem was anticipated due to the additional current transfer and because for some reason the 9W8 trip coil dropped out when the breaker 52a contact opened but picked back up and remained energized until the end of the record. A scheduled inspection of this breaker is pending. It is expected that the actual trip coil couldn't have been picked up for too long (seconds or minutes) or it would have overheated and burned up. This line exit has since been successfully test tripped so the trip coil is not burned up.

Other information to consider is that this was a simultaneous fault that started first on the BM11 exit due to a broken standoff ground connection on a pole. The ground wire first hit the BM11 exit line and tripped that line exit first so the 11B7 and 11M9 breakers are open for most of the WM9 exit line fault. As the B phase fault current is passed back and forth from the 9W8 to the 9M9, the current has to pass through the 7M9 OCB and the current on this breaker can be seen flopping 180° every half cycle from the time of the first transfer until the fault is cleared. (See Figure 12-2)

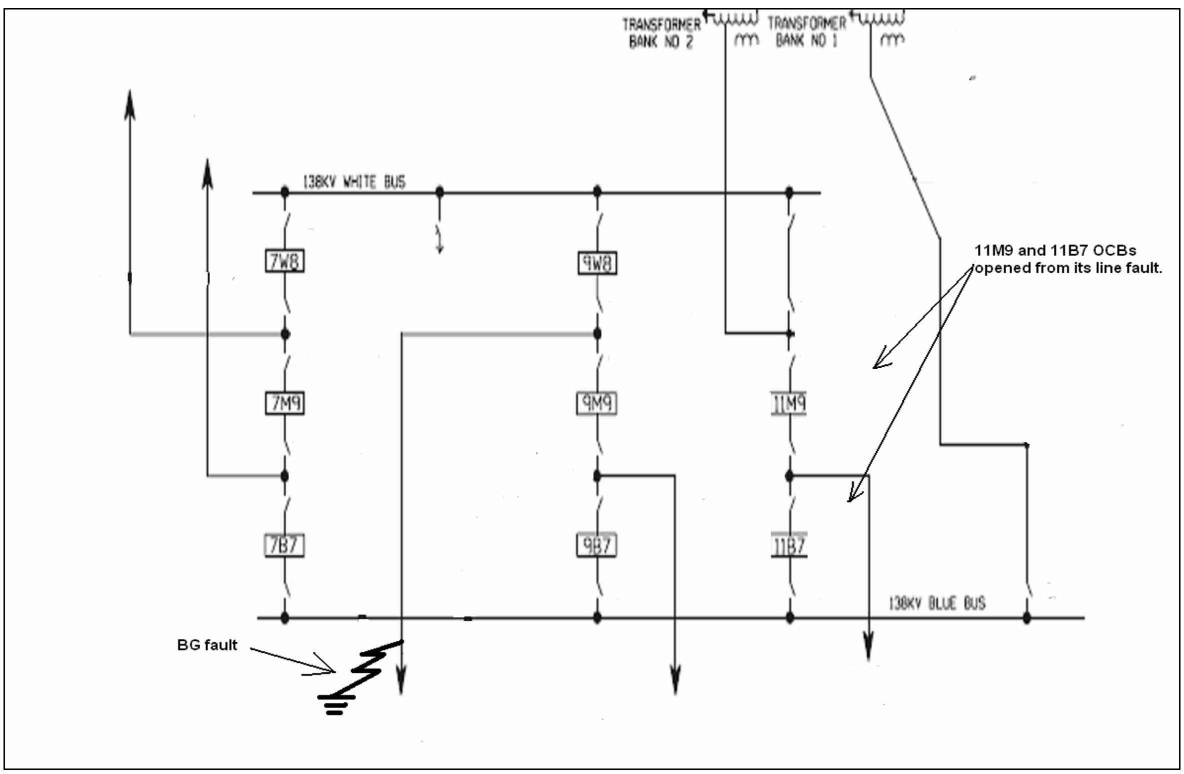


Figure 12-1

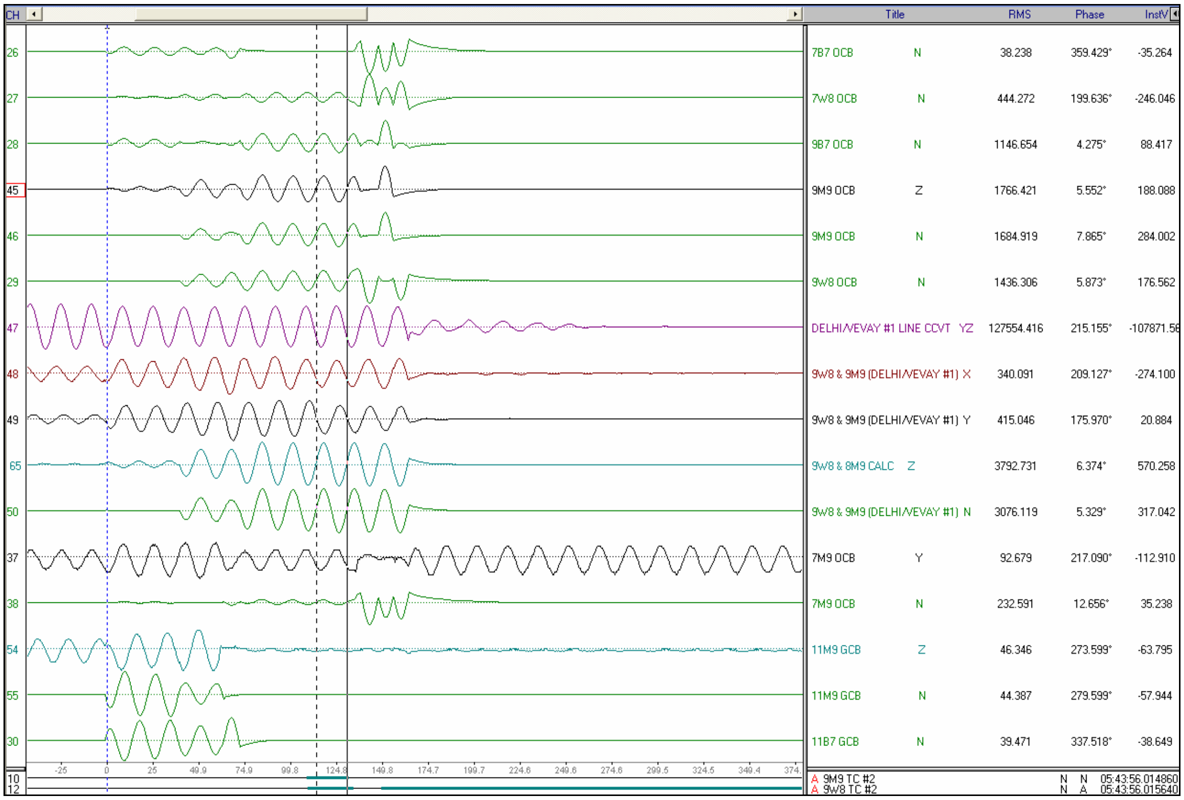


Figure 12-2

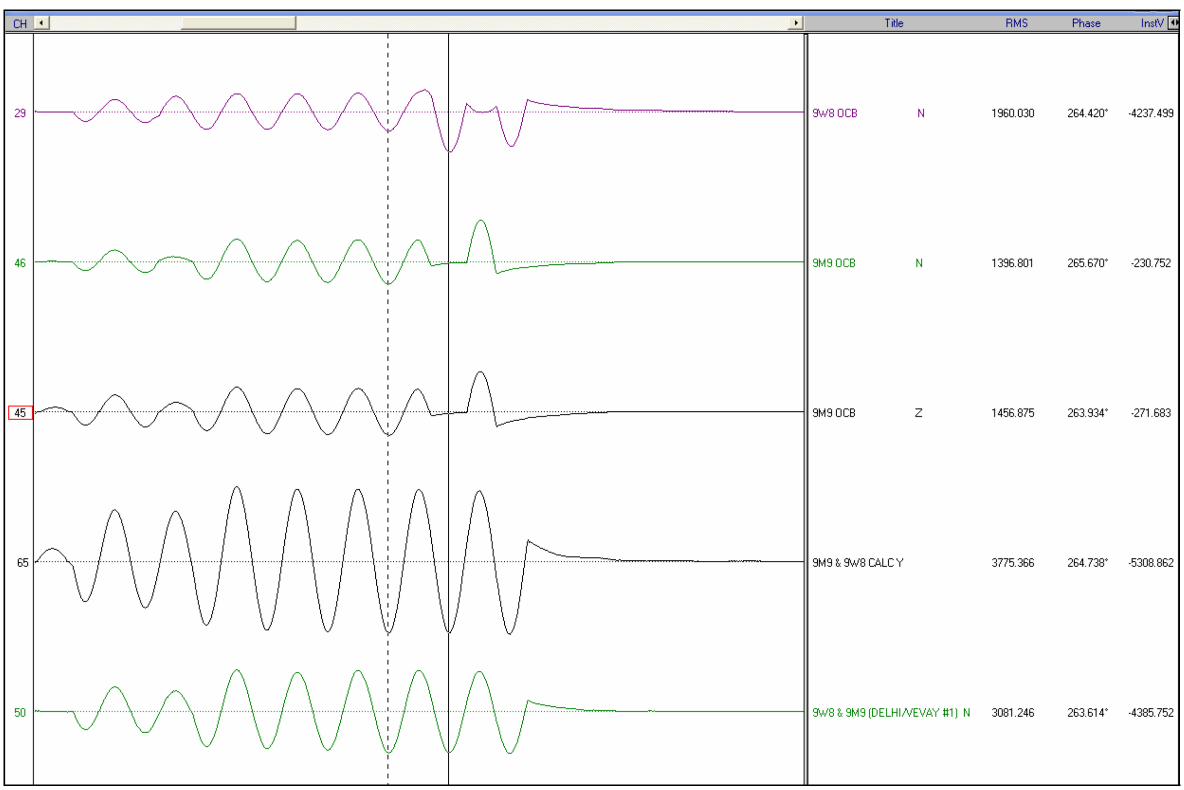


Figure 12-3

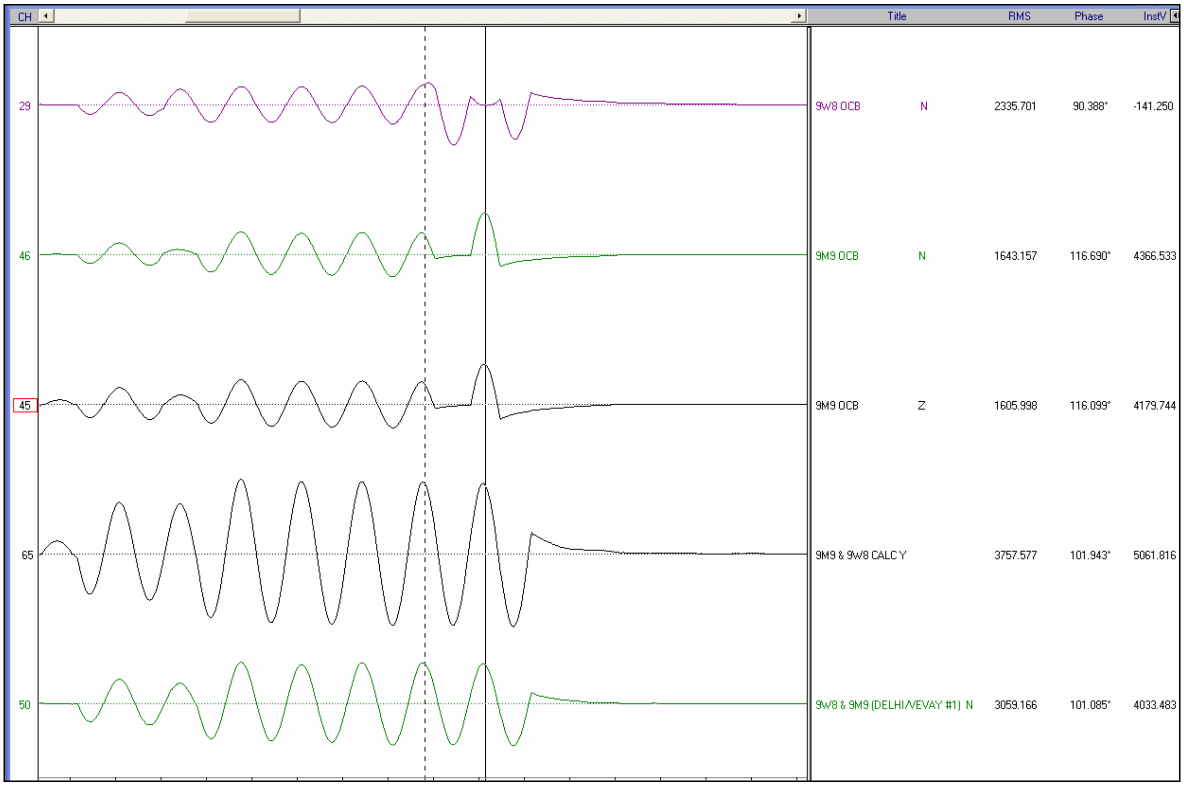


Figure 12-4

<u>EXAMPLE FAULT #13</u>

In this fault, the line was reconductored between the breaker at station One and the switch at station Two. Unfortunately the phases were rolled 120º as they were brought into the switch at station Two. The line was energized from station One up to the clip on the open switch at station Two. The blade side of the switch was energized from station Two. The line was to be put in service by closing this switch at station Two.

The combination of the misalignment of the blades on the switch and the speed at which the switch will close resulted in the C phase blade making contact with (what is now) the A phase clip at least 7.5 cycles before the other phases made contact. Judging by the arc resistance calculated into the fault and the fact that as the fault progressed the currents increased slightly, the C phase blade actually arced to the A phase clip before they physically made contact.

What this resulted in was an unbalanced phase-to-phase fault with ground return. The breaker at station Two was tripped in 4.5 cycles by the instantaneous element of an electromechanical ground relay and the breaker opened in 3.0 cycles for a total fault time of 7.5 cycles. When the breaker at station Two opened the fault was cleared. There wasn't enough current to operate the instantaneous element of the ground relay at station One; if the fault would have continued, the breaker at station One would have operated on the time element.

Figure 13-1 is an equivalent drawing.  Based on the current recorded on the DFR record from station Three the fault appears to be a single line-to-ground fault on the A phase. From the digital relay record from station Four the fault appears to be a single line-to-ground fault on the C phase, although the voltages tell a different story.   Station Five is electrically closer to station Four than it is to station Three.

Note that Figure 13-1 does not show the grounded-wye grounded-wye delta autotransformers at stations Three, Four and Five but they need to be considered a source and return for the ground current.  Figure 13-2 is the record from station Three, Figure 13-3 is the record from station Four and Figure 13-4 is the record from station Five.

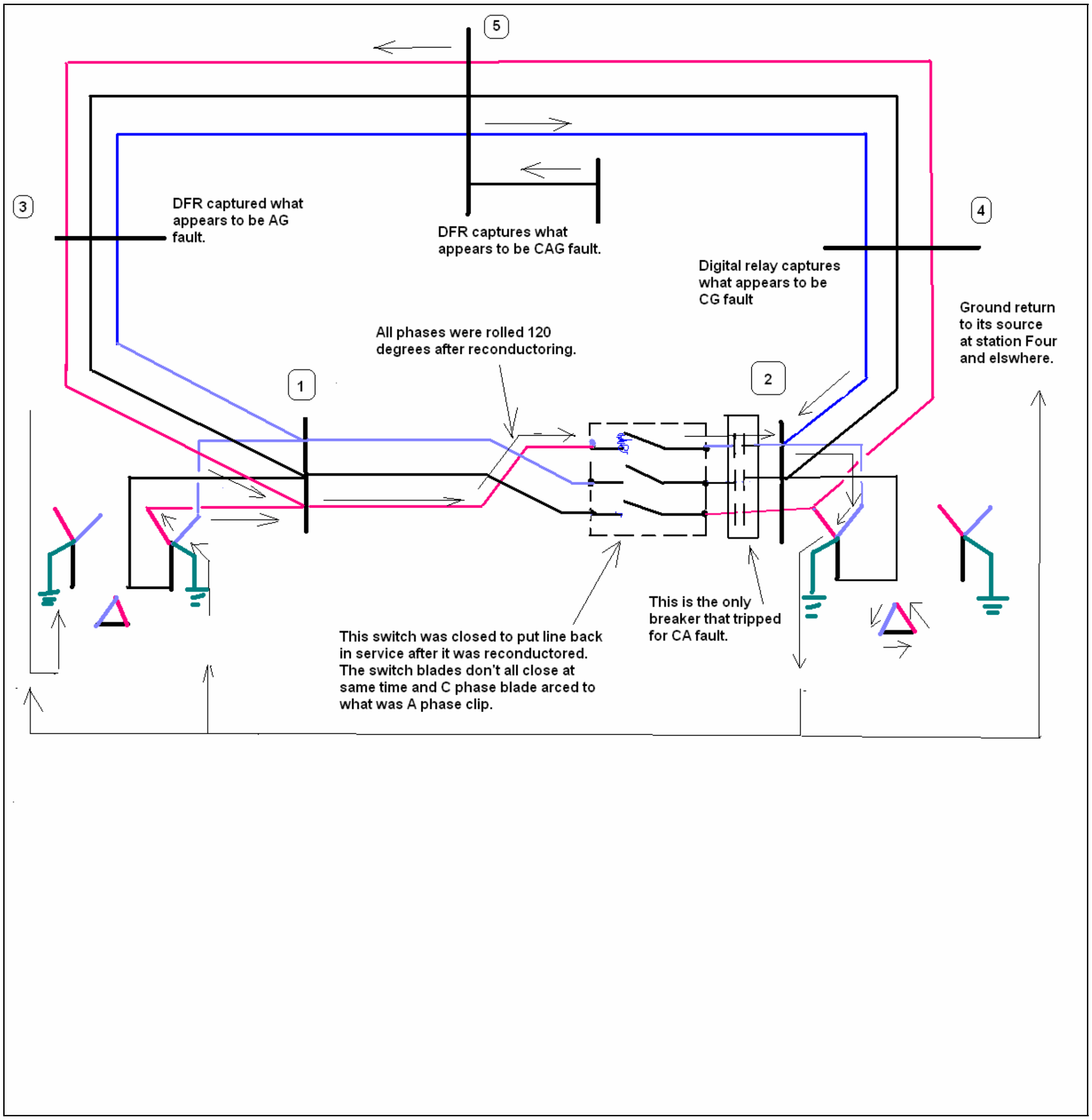


Figure 13-1

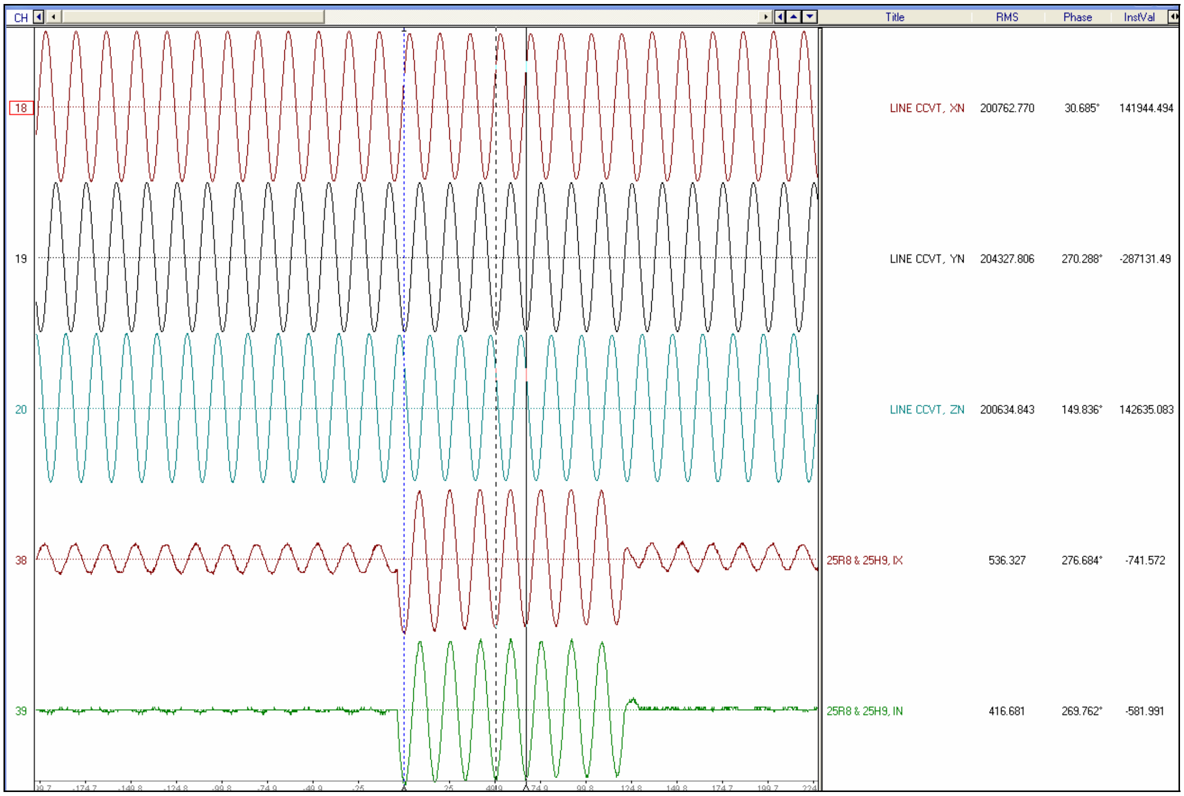


Figure 13-2

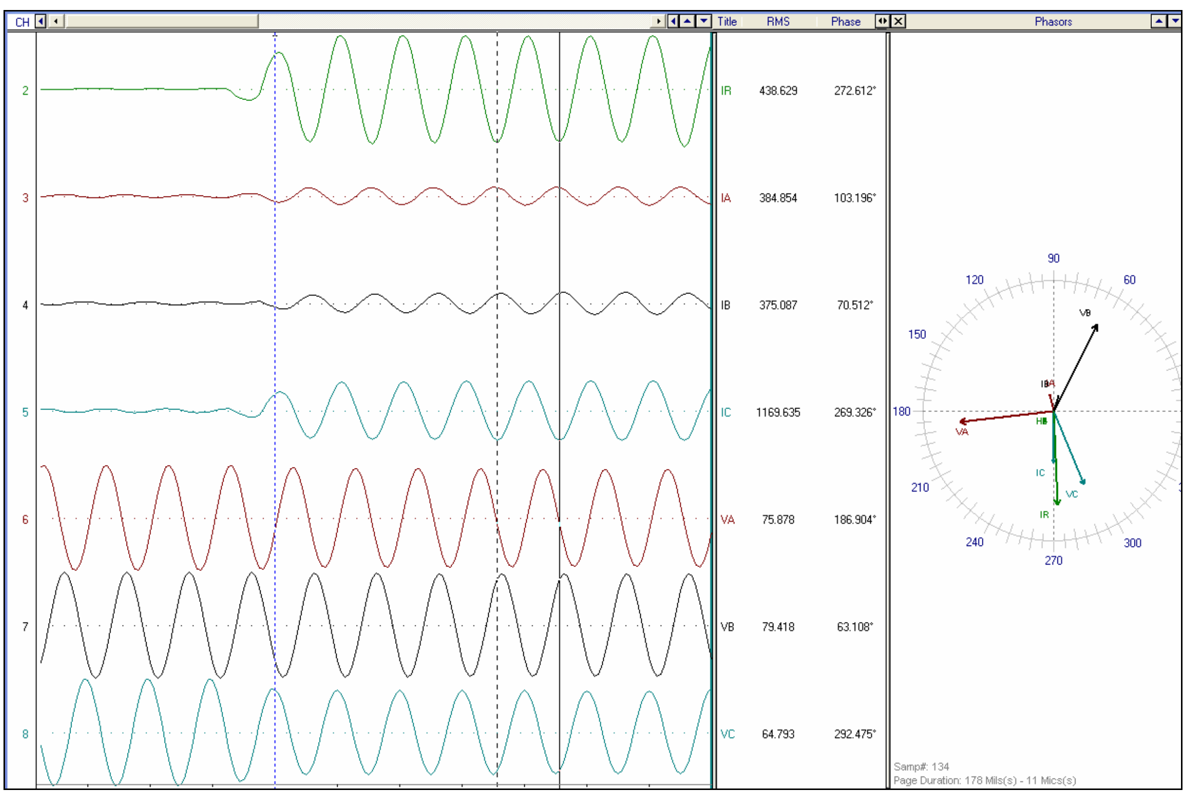


Figure 13-3

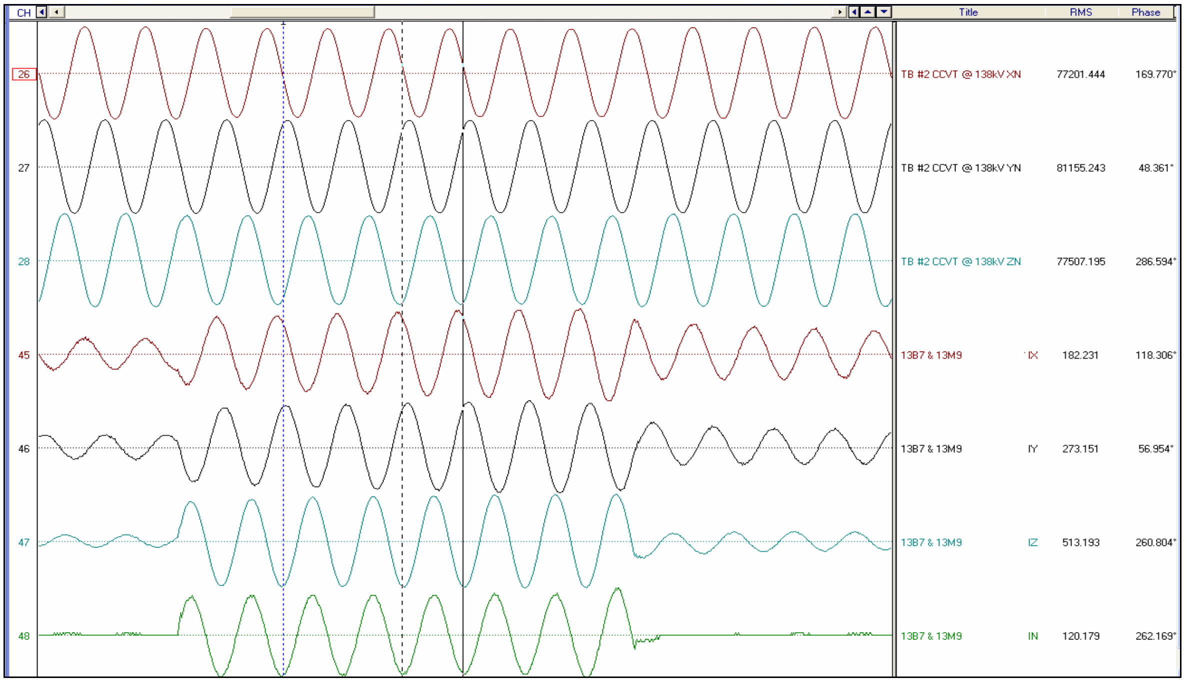

Figure 13-4

CONCLUSION

No matter how much experience a person has, he or she can't know everything. Being a good fault analyst is as simple as just being able to recognize when things don't look right. Once you recognize that situation, the records and data should be examined much more closely and the problem(s) will usually be found. In the process, experience is gained, and future capabilities are enhanced.

ACKNOWLEDGEMENTS

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| | |
|---|---|
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| Richard Pienkos | System Protection – System Relaying |
| Charles Rogers | System Protection – Protection Services |
| Theodore Underwood | System Performance - Substation |
| Matthew Wykstra. | System Protection – Fault Analysis |

BIOGRAPHY

R. J. (Jeff) Ricker received an Associate Degree in Electrical Power in 1977 from Ferris State University, Big Rapids, Michigan. He joined the System Protection (Relaying) Department of Consumers Energy in 1978 and has worked there since with ever increasing responsibilities.

In 1982, Jeff teamed up with a colleague (Len Gonerka) and jointly they revolutionized the company's fault analysis process. Jeff and Len were instrumental in taking the fault analysis tasks from computer punch cards, in house short circuit programs and wet develop oscillographs to a system using a commercial short circuit program, sequence of events recorders, digital relays and digital fault recorders that have remote access and are time tagged with GPS clocks. Jeff now leads this fault analysis activity.

Consumers Energy analyzes every fault on the transmission and the high voltage (46 kV) looped distribution systems to verify proper relay operation and fault clearance. Jeff estimates that he has analyzed 3000 to 4000 faults in the past 24 years.

REFERENCE SHEET FOR BREAKER-AND-A-HALF SCHEME