Using the 121GRAPH Program

by

Dix Fulton
Seattle City Light
Seattle, Washington

Presented to:

Western Protective Relay Conference
Spokane, Washington
October 22-24, 1991

Using the 121GRAPH Program

Dix Fulton
Seattle City Light
Seattle, Washington

ABSTRACT

The paper describes development and use of the 121GRAPH program to graph event reports from an SEL 121 relay. Seattle City Light has developed this program to aid in quick visualization and comparison of fault events by protection engineers. Comparative analysis of the graphs from the program has led engineers to new insights and questions concerning the power system and protection operation during faults.

Among the features included in the program are:

1. ease of use and portability
2. high-resolution printed graphs
3. direct reading by program of relay event reports and settings
4. automatic scaling
5. interpolation between ¼-cycle measurement samples
6. time-domain and impedance-domain graphs
7. three-phase quantities, sequence quantities, status indications, and time reference on a common time axis.

The program development took place on a basic IBM PC, and is intended for use on any compatible machine. Seattle has used modem communications with its relays to gather data for analysis and display by the program.

INTRODUCTION

Seattle City Light began using computer-based relays in 1987. Like some other utilities, we first used the devices only as fault locators. As operating experience was gained, the utility developed confidence to use these relays for primary protection of our 240kV transmission lines. These relays offer impedance relay protection for phase faults, directional overcurrent protection for ground faults, fault location, and 11-cycle event recording.

After we sustained our first few faults, we became intrigued with the information recorded in the 11-cycle event report recorded with each fault. Although we were not sure just how to mine the event reports for information about the power system, we recognized nevertheless that they contained information for future use. Therefor, each report was transferred from the relay's memory for permanent storage before subsequent faults wrote over it. We have collected a database of about 60 fault event records since the first installation. These event records are available to our relay engineers for study.

We have used oscillograph charts for the analysis of faults for many years, but the analog oscillographs we have installed are limited by scale factors, accuracy, resolution, and non-permanent chart paper. Also, only single-phase voltages and currents are recorded, further limiting the use of oscillograph records.

The relay event reports which we record have characteristics which contrast favorably with these weaknesses of the oscillograph charts. It was apparent from our first use of the relay's event reports, however, that they lacked the powerful graphic message of the analog oscillograph.

Seattle City Light set out to make a straightforward program to create charts of the relay event reports in the spirit of oscillograph traces with which our relay engineers were familiar. Our first efforts employed BASIC to draw time-domain traces on a low resolution IBM PC screen. Later we used a Hewlett-Packard pen plotter which was procured for computerized drafting. We have recently expanded our efforts to include drawing graphs on the impedance plane, and we are now printing our graphs with a new Hewlett-Packard Laserjet III printer.

Seattle City Light is a municipal utility, and is not marketing computer programs. The 121GRAPH program for the IBM-PC which has come out of this development is therefor not a commercial-grade product. Nevertheless, our engineers have found it to be a useful tool in understanding the event reports generated by our computerized relays. The program reads an event report which has been received from one of our Schweitzer model 121 relays, and draws the 11-cycle fault on the PC video display and on a Laserjet printer. Both an oscillographic trace in the time domain, and an impedance trace in the R-X plane are drawn.

PROGRAM DESIGN

Input

121GRAPH is designed to read a stored event report. At our Seattle engineering office, we download the event report after every fault using the Procomm communications program, and store it on a disk. If there is a reclose operation and a second trip, or other related events, we may store several event reports in the same disk file. A sample input file is shown in Figure 1.

```
Golden Mountain 230kv Line                   Date: 12/18/90    Time: 22:56:23.108
FID=SEL-121G-R107-V656mpac11-D881024

                      Currents                 Voltages          Relays Outputs Inputs
                       (amps)                    (kV)
                                                                 52265L TCAAAAA DPBD5E
   IPOL      IR      IA      IB      IC      VA      VB      VC  011710 PL1234L TTTC2T
                                                                 P3PNNP             A

      0      -5     159     -19    -136   128.9   -24.2  -104.2  ...... ....... ....*.
      0       9     -30     170    -128   -50.7   135.0   -87.3  ...... ....... ....*.
      0       5    -159      19     136  -128.9    24.2   104.2  ...... ....... ....*.
      0      -9      30    -170     128    50.7  -135.0    87.3  ...... ....... ....*.

      0      -5     159     -19    -136   128.9   -24.2  -104.2  ...... ....... ....*.
      0       9     -30     174    -128   -50.7   135.0   -87.3  ...... ....... ....*.
      0       2    -155      15     136  -128.8    24.2   104.2  ...... ....... ....*.
      0      -7      26    -174     128    50.7  -135.0    87.3  ...... ....... ....*.

      0      -2     155     -15    -132   128.8   -24.2  -104.2  ...... ....... ....*.
      0       7     -26     174    -132   -50.6   135.0   -87.3  ...... ....... ....*.
      4       5    -159      15     132  -128.9    24.2   104.2  ...... ....... ....*.
     -4     -12      30    -174     132    50.7  -135.0    87.3  ...... ....... ....*.

     -4      -2     159     -19    -132   129.0   -23.7  -105.8  ...... ....... ....*.
      4       7     -34     997    -951   -51.3   134.8   -77.1  ...... ....... ....*.
      0      -7    -166    3118   -2956  -131.0     6.7   104.9  M..... ....... ....*.
      0      30      49   -4621    4583    57.5   -92.1    45.1  H..... ....... ....*.
   ------------------------------------------------------------------------------------
      0       7     181   -8445    8245   126.4   -22.3   -90.7  H.1... *.*.... ....*.
      0     -69     -64    7671   -7645   -57.7    54.1   -15.7  H.1... *.*.... ....*.
      0      -2    -189   11096  -10869  -123.3    56.5    75.5  H.1... *.*.... ....*.
      0      83      68   -7751    7736    53.1   -59.4     6.8  H.1... *.*.... ....*.

      0       2     185  -11409   11183   125.7   -53.7   -71.5  H.1... *.*.... ....*.
      0     -87     -68    7573   -7566   -53.0    51.5    -4.0  H.1... *.*.... ....*.
      0       0    -185   11269  -11043  -124.4    56.4    71.5  H.1... *.*.... ....*.
      0      87      72   -7543    7532    51.5   -50.0     2.1  H.1... *.*.... .*..*.

      0       0     185  -11164   10941   124.2   -56.7   -71.7  H.1... *.*.... .*..*.
      0     -83     -68    7566   -7554   -51.2    51.2    -1.9  H.1... *.*.... ....*.
      0      25    -132   11062  -10862  -123.1    54.4    71.6  H.1... *.*.... ....*.
      0      64      34   -7600    7600    49.4   -49.3     1.6  H.1... *.*.... .*..*.

      0     -74      49  -10945   10779   122.9   -55.7   -71.8  H.1... *.*.... .*..*.
      0     -55      -8    7638   -7649   -47.5    50.9    -1.4  H.1... *.*.... .*....
      0      83      -8   10711  -10582  -122.6    53.3    72.5  H.1... *.*.... .*....
      0      60       4   -6781    6803    39.2   -47.3    -4.7  H.1... *.*.... ......

      0     -46       0   -7419    7347   126.5   -48.4   -68.8  H.1... *.*.... ......
      0     -44       0    3266   -3288   -26.4    27.2    13.7  H.1... *.*.... **....
      0      14       0    2435   -2416  -129.2    58.4    62.6  M.1... *.*.... **....
      0      18       4    -370     378    19.0   -15.0   -16.4  M.1... *.*.... **....

      0      -5       0    -336     340   128.5   -65.9   -61.0  ...... ....... **....
      0      -5      -8      49     -49   -18.4    17.3    13.3  ...... ....... **....
      0       2       0      42     -45  -128.6    57.3    61.5  ...... ....... **....
      0       0       4     -15      11    16.7   -11.2    -9.6  ...... ....... **....

      0       0       0       0       4   124.2   -60.8   -62.3  ...... ....... **....
      0       0       0      15     -11     7.8    15.4     9.8  ...... ....... **....
      0       0      -4      -8       4  -119.5    61.7    60.0  ...... ....... **....
      0       0       4     -15      11   -47.0   -19.8   -10.5  ...... ....... **....
Event   : 1BC    Location   : 2.61   mi  0.24   ohms sec
Duration: 5.25   Flt Current: 13401.

R1   =1.82     X1   =10.64    R0   =5.87     X0   =36.76    LL   =14.13
CTR  =240.00   PTR  =2000.00  MTA  =80.00    LOCAT=Y
79OI1=0.00     79OI2=0.00     79OI3=0.00     79RS =7200.00
Z1%  =85.00    Z2%  =120.00   Z3%  =135.00
Z1DP =0.00     Z2DP =18.00    Z3DP =36.00
50L  =1440.00  50M  =2000.00  50MFD=18.00    50H  =5000.00
51NP =240.00   51NTD=2.75     51NC =3        51NTC=Y
50N1P=3840.00  50N2P=3000.00  50N3P=1200.00
Z1DG =0.00     Z2DG =18.00    Z3DG =36.00
52BT =30.00    ZONE3=F        32QE =Y        32VE =N        32IE =N
OSB1 =N        OSB2 =N        OSB3 =N        OSBT =30.00    LOPE =Y
TIME1=5        TIME2=0        AUTO =2        RINGS=1
```

Figure 1

Although the format of the event report is laid out for direct reading by people, its format is regular enough to allow the program to read it as well. The program cannot read the event report correctly, however, if it is edited and its format changed.

While reading current and voltage samples from an event report, the program also reads the status of the six relay elements, seven output contacts, and six input terminals associated with each sample. After these analog and status values are read for each of the 44 sample intervals, the program completes its input by reading the fault summary and the settings report. These last items are used in plotting the impedance trace for the fault.

Interpolation

By comparison with an oscillograph chart or a digital fault recorder record, the Schweitzer relay event report comprises voltage and current samples taken at widely spaced intervals (¼ cycle at 60Hz). To illustrate this effect, a graph of the phase "B" current from Figure 1 is shown in Figure 2. Because the sample rate of the information is too slow to describe any fractional-cycle transients, and is dc filtered anyway, we have chosen to interpolate by fitting the samples to a simple 60Hz sinusoidal waveform. This interpolation technique works by finding the unique 60Hz sinusoid which passes through each pair of adjacent samples. Although the technique uses complex arithmetic, it is fast because it avoids trigonometry or transcendental computations. We have found that plotting interpolated points at 18° intervals (20/cycle) yields a smooth-appearing waveform.

The calculations are performed in FORTRAN, which supports complex arithmetic directly. A complex variable is formed using one sample as the real part, and the previous sample as the imaginary part. Once we calculate the value of an 18° rotation vector, $1\underline{/18^\circ} = 0.31+j0.95$, we can multiply the phasor by this rotation vector four times per sample to derive the four intermediate interpolated values between samples for graphing. Although the first derivative of the resulting curve is discontinuous at the sample points when the input changes abruptly, the plotted trace is always continuous.

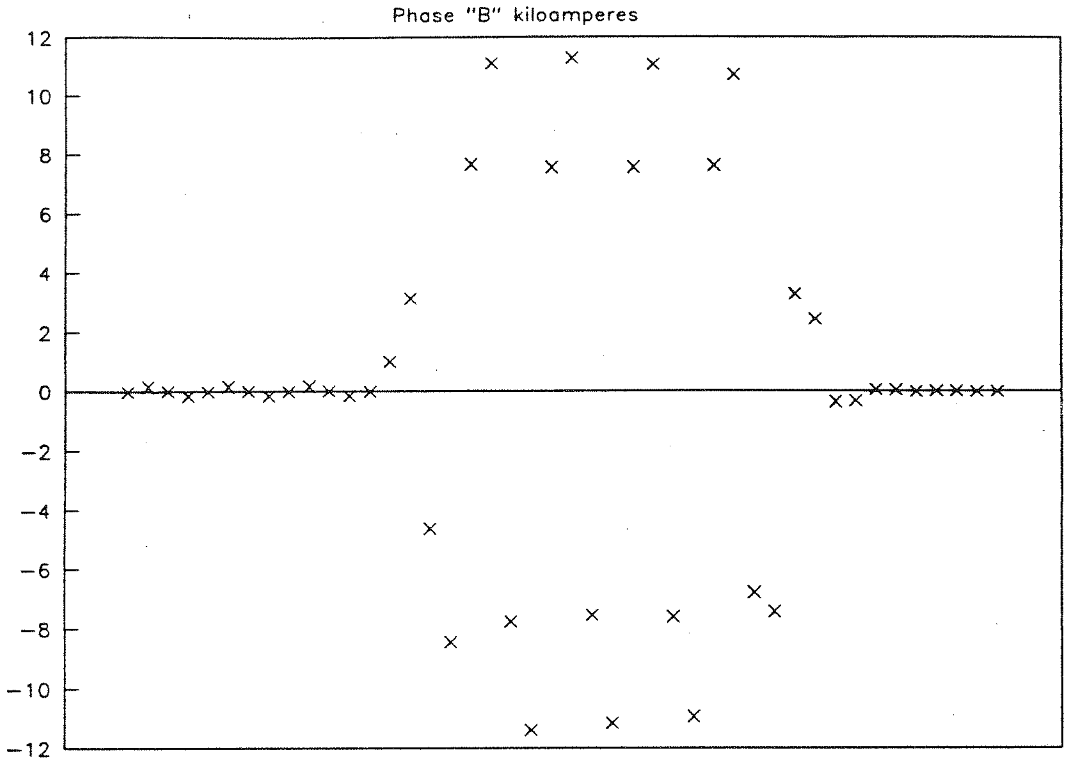


Figure 2

Sequence values

As is shown in Figure 1, current and voltage samples are available for all three phases in the event report. The availability of three-phase data allows the program to calculate positive-sequence, negative-sequence, and zero-sequence traces for both voltage and current. Once again, we use the complex arithmetic built into FORTRAN to simplify these calculations, while avoiding computationally expensive transcendental calculations. The program uses complex expressions like:

```
POSITIVE = PHASOR(1) + PHASOR(2)*a   + PHASOR(3)*a*a
NEGATIVE = PHASOR(1) + PHASOR(2)*a*a + PHASOR(3)*a
ZERO     = PHASOR(1) + PHASOR(2)     + PHASOR(3)
```

where "a" is the 120° rotation operator: -0.50 +j0.87

The computer evaluates these expressions using only scalar addition and multiplication.

Scaling

Scaling for graphs within 121GRAPH is automatic. The program scans the event report for maximum and minimum values of current, voltage, and impedance. These limits are then used to calculate separate scale factors for these three quantities. The data are scaled and plotted in such a way as to provide the maximum resolution on the output page.

The program design does not anticipate that the user will measure quantities directly from the graphs, because they contain no information which is not available numerically from the corresponding event report, itself. For reference, a reminder of the full-scale values are shown at the ends of voltage, current, and reactance axes on the printed output. By convention, the scaling of the graphs, like the scaling of the event reports, is based on RMS values rather than on instantaneous values.

Output

The output of the program is two pages of graphs. These are displayed in color on the video display to distinguish phases. The pages are optionally printed concurrently on a Laserjet III printer. The first (oscillograph) page shows the data from the ¼-cycle samples plotted vertically against the 11-cycle report duration plotted horizontally. The second (impedance) page shows the 11-cycle trace of the fault impedance against a backdrop of the line and relay impedances.

Oscillograph Page

The first page is shown in Figure 3. The vertical axis marks the time reference. The time-axis origin is labelled with the time-stamp from the top line of the event report. The time axis extends from 4 cycles behind to 7 cycles ahead of the vertical axis.

Phase quantities read directly from the event report are shown on the top half of the page. Symmetrical components are shown on the bottom half. On each half of the page, the voltage traces are shown above the corresponding current traces. The color key is as follows:

		Phase traces	Sequence traces
-·-··-	blue(cyan)	phase A	zero sequence
-·-·-·-	white	phase B	negative sequence
- - - -	red(magenta)	phase C	positive sequence

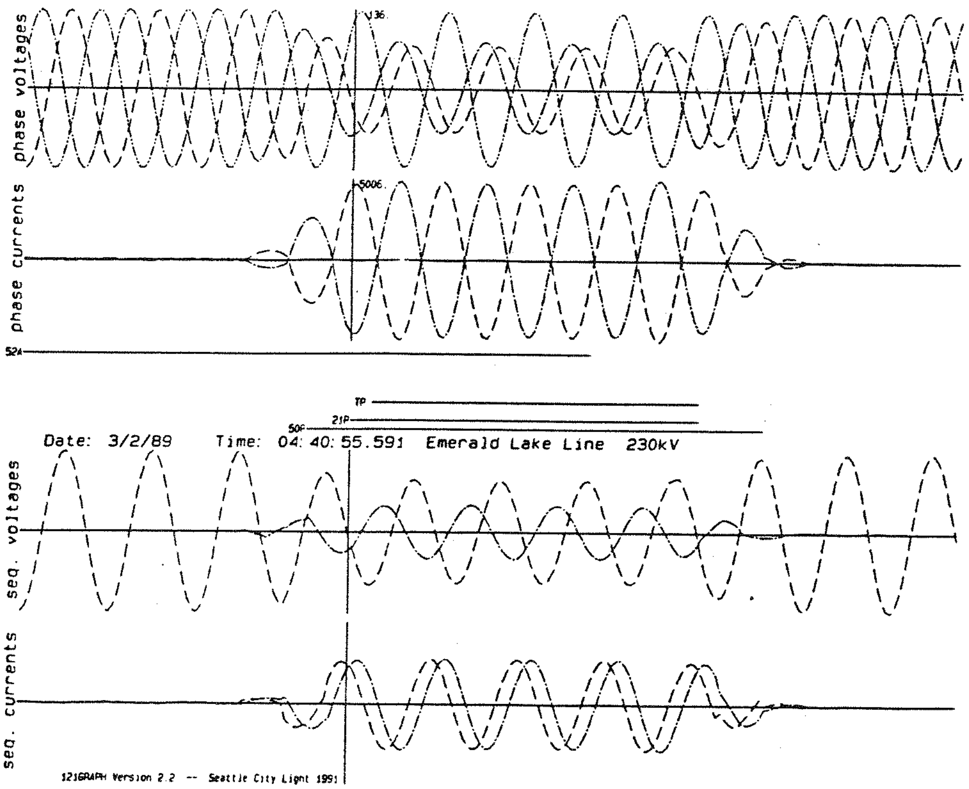


Figure 3

In keeping with the Seattle City Light convention, only the "C"-phase sequence quantities are shown in the lower half of the page. With this convention in effect, a phase-"C"-to-ground fault will show its three sequence currents equal and in phase at the bottom of the page. "A"-phase sequence quantities, of course, will lead or lag the corresponding "C"-phase quantities by 120°.

Positive sequence Negative sequence

Figure 4

The sinusoidal traces are separated by a band of horizontal lines at the center of the page showing, the 19 status values during the period of the event report. Each line shows up when its status value is "ON", and disappears when its status value is "OFF". The lines are drawn in the order that the status indicators appear on the event report, with the "50P" status shown at the bottom of the band, and the "ET" status shown at the top.

Impedance Page

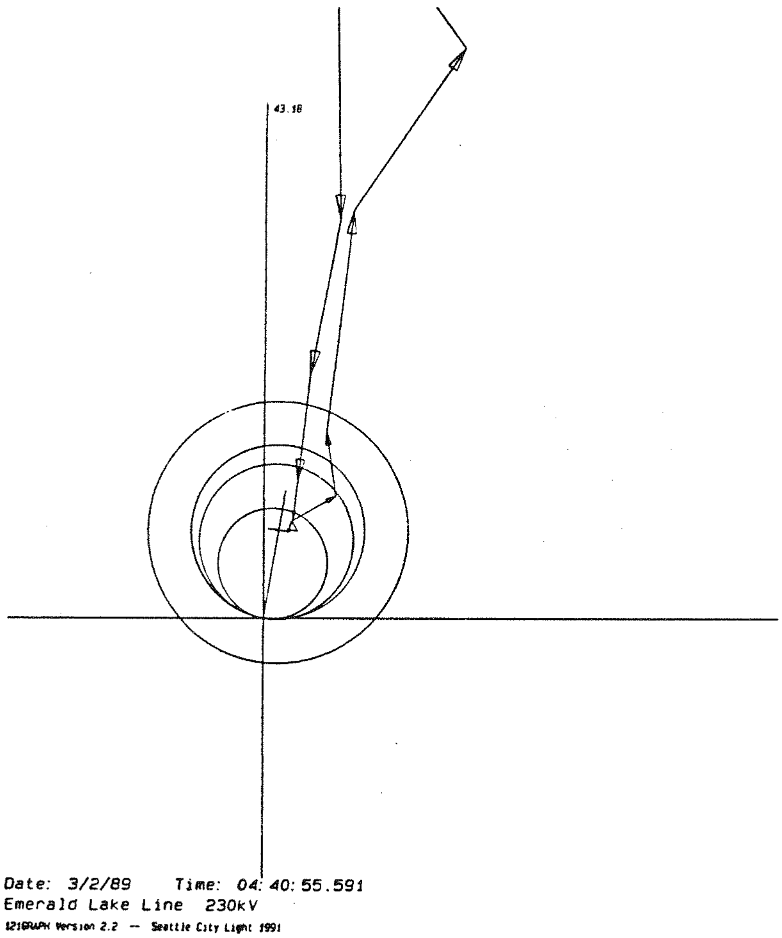


Figure 5

The second page of output is shown in Figure 5. This page shows the transmission line, the calculated fault point, and the relay's mho-characteristic zone-circles as background for the fault trace. The 11 cycles of fault data are plotted as points on the impedance plane. Each of these items is drawn by a subroutine called with complex-number arguments.

The graphic origin of the impedance page marks the model 121 relay location. The transmission line is drawn from the relay to its far end in the first quadrant. Unless the fault is a ground fault, the zone 1, zone 2, zone 3 and zone 4 impedance circles surround the line. A tick mark is drawn on the line at the point where the relay has calculated the fault to be. For external faults, the tick mark is show beyond the far end of the line.

The impedance is drawn against this backdrop. Adjacent points on the path are separated by the ¼-cycle sample interval of 4 milliseconds, and are connected by line segments. On the screen, the path is traced one sample at a time, as the viewer watches an animation of the developing fault. On the corresponding Laserjet output, the line segments are shown with arrowheads to indicate their direction.

For a typical fault the user sees the impedance swiftly enter the field of view, travelling from the prefault load point toward the origin, crossing the mho circles until it reaches the transmission line. The impedance lingers for a few cycles near the line until the breaker contacts open, and then disappears toward infinity as the arc is extinguished.

WHAT WE HAVE LEARNED

Looking Back

On the Seattle system, our relays are applied to look forward into the protected lines. When we use a model 121 relay, event reports are created automatically only for internal faults on these lines. After applying the 121GRAPH program to study these internal fault records, we decided to experiment with recording and graphing faults behind the relay.

For the permissive overreaching transfer trip schemes typical for our lines (see Figure 6), a microwave signal is transmitted to the opposite terminal whenever a zone 2 fault is detected. This signal, when received, allows the far end to trip without delay for any internal fault. Because it is based on an overreaching element, the permissive signal is transmitted for a range of faults beyond the far end of the line.

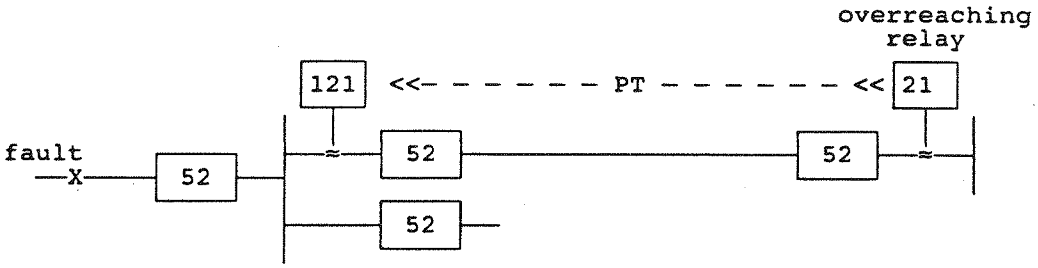


Figure 6

We have been able to use the overreaching action of the remote terminal to look behind the relay. If a fault occurs on a line behind the relay, but within the pickup zone of the overreaching relay at the far end of the line, the local terminal will receive the permissive signal from the microwave circuit. Although no local evidence of a fault is observed by the relay, it will initiate a fault record when the permissive signal is received. The fault record triggered in this way will show the depressed station voltage and current contribution to the fault from the protected line. (See Figure 7)

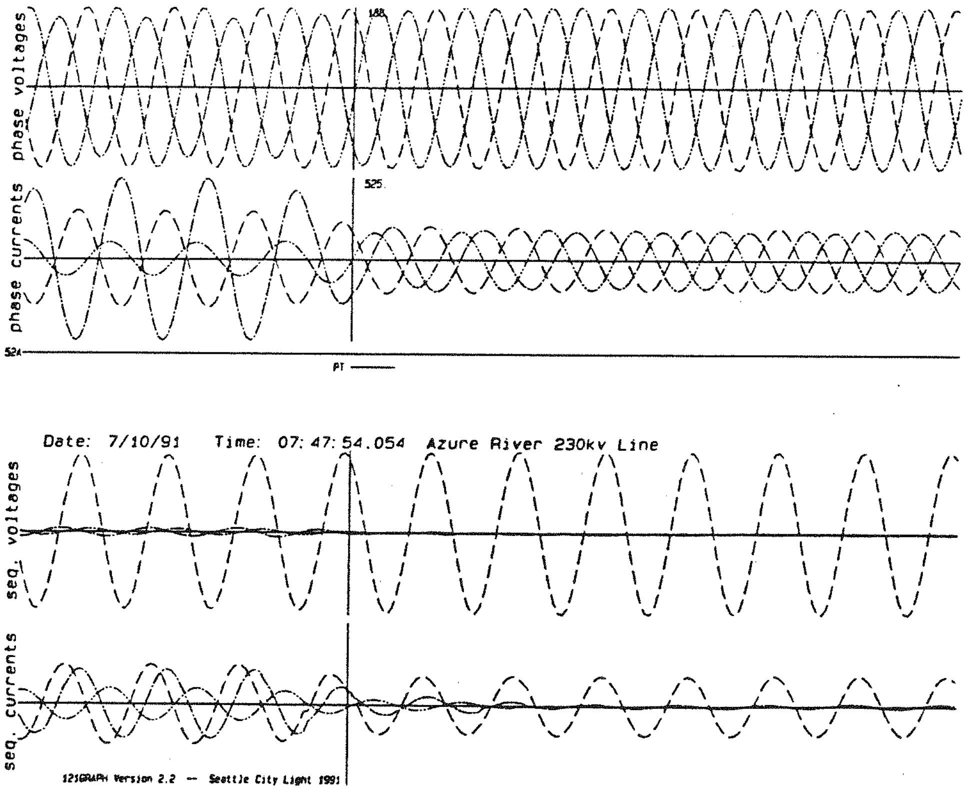


Figure 7

The Lingering Potential

Comparison study of the graphs of faults on a line protected by 121 relays at either end have revealed an interesting phenomenon which had been overlooked until the 121GRAPH output became available. A careful review of analog oscillograph traces has since confirmed the existence of the phenomenon, but our engineers have yet to explain the events which the equipment has recorded.

Figure 8 furnishes the background context for understanding this phenomenon. The 121 relays protect the lines at both ends. At the left terminal, the voltage inputs to the relay are taken from voltage devices on the line side of the circuit breaker. At the right terminal, the voltage inputs are taken from the bus side. After the fault cleared, we expected the voltage to vanish promptly in the left terminal event record, and to return to nominal levels in the corresponding right terminal event record. Actual recordings show otherwise.

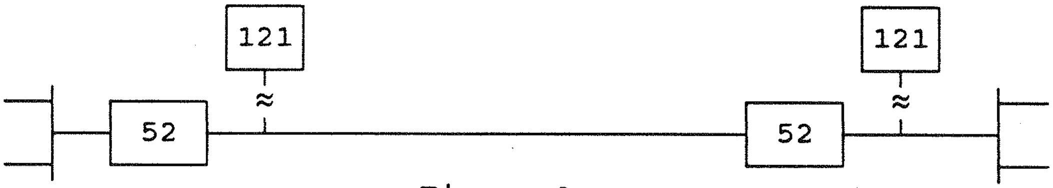
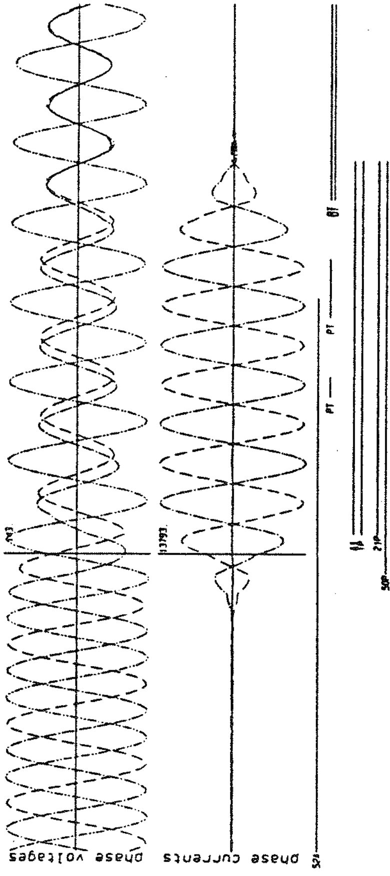


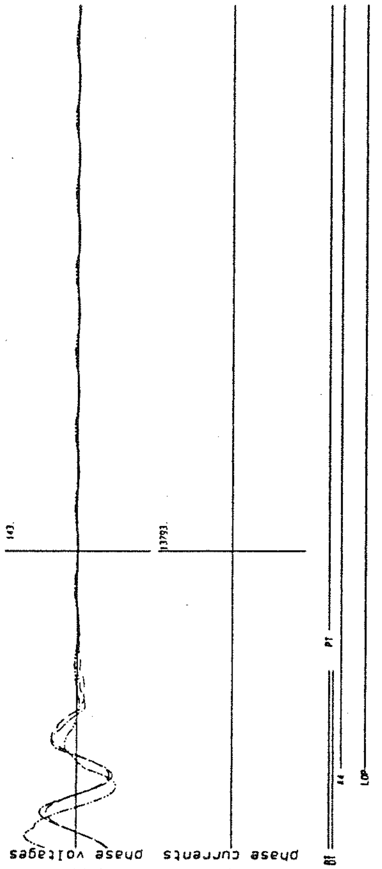
Figure 8

Figure 9 shows the graphs of three event reports with a common time reference. Two of these events occurred at the left terminal, the second immediately following the first. The third was taken from the right terminal, where the voltage came from the bus instead of from the line. The graphs clearly show five cycles of fault current fed from the left terminal, and five-and-a-half cycles of current fed from the right. After the right breaker opens, the right terminal bus voltage rebounded to a balanced 240kV as expected.

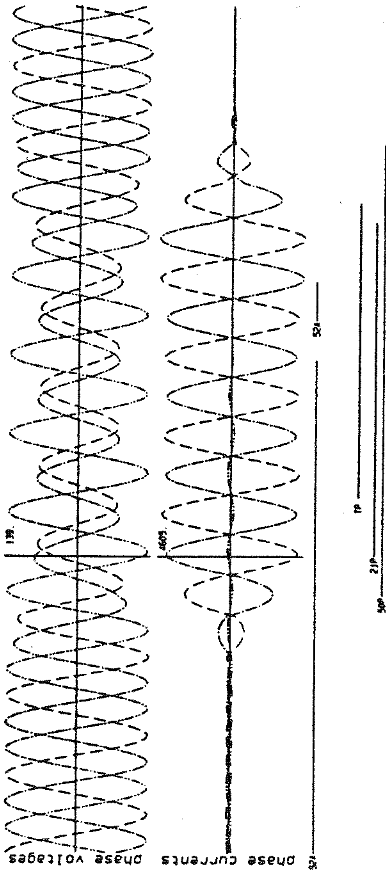
The line voltage at the left terminal exhibited an unexpected pattern, however. The small difference between the V_B and V_C during the period of fault current is explained as the effect of the small impedance of the line between the measurement point and the fault. Similarly, the coincidence of V_B and V_C immediately after the left breaker opens is explained as the open-circuit measurement by the left relay of the voltage at the fault point, as the fault current continues to be fed from the right terminal. Yet unexplained, however, is the apparent lingering on the line of about 180kV for 3 cycles following the final opening of the right breaker.



Date: 12/18/90 Time: 22:56:23.108 Golden Mountain 230kv Line Left Terminal



Date: 12/18/90 Time: 22:56:23.291 Golden Mountain 230kv Line Left Terminal



Date: 12/18/90 Time: 22:56:11.679 Golden Mountain 230kv Line Right Terminal

Figure 9

Unfortunately, the event report from the right terminal wasn't available until several days after we studied the event report from the left terminal. In the interim, we mistakenly concluded that the right breaker had a slow, 9-cycle opening time. The graph of the right terminal event report effectively contradicts this explanation. Station oscillograph traces, although with poorer resolution and doubtful synchronization, confirm the evidence of the graphs. The voltage is sustained for several cycles after the fault is cleared. We are pursuing the theory that what we have observed is related to 60Hz ringing in the capacitor potential devices used at the left terminal.

Unbalanced normal voltage conditions

Finally, the 121GRAPH program has called our attention to imbalance under normal load. To study a line under load, an event report may be triggered at will. The non-fault event report obtained this way may contain evidence of unbalanced inputs which are not obvious from looking at a 6x44 tabulation of sample measurements. Graphing the non-fault event report makes it easy to evaluate an imbalance quickly and to quantify it roughly, by looking at either at the phase quantities or the sequence quantities.

CONCLUSION

The 121GRAPH program has helped Seattle City Light better understand the operations of both its electric system and the modern relays which protect it. The program has breathed life into the static images in the textbooks on the bookshelves of our relay engineers. It has helped us gain confidence in our protection system.