# A Unique Application of Current Differential Relaying at the Los Angeles Department of Water and Power's HVDC Converter Station in Sylmar, CA

By

**Fahrudin Mekić**
ABB Inc.

**Jeffrey Thornburg**
The Los Angeles Department of Water and Power

**Ron Y. Beltran**
ABB Inc.

Presented to:
**31th Western Protective Relaying Conference**
Spokane, Washington
October 19-21, 2004

# I. A Quick Introduction to HVDC Transmission Systems

## 1.1 INTRODUCTION

Transmitting energy in the form of high-voltage direct current (DC) is a technical and economical alternative to alternating-current (AC) transmission. It is used for transferring power in bulk over large distance by overhead transmission line; coupling non-synchronous networks ;and supplying densely populated areas that are transmission constrained.

The basic principle of a typical High-Voltage Direct-current (HVDC) link is shown in Figure 1. The AC voltage of a supply system, which may also be a single power station, is first transformed to a value suitable for transmission. It is then rectified in a converter arrangement with controlled valves. A second converter is required at the other end of the link. This is operated as an inverter and converts the DC back into AC, which is then transformed to the voltage of the network being supplied.

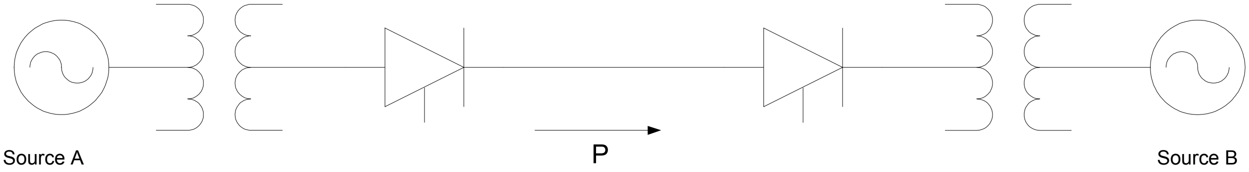


**Figure 1:** Block diagram of a typical HVDC link

The flow of power along the line is determined by the difference between the DC voltages at the ends of the line and by the resistance of the line, according to the formula:

$$P_d = \frac{V_{d1}^2 - V_{d2}^2}{2 * R}$$

$P_d$ is the power referenced to the middle of the line; $V_{d1}$ and $V_{d2}$ are the DC voltages at the beginning and end of the line; and $R$ is the line resistance.

The frequency and phase position of the two networks connected via the HVDC link have no effect on the transmitted power. Therefore, transmission stability is not a problem as networks of different frequency can be coupled. Utilizing the three-phase bridge circuit used in HVDC systems, the equation for the DC voltage of the converted is:

$$V_d = k * V_v * (\cos\alpha - \frac{v_k}{2} * \frac{I_d}{I_{dN}})$$

Note that $V_v$ is the valve-side voltage of transformer, $\alpha$ is the control angle of the converter, $v_k$ is the transformer's relative impedance voltage and $I_d$ is the DC current. Since the DC voltage can be altered almost instantly with the phase-angle control system of the converters, the transmitted power can be varied very quickly and within wide limits.

By changing the control from rectifier to inverter mode $(\alpha > 90^0)$; it is possible to reverse the DC voltage and hence the energy flow direction, whereupon the speed of reversal can be adapted as necessary to the needs of the coupled networks. The fast response of the converter control can even be used to support stability by slightly modulating the transmitted power to attenuate power fluctuation in one of the networks.

Because of delayed ignition and commutation overlap, line-commutated converters require fundamental frequency reactive power:

$$Q = P_d * \tan g(\varphi)$$

$$\varphi = \arccos(\cos\alpha - \frac{v_k}{2} * \frac{I_d}{I_{dN}})$$

where $\varphi$ is the displacement angle of the fundamental frequency.

The fundamental frequency reactive power requirements of the HVDC converter at rated load are about 50% of the active power. By means of special control modes it can be varied within certain limits, so a HVDC converter can assist to maintain voltage stability in the three-phase network.

## 1.2 HVDC SYSTEM COMPONENTS

### HVDC Converter station – Equivalent Circuit

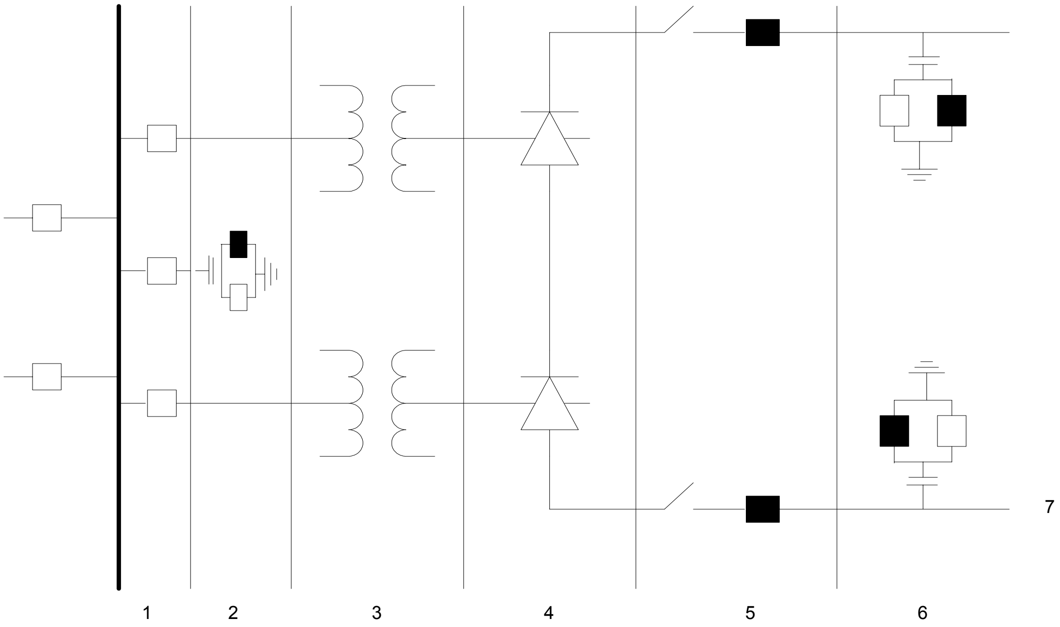


**Figure 2. HVDC Converter Station – Equivalent Circuit representation. Please note components identified below:**

1. AC Switchgear
2. AC filter and reactive power compensation
3. Converter transformers
4. Converter bridges
5. DC switchgear
6. Smoothing rector and dc filter
7. DC line poles 1 and 2

The AC switchgear consists of the feeders to the converters, and also the various branches for filter circuit and capacitor banks. The AC filters are required to absorb current harmonics generated by the converter, and to reduce distortion of the system voltage.

With 12-pulse converter units it is customary to use tuned series resonant circuits for the 11th and 13th harmonics together with broad-band high-pass filters for the higher harmonics. These AC filters also furnish some of the fundamental frequency reactive power needed by the converters. The remainder has to be provided by capacitor banks.

The converter transformers convert the network voltage into the three-phase voltage needed by the converter bridges. A 12-pulse converter unit requires two transformers connected differently to produce the two three-phase systems with a phase offset of 30 degrees. Converter transformers for HVDC are built with two or three windings in single-phase or three-phase units. When the converter valves operate, the windings on the valve side are galvanically connected to a high DC side, and the dielectric strength of their main insulation therefore has to be designed for high DC voltage. Windings and iron have to be specially dimensioned owing to the high harmonic currents and the consequent leakage flux.

The converter units each consist of two three-phase bridge arrangements with their respective transformers, one of which is in Wye/Wye connection, and other in Wye/Delta connection (150 degrees phase shift). On the DC side they are connected in series and on the AC side are brought to a common circuit breaker to form a twelve-pulse unit.

A 12-pulse converter unit consists of twelve valves made of thyristors. Due to high valve voltages up to a hundred thyristors are connected in series. To obtain a uniform voltage distribution the tyristors have additional circuitry consisting mainly of RC components .The valves are ignited electronically by devices triggered by light pulses fed through fiber-optic cables.

Ground faults on a DC line are cleared by controlling the voltage to zero. DC circuit breakers are therefore not necessary with a straightforward HVDC link. Multi-terminal HVDC systems can however benefit from HVDC breakers as these improve the system's performance. The first multi-terminal HVDC transmission system was commissioned in North America in early 1992.

The smoothing reactors used on DC side of HVDC stations smooth the direct current and limit the short-circuit current in the event of line faults.

The DC voltage is filtered with DC filters. Their characteristics are matched to the date of the transmission line as this is particularly important to avoid resonance at the 1st and 2 nd harmonics of the network frequency.

The lines for the two DC poles are usually carried on a transmission tower. This is called a bipolar line.

**Figure 3. New Bi-pole installation at LADWP.**

## II. THE LOS ANGELES DEPARTMENT OF WATER AND POWER SYLMAR CONVERTER REPLACEMENT PROJECT

This project includes the installation of a 3100MW DC bipole consisting of two - 500kV DC poles each designed as 12-pulse converters rated at 1550MW. The new bipole replaces two, older bipoles scheduled for removal. Two, ½ mile long bus-ties spanning the Interstate 5 expressway connect each pole to the 230kV Sylmar Switching Station using a double-bus-double-breaker configuration. The AC current rating of each of the 230kV bus ties are 5000 amps. Each of the 230kV AC bus ties includes a "T"-tapped AC filter yard connected through a main, 230kV breaker.

## LADWP SYLMAR AC BUS TIE PROTECTION REQUIREMENTS

1. Primary High-Speed Line Current Differential Relay.
2. Coordinated Back-up Step-Distance Relay.
3. Breaker Failure Relays.

## LADWP RELAY CONCERNS

1. The line current differential relays must be secure and reliable for all faults occurring during both monopole and bipole operation of the station, at any power level up to and including the full rating, and for any filter bank configuration. Of particular concern are the effects of all possible harmonic currents on the relay's operating algorithms. The line

current differential relays must be flexible to accommodate both 56kb RS422 communications as well as C37.94 standard over fiber optics, depending on the final design by the telecommunications groups.

2. Primary and backup protections must not trip for converter firing failures or filter group short circuits.
3. AC relay trips must open both the AC switchyard breakers and block the DC converters to clear the fault and prevent damage of filter groups and converter transformers caused by high currents.
4. The HVDC converter transformers were equipped with 3 sets of ANSI C800 5000/5 relay CT's on the AC side, 230kV bushings. 2 – CT sets were used by the Contractor for the converter transformer protection. The 3rd CT was made available to the LADWP for AC bus tie relaying.

### III. SYSTEM MODELING AND SIMULAITON

The basic model used for the simulation of different fault types is shown in Figure 3. Two current differential relays are connected at the measuring points I_LiP3 and I_TrP3. The other two current differential relays are connected to measuring points I_LiP4 and I_TrP4. COMTRADE files are generated for different fault types at different fault locations as shown in Figure 3 and listed in Table 1 using PSCAD/EMTDC software.

PACIFIC INTERTIE TRANSMISSION

Simulated Fault Cases

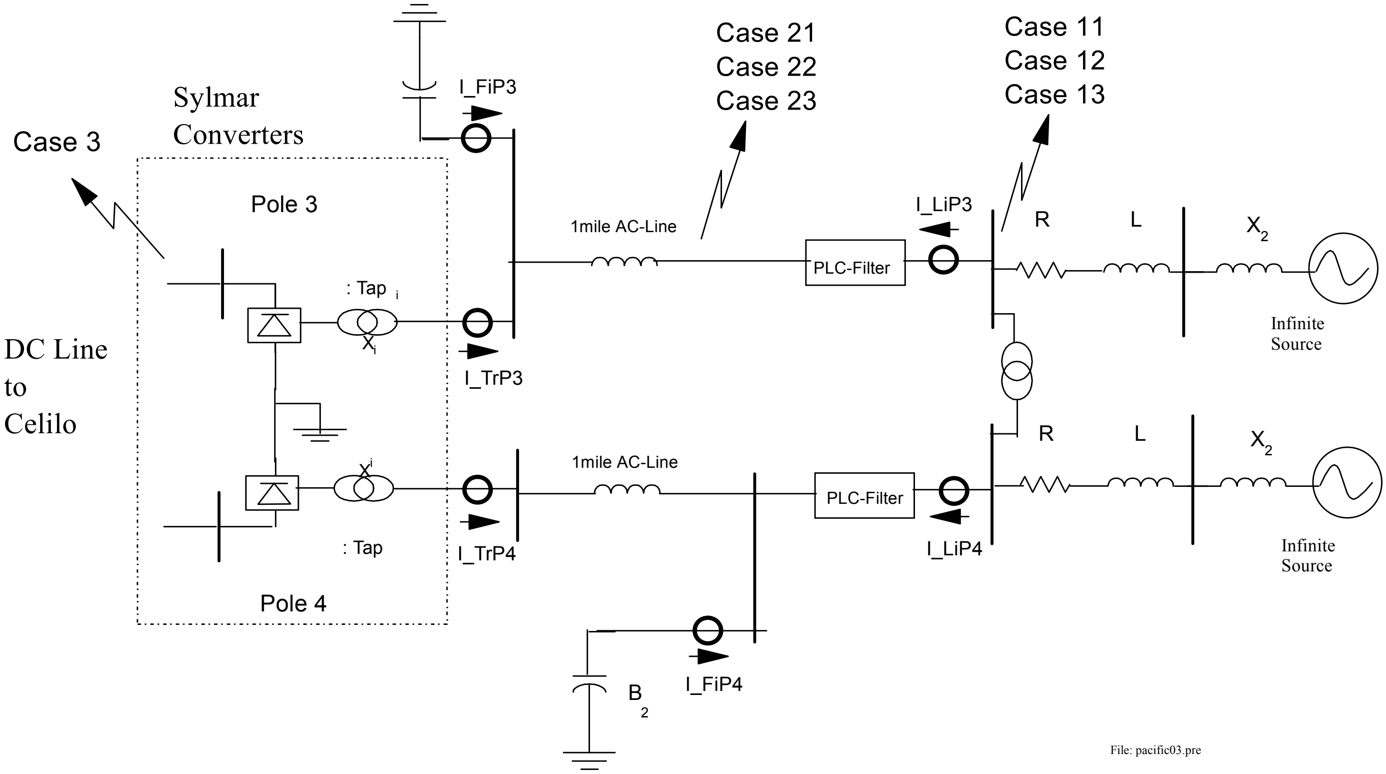


**Figure 4. Pacific DC Intertie simulated system for different types of internal and external faults.**

## Table 1. Summary of simulated faults.

| Case # | Fault # | Fault Type |
|---|---|---|
| | | |
| **11** | **1.1** | AG |
| **12** | **1.2** | AB |
| **13** | **1.3** | ABCG |
| **14** | **1.4** | ABG |
| **15** | **1.5** | ABC |
| **11** | **1.6*** | BG |
| **11** | **1.7*** | CG |
| **12** | **1.8*** | BC |
| **12** | **1.9*** | CA |
| **14** | **1.10*** | BCG |
| **14** | **1.11*** | CAG |
| **3** | **3.** | DC Line fault in the Sylmar station |
| | | |
| **21** | **2.1** | AG |
| **22** | **2.2** | AB |
| **23** | **2.3** | ABCG |
| **24** | **2.4** | ABG |
| **25** | **2.5** | ABC |
| **21** | **2.6*** | BG |
| **21** | **2.7*** | CG |
| **22** | **2.8*** | BC |
| **22** | **2.9*** | CA |
| **24** | **2.10*** | BCG |
| **24** | **2.11*** | CAG |
| | | |

## IV. Play-Back of COMTRADE Files Using Real-Time Digital Simulator (RDS1)

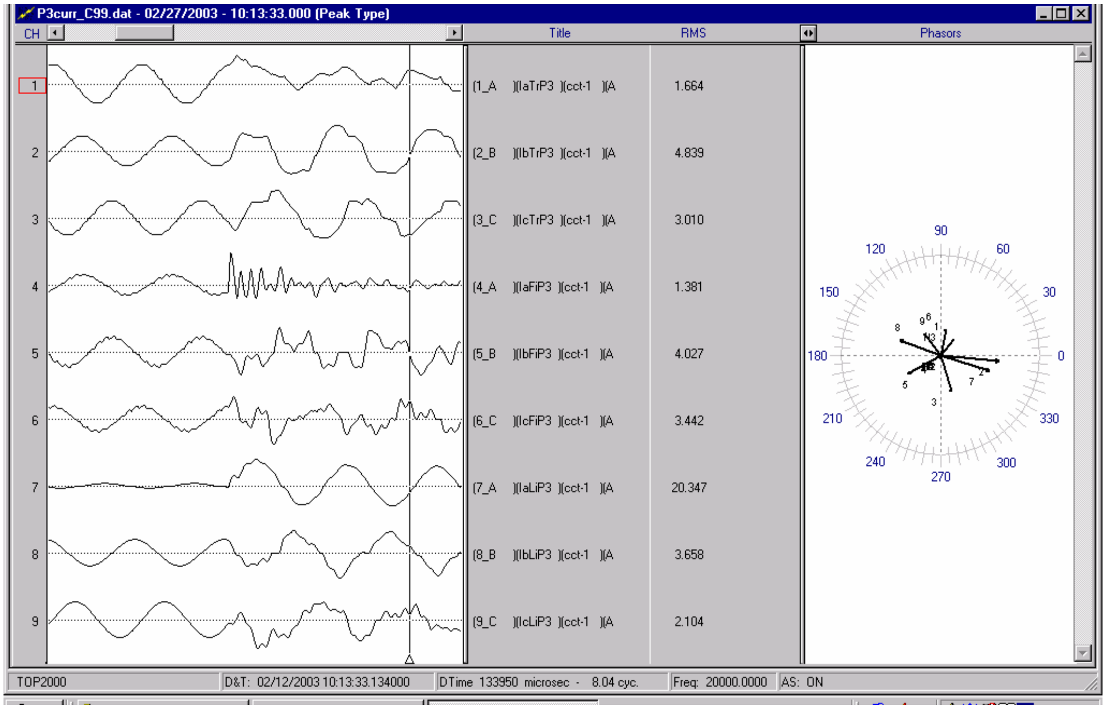
Real-time Digital Simulator with amplifiers and relays, used for playing back the COMTRADE files to current differential relays. The simulator is based on the ARENE, from Anhelco. Simulator outputs are presented to the relays through amplifiers. A Laptop computer is used to interface with the relays by taking care of the such tasks as uploading and downloading settings as well as oscillographic data.

## V. TEST RESULTS

The Pacific intertie AC line at Sylmar substation was protected by current differential relays as per Figure 3. Only bipolar operation of the DC system was simulated. Different types of internal and external faults were simulated. Detailed test results are listed in Table 1 and Figures 5 thru Figure 16:

- Current differential relays connected to the I_LiP3 and I_TrP3 measuring points operated correctly for each internal fault and restrained correctly for each external fault.

- Current differential relays connected to the I_LiP4 and I_TrP4 measuring points restrained for each fault as they are external faults.

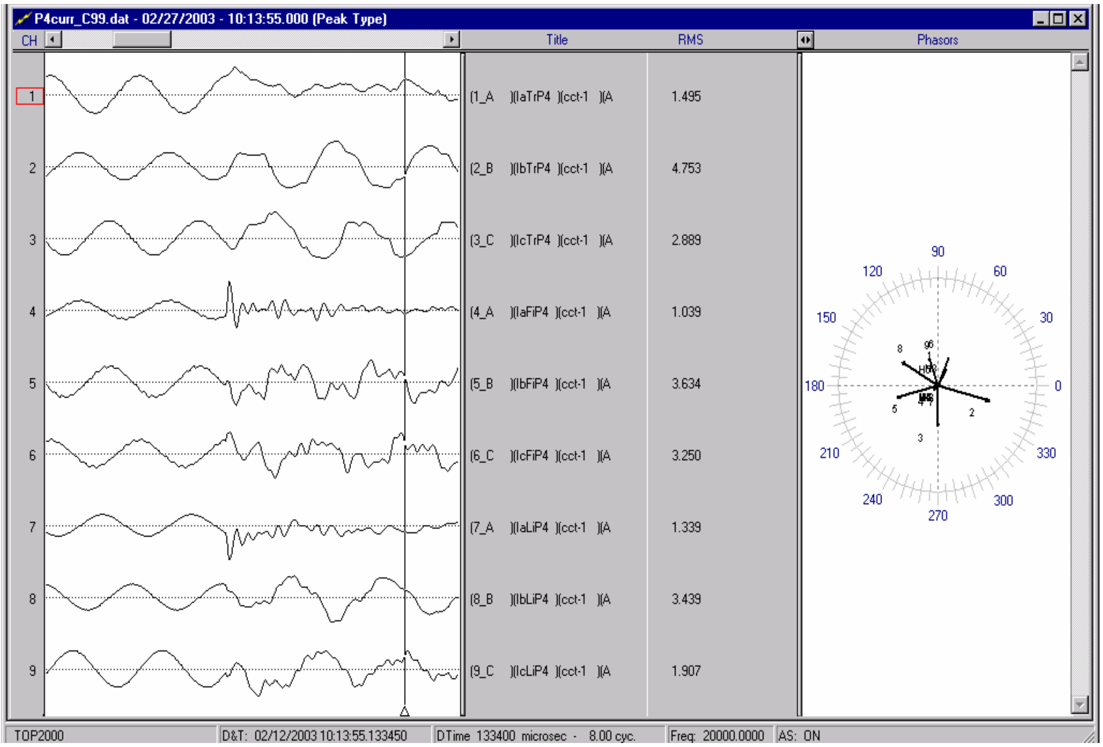


P3curr_C99.dat - 02/27/2003 - 10:13:33.000 (Peak Type)

| CH | Title | RMS |
|---|---|---|
| 1 | (1_A ](IaTrP3 ](cct-1 ](A | 1.664 |
| 2 | (2_B ](IbTrP3 ](cct-1 ](A | 4.839 |
| 3 | (3_C ](IcTrP3 ](cct-1 ](A | 3.010 |
| 4 | (4_A ](IaFiP3 ](cct-1 ](A | 1.381 |
| 5 | (5_B ](IbFiP3 ](cct-1 ](A | 4.027 |
| 6 | (6_C ](IcFiP3 ](cct-1 ](A | 3.442 |
| 7 | (7_A ](IaLiP3 ](cct-1 ](A | 20.347 |
| 8 | (8_B ](IbLiP3 ](cct-1 ](A | 3.658 |
| 9 | (9_C ](IcLiP3 ](cct-1 ](A | 2.104 |

TOP2000 | D&T: 02/12/2003 10:13:33.134000 | DTime 133950 microsec - 8.04 cyc. | Freq: 20000.0000 | AS: ON

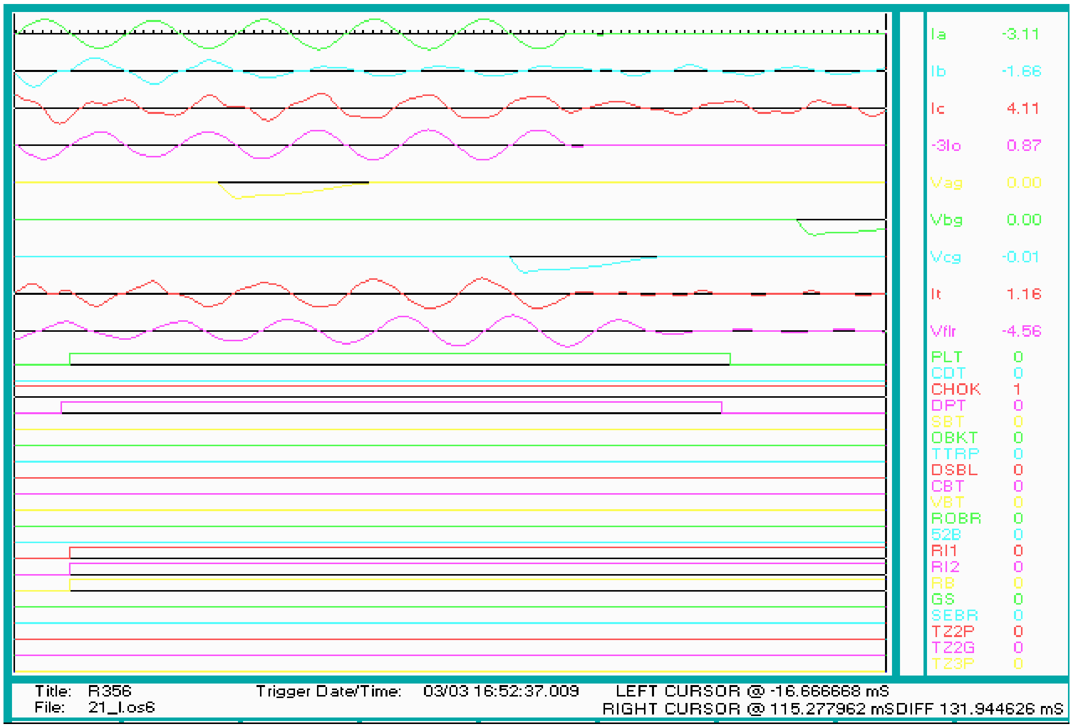
**Figure 5. Simulated waveforms for AG (Case 21) Fault – Pole 3 line and transformer currents.**



| CH | Title | RMS |
|---|---|---|
| 1 | (1_A ](IaTrP4 ](cct-1 ](A | 1.495 |
| 2 | (2_B ](IbTrP4 ](cct-1 ](A | 4.753 |
| 3 | (3_C ](IcTrP4 ](cct-1 ](A | 2.889 |
| 4 | (4_A ](IaFiP4 ](cct-1 ](A | 1.039 |
| 5 | (5_B ](IbFiP4 ](cct-1 ](A | 3.634 |
| 6 | (6_C ](IcFiP4 ](cct-1 ](A | 3.250 |
| 7 | (7_A ](IaLiP4 ](cct-1 ](A | 1.339 |
| 8 | (8_B ](IbLiP4 ](cct-1 ](A | 3.439 |
| 9 | (9_C ](IcLiP4 ](cct-1 ](A | 1.907 |

TOP2000 | D&T: 02/12/2003 10:13:55.133450 | DTime 133400 microsec - 8.00 cyc. | Freq: 20000.0000 | AS: ON

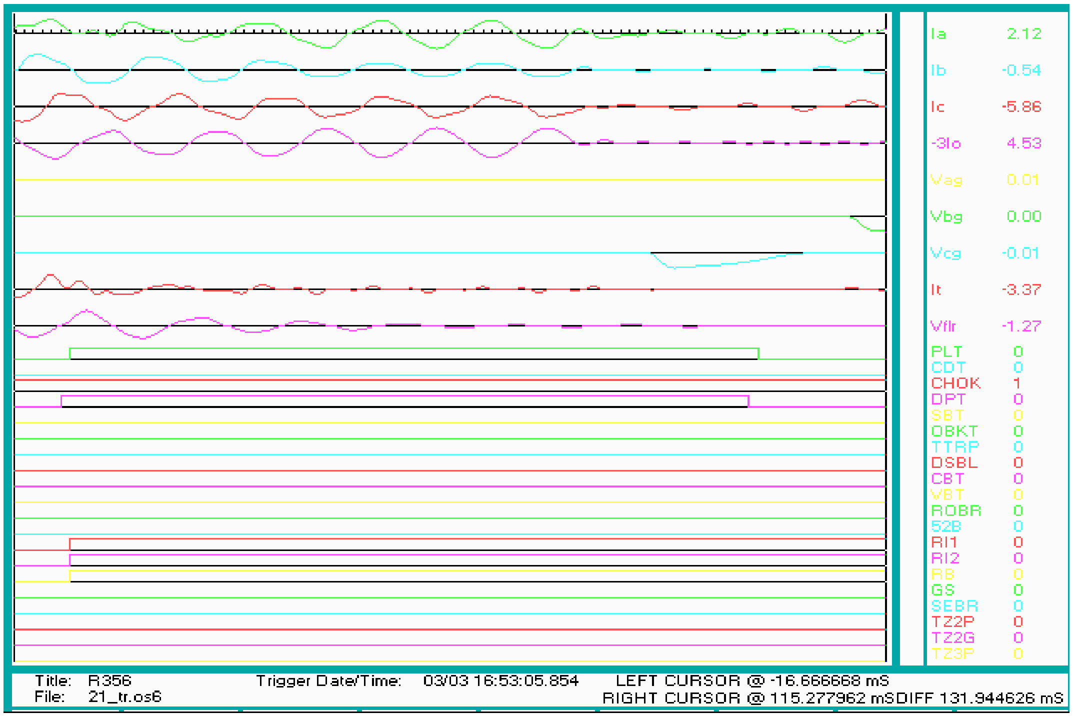
Figure 6. Simulated waveforms for AG (Case 21) Fault – Pole 4 line and transformer currents.



| | |
|---|---|
| Ia | -3.11 |
| Ib | -1.66 |
| Ic | 4.11 |
| -3Io | 0.87 |
| Vag | 0.00 |
| Vbg | 0.00 |
| Vcg | -0.01 |
| It | 1.16 |
| Vflr | -4.56 |
| PLT | 0 |
| CDT | 0 |
| CHOK | 1 |
| DPT | 0 |
| SBT | 0 |
| OBKT | 0 |
| TTRP | 0 |
| DSBL | 0 |
| CBT | 0 |
| VBT | 0 |
| ROBR | 0 |
| 52B | 0 |
| RI1 | 0 |
| RI2 | 0 |
| RB | 0 |
| GS | 0 |
| SEBR | 0 |
| TZ2P | 0 |
| TZ2G | 0 |
| TZ3P | 0 |

Title: R356
File: 21_l.os6
Trigger Date/Time: 03/03 16:52:37.009
LEFT CURSOR @ -16.666668 mS
RIGHT CURSOR @ 115.277962 mS DIFF 131.944626 mS

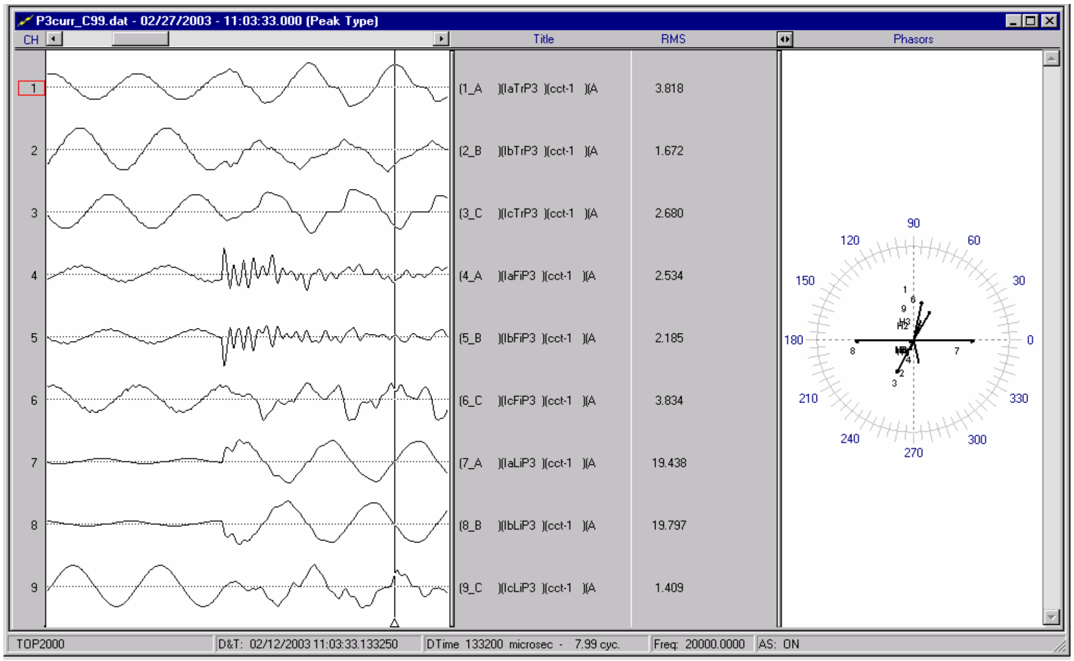
. Figure 7. Relay response in the line end for internal AG fault.



| | |
|---|---|
| Ia | 2.12 |
| Ib | -0.54 |
| Ic | -5.86 |
| -3Io | 4.53 |
| Vag | 0.01 |
| Vbg | 0.00 |
| Vcg | -0.01 |
| It | -3.37 |
| Vflr | -1.27 |
| PLT | 0 |
| CDT | 0 |
| CHOK | 1 |
| DPT | 0 |
| SBT | 0 |
| OBKT | 0 |
| TTRP | 0 |
| DSBL | 0 |
| CBT | 0 |
| VBT | 0 |
| ROBR | 0 |
| 52B | 0 |
| RI1 | 0 |
| RI2 | 0 |
| RB | 0 |
| GS | 0 |
| SEBR | 0 |
| TZ2P | 0 |
| TZ2G | 0 |
| TZ3P | 0 |

Title: R356 Trigger Date/Time: 03/03 16:53:05.854 LEFT CURSOR @ -16.666668 mS
File: 21_tr.os6 RIGHT CURSOR @ 115.277962 mSDIFF 131.944626 mS

Figure 8. Response of relay in the transformer end for internal AG fault.

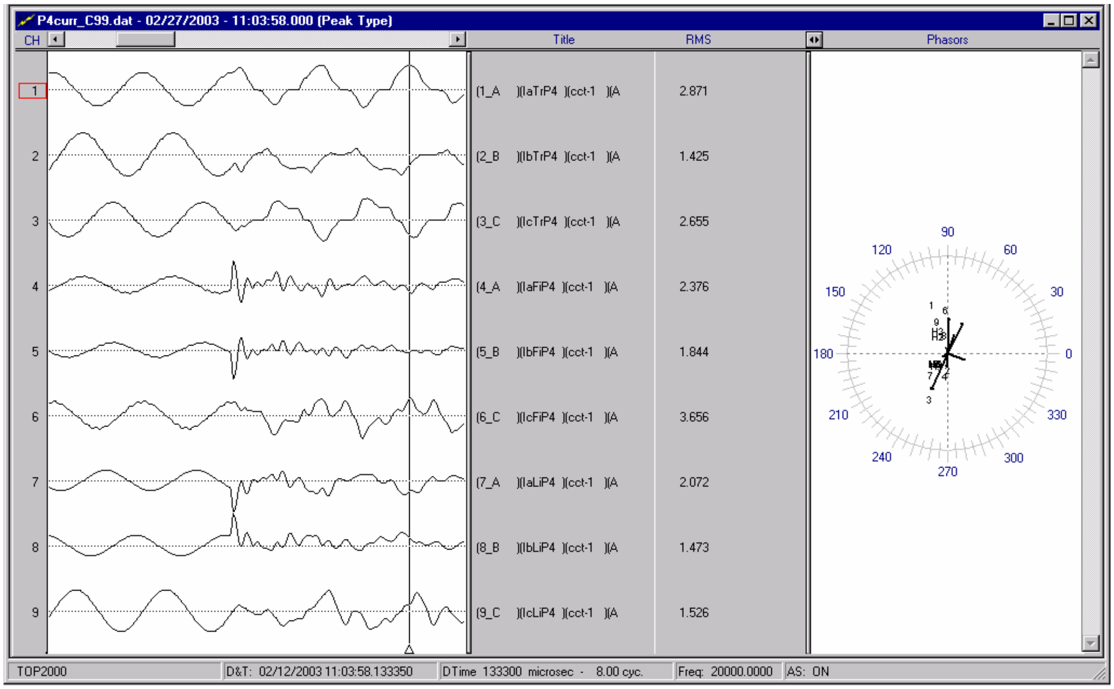


P3curr_C99.dat - 02/27/2003 - 11:03:33.000 (Peak Type)

| CH | Title | RMS |
|---|---|---|
| 1 | (1_A ](IaTrP3 ](cct-1 ](A | 3.818 |
| 2 | (2_B ](IbTrP3 ](cct-1 ](A | 1.672 |
| 3 | (3_C ](IcTrP3 ](cct-1 ](A | 2.680 |
| 4 | (4_A ](IaFiP3 ](cct-1 ](A | 2.534 |
| 5 | (5_B ](IbFiP3 ](cct-1 ](A | 2.185 |
| 6 | (6_C ](IcFiP3 ](cct-1 ](A | 3.834 |
| 7 | (7_A ](IaLiP3 ](cct-1 ](A | 19.438 |
| 8 | (8_B ](IbLiP3 ](cct-1 ](A | 19.797 |
| 9 | (9_C ](IcLiP3 ](cct-1 ](A | 1.409 |

TOP2000 D&T: 02/12/2003 11:03:33.133250 DTime 133200 microsec - 7.99 cyc. Freq: 20000.0000 AS: ON

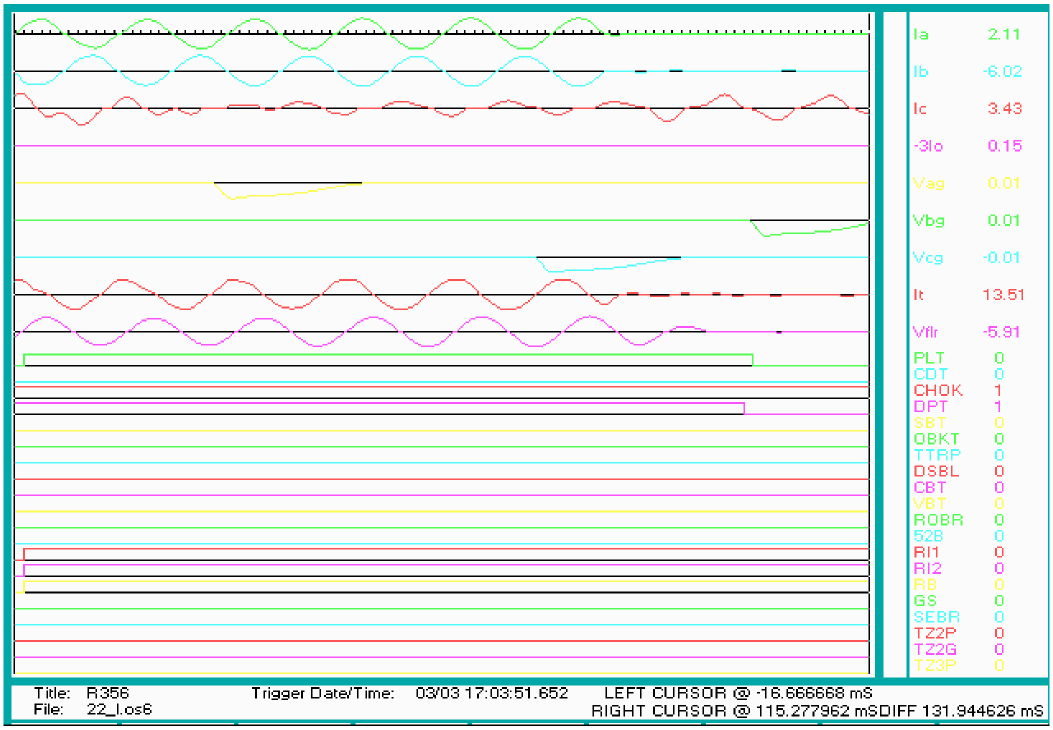
Figure 9. Simulated waveforms for AB (Case22) Fault – Pole 3 line and transformer currents.


P4curr_C99.dat - 02/27/2003 - 11:03:58.000 (Peak Type)

| CH | Title | RMS |
|---|---|---|
| 1 | (1_A ](IaTrP4 ](cct-1 ](A | 2.871 |
| 2 | (2_B ](IbTrP4 ](cct-1 ](A | 1.425 |
| 3 | (3_C ](IcTrP4 ](cct-1 ](A | 2.655 |
| 4 | (4_A ](IaFiP4 ](cct-1 ](A | 2.376 |
| 5 | (5_B ](IbFiP4 ](cct-1 ](A | 1.844 |
| 6 | (6_C ](IcFiP4 ](cct-1 ](A | 3.656 |
| 7 | (7_A ](IaLiP4 ](cct-1 ](A | 2.072 |
| 8 | (8_B ](IbLiP4 ](cct-1 ](A | 1.473 |
| 9 | (9_C ](IcLiP4 ](cct-1 ](A | 1.526 |

TOP2000 | D&T: 02/12/2003 11:03:58.133350 | DTime 133300 microsec - 8.00 cyc. | Freq: 20000.0000 | AS: ON

Figure 10. Simulated waveforms for AB (Case 22) Fault– Pole 4 line and transformer currents.



| | |
|---|---|
| Ia | 2.11 |
| Ib | -6.02 |
| Ic | 3.43 |
| -3Io | 0.15 |
| Vag | 0.01 |
| Vbg | 0.01 |
| Vcg | -0.01 |
| It | 13.51 |
| Vflr | -5.91 |
| PLT | 0 |
| CDT | 0 |
| CHOK | 1 |
| DPT | 1 |
| SBT | 0 |
| OBKT | 0 |
| TTRP | 0 |
| DSBL | 0 |
| CBT | 0 |
| VBT | 0 |
| ROBR | 0 |
| 52B | 0 |
| RI1 | 0 |
| RI2 | 0 |
| RB | 0 |
| GS | 0 |
| SEBR | 0 |
| TZ2P | 0 |
| TZ2G | 0 |
| TZ3P | 0 |

Title: R356 Trigger Date/Time: 03/03 17:03:51.652 LEFT CURSOR @ -16.666668 mS
File: 22_I.os6 RIGHT CURSOR @ 115.277962 mSDIFF 131.944626 mS

Figure 11. Response of relay in the line end for internal AB fault.

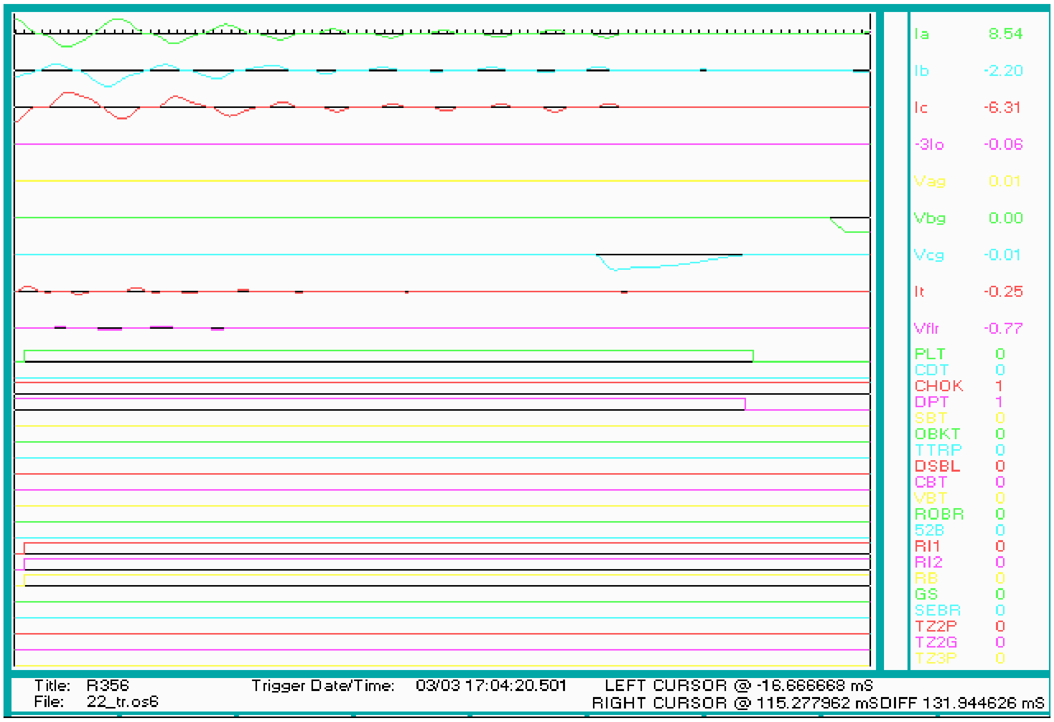
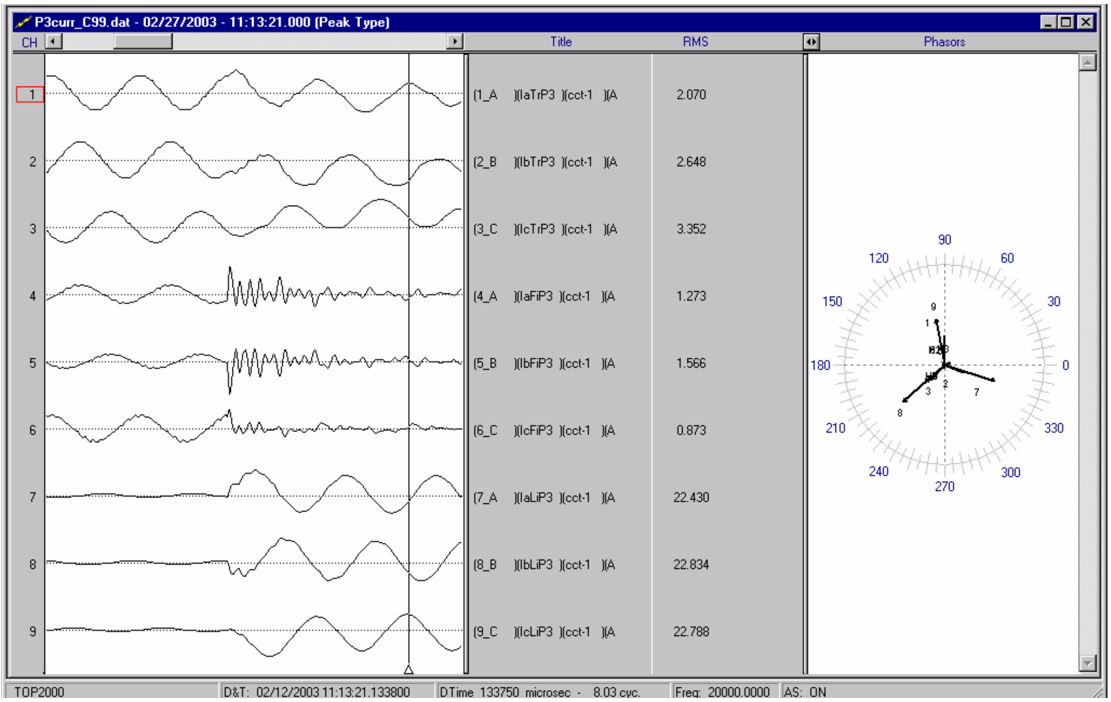


**Figure 12. Response of relay in the transformer end for internal AB fault.**

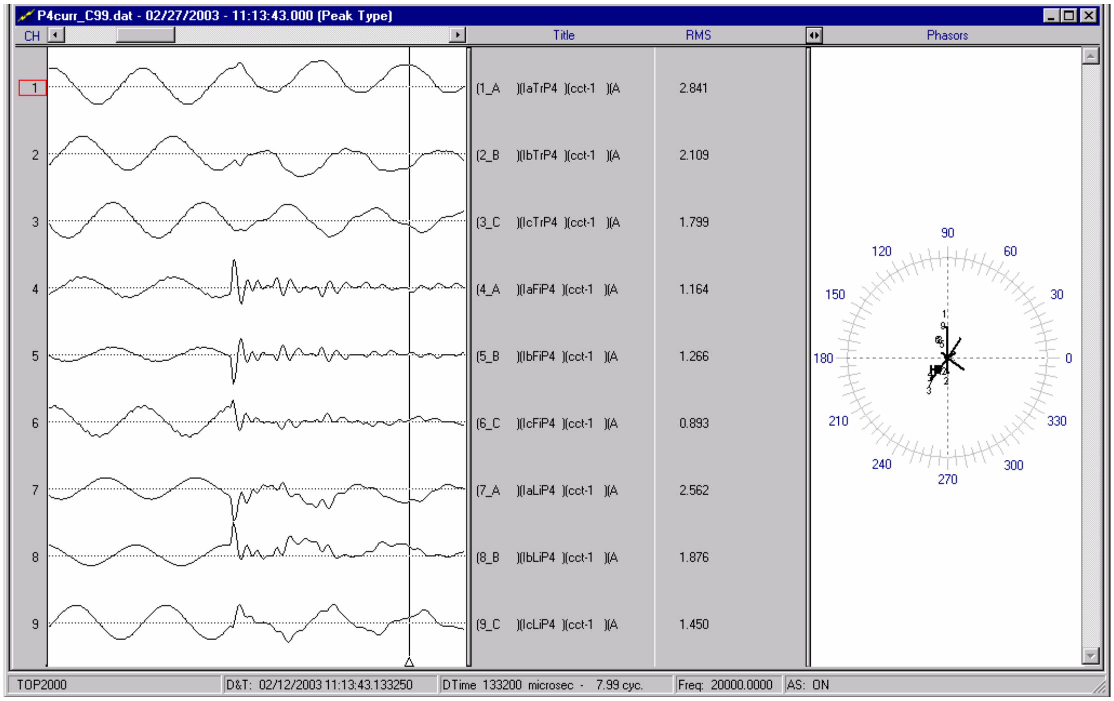


P3curr_C99.dat - 02/27/2003 - 11:13:21.000 (Peak Type)

| CH | Title | RMS |
|---|---|---|
| 1 | (1_A )(IaTrP3 )(cct-1 )(A | 2.070 |
| 2 | (2_B )(IbTrP3 )(cct-1 )(A | 2.648 |
| 3 | (3_C )(IcTrP3 )(cct-1 )(A | 3.352 |
| 4 | (4_A )(IaFiP3 )(cct-1 )(A | 1.273 |
| 5 | (5_B )(IbFiP3 )(cct-1 )(A | 1.566 |
| 6 | (6_C )(IcFiP3 )(cct-1 )(A | 0.873 |
| 7 | (7_A )(IaLiP3 )(cct-1 )(A | 22.430 |
| 8 | (8_B )(IbLiP3 )(cct-1 )(A | 22.834 |
| 9 | (9_C )(IcLiP3 )(cct-1 )(A | 22.788 |

TOP2000 | D&T: 02/12/2003 11:13:21.133800 | DTime 133750 microsec - 8.03 cyc. | Freq: 20000.0000 | AS: ON

**Figure 13. Simulated waveforms for ABCG (Case 23) Fault – Pole 3 line and transformer currents.**

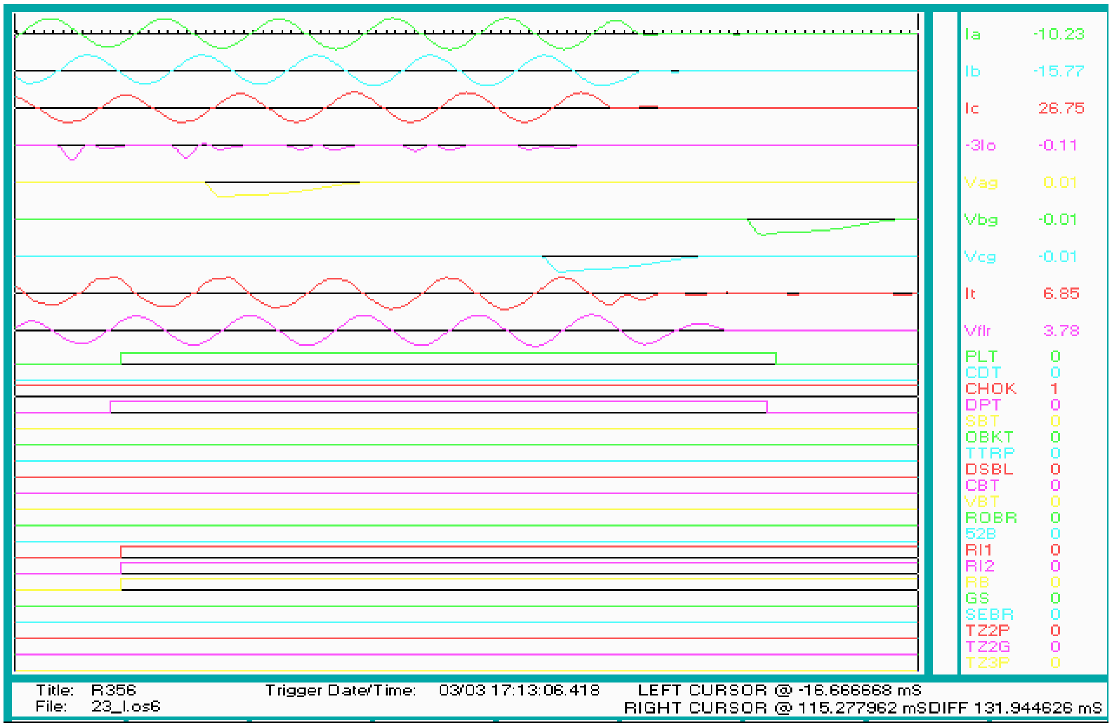


P4curr_C99.dat - 02/27/2003 - 11:13:43.000 (Peak Type)

| CH | Title | RMS |
|---|---|---|
| 1 | (1_A )(IaTrP4 )(cct-1 )(A | 2.841 |
| 2 | (2_B )(IbTrP4 )(cct-1 )(A | 2.109 |
| 3 | (3_C )(IcTrP4 )(cct-1 )(A | 1.799 |
| 4 | (4_A )(IaFiP4 )(cct-1 )(A | 1.164 |
| 5 | (5_B )(IbFiP4 )(cct-1 )(A | 1.266 |
| 6 | (6_C )(IcFiP4 )(cct-1 )(A | 0.893 |
| 7 | (7_A )(IaLiP4 )(cct-1 )(A | 2.562 |
| 8 | (8_B )(IbLiP4 )(cct-1 )(A | 1.876 |
| 9 | (9_C )(IcLiP4 )(cct-1 )(A | 1.450 |

TOP2000 | D&T: 02/12/2003 11:13:43.133250 | DTime 133200 microsec - 7.99 cyc. | Freq: 20000.0000 | AS: ON

**Figure 14. Simulated waveforms for ABCG (Case 23) Fault – Pole 4 line and transformer currents.**



```
Ia      -10.23
Ib      -15.77
Ic       26.75
-3Io     -0.11
Vag       0.01
Vbg      -0.01
Vcg      -0.01
It        6.85
Vflr      3.78
PLT       0
CDT       0
CHOK      1
DPT       0
SBT       0
OBKT      0
TTRP      0
DSBL      0
CBT       0
VBT       0
ROBR      0
52B       0
RI1       0
RI2       0
RB        0
GS        0
SEBR      0
TZ2P      0
TZ2G      0
TZ3P      0
```

```
Title:  R356          Trigger Date/Time:   03/03 17:13:06.418    LEFT CURSOR @ -16.666668 mS
File:   23_l.os6                                               RIGHT CURSOR @ 115.277962 mSDIFF 131.944626 mS
```

Figure 15. Response of relay in the line end for internal ABCG fault.

```
Ia        3.69
Ib       -4.50
Ic        0.77
-3Io     -0.02
Vag       0.01
Vbg       0.00
Vcg       0.00
It       -2.73
Vflr     -0.30
PLT       0
CDT       0
CHOK      1
DPT       0
SBT       0
OBKT      0
TTRP      0
DSBL      0
CBT       0
VBT       0
ROBR      0
52B       0
RI1       0
RI2       0
RB        0
GS        0
SEBR      0
TZ2P      0
TZ2G      0
TZ3P      0
```

```
Title:  R356          Trigger Date/Time:   03/03 17:13:35.269    LEFT CURSOR @ -16.666668 mS
File:   23_tr.os6                                              RIGHT CURSOR @ 115.277962 mSDIFF 131.944626 mS
```

Figure 16. Response of relay in the transformer end for internal ABCG fault.

## Conclusion:

The paper reviewed the HVDC system and various types of faults. Various types of faults was produced in order to see the performance of the numerical current differential relay. Application and settings of the protection scheme had been verified through the modeling of dynamic phenomena in transient models of the HVDC system.

The DC Converter Station at Sylmar is truly a unique and essential component of the Transmission infrastructure in the Western U.S. It is found that through the necessary testing and accurate system modeling; an “off the shelf” current differential relay can provide the required level of security and dependability for this unique application. Thank you to the Los Angeles Department of Water and Power for providing information and access to the project site.

# BIBLIOGRAPHY

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2. Verification of REL356 for the PACIFIC DC Intertie, March 07 2003, Fahrudin Mekic, Ratan Das
3. Elmore, W. A., editor, *Protective Relaying: Theory and Applications*, Marcel Dekker, Inc., 1994.
4. ATP is the royalty-free version of the Electromagnetic Transients Program (EMTP). For more info please visit one of the following web sites: http://www.eeug.de/ or http://www.ee.mtu.edu/atp/

# BIOGRAPHICAL SKETCHES

**Fahrudin Mekić** was born in former Yugoslavia in 1967. He received his BSEE with honors from Sarajevo University, Bosnia and Herzegovina in 1991 where he also worked as research assistant. He received his MSEE degree from Istanbul Technical University, Turkey in 1996. Since 1996 he has been working in the area of power system protection and control within ABB, where he had various engineering positions. Currently he is Senior Application Engineer with the Substation Automation and Protection Division, ABB Inc, in Allentown, PA. Fahrudin has published several technical papers in the area of protection and reliability. He is currently responsible for the application and technical issues associated with ABB relays. He is a member of IEEE.

**Jeffrey Thornburg** was born in San Diego, CA in 1960. He received his BSEE degree from San Diego State University in 1982. He received his MSEE from USC in 1987. He received his MBA from Pepperdine University in 1990. Jeffrey has worked as a relay application engineer and a generating stations design engineer for the Los Angeles Department of Water and Power since 1984. He is currently responsible for various high voltage relay protection projects for the DWP 230kV and 500kV transmission systems.

**Ron Y. Beltran, P.E.** is the Regional Technical Manager for the Substation Automation and Protection Division of ABB in Los Angeles, CA supporting product sales in the Southwestern U.S. He received his B.S.E.E. from Stanford University in 1989 and his M.B.A. from the University of California, Irvine in 1996. He began his career at Mobil Oil in 1989 and worked as an Electrical Engineer and Project Manager on electrical and automation projects for all types of petroleum facilities in Texas and California. He then worked at Pacific Gas and Electric (PG&E) with assignments in Transmission Substation Engineering and Transmission Planning. He joined ABB in 2000 as a Regional Technical Manager in Los Angeles. He is a senior member of IEEE and a registered professional engineer in the state of California. His areas of interest include protective relaying and substation automation applications