Using a Multiple Analog Input Distance Relay as a DFR

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Introduction

IN July of 2000 Entergy experienced a severe mis-operation at Morrilton Substation for a remote fault. Several of the 161 kV lines operated for a fault on a 500kV line at a nearby substation. Routine fault investigation failed to identify the cause for the mis-operation at Morrilton.

Morrilton is a 161kV transmission substation, with four single-breaker transmission lines originating at the station. The lines are protected by a directional comparison blocking scheme, utilizing electro-mechanical relays and power line carrier. Since no recording is available at the substation, Entergy decided to install a portable DFR to capture future events. However, while researching equipment options, Entergy realized that a modern numerical distance protection relay, that could record faults on all 4 transmission lines, would be a more cost-effective solution than a portable DFR. To that end, Entergy chose to replace the protection on the Morrilton-Pleasant Hill line with a numerical distance relay that has multiple sets of analog current and voltage inputs, simultaneously providing primary protection for the line and DFR recording for the entire substation.

Most microprocessor based relays do provide fault recording capabilities, but typically only for the protected line or element, using only a low sampling rate, and capturing only filtered data used for protection functions. However, there are numerical distance relays available that have the hardware design and software design to provide both protection, and robust recording, in a cost-effective package. There are relays available that provide as many as 18 analog channels to capture data from many sources, capture unfiltered data at a DFR-quality sampling rate, and additionally provide power swing (or disturbance) recording capabilities. Entergy's installation utilitizes these capabilities of such a distance relay to act as a cost-effective DFR at Morrilton Substation, performing fault recording of all 4 transmission lines, the bus voltage, and ground polarizing voltage.

This paper describes Entergy's installation of the distance relay at Morrilton Substation to provide line protection, as well as station fault recording. The paper discusses some of the performance tradeoffs between using a true DFR and a relay with DFR capabilities, such as flexibility of assigning analog channels and the types of recording triggers available. In addition, the paper displays fault records from Morrilton Substation, and analyzes some of these fault events.

Existing Protection Scheme

MORRILTON Substation is a small 161 kV transmission substation, with 4 single-breaker transmission lines. The station also includes a 161 kV-13.8 kV distribution transformer and several distribution circuits. The small size of the station means it's not cost-effective to install a separate DFR. 161 kV stations are also generally not critical enough to justify installing a DFR.

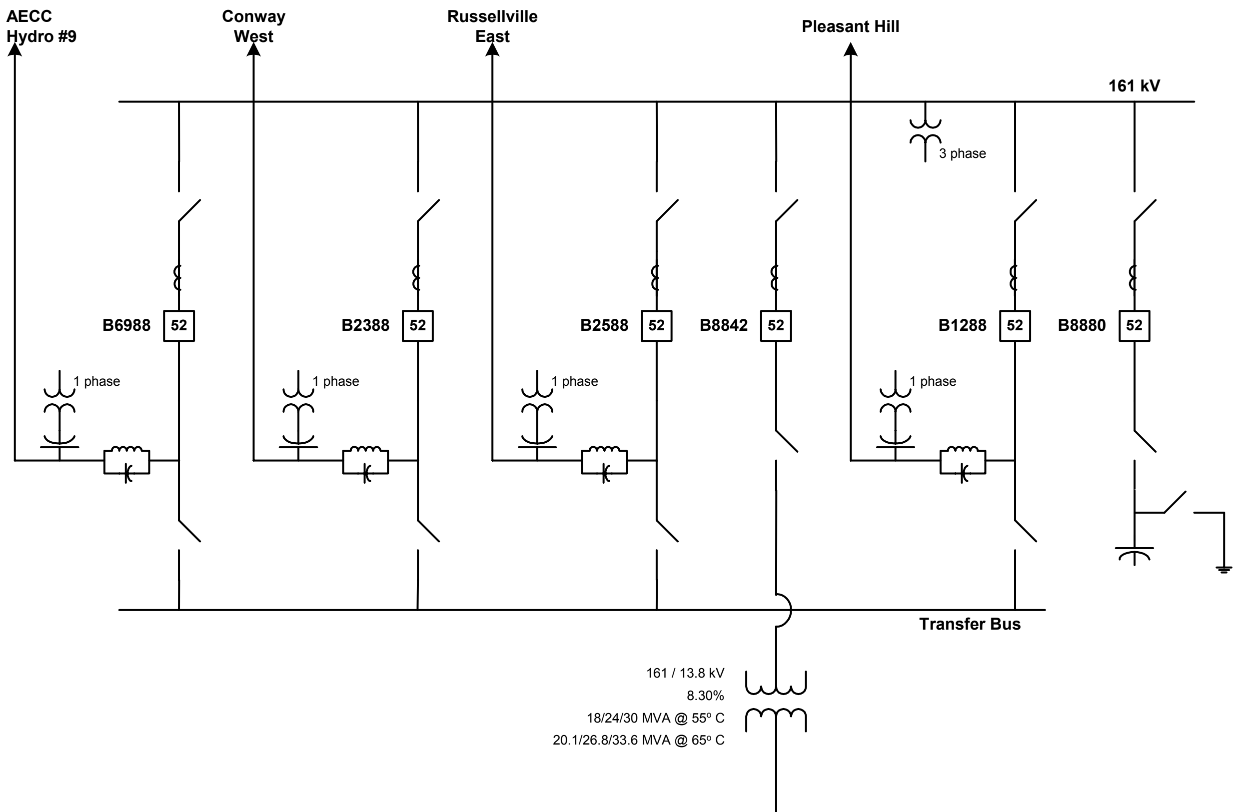

Figure 1: Morrilton Substation one line

The protection system on all 4 transmission lines is identical, and employs electro-mechanical relays. The protection scheme is a Directional Comparison Blocking (DCB) pilot protection scheme, using power line carrier for the blocking signal. Each line uses 2 three-phase CEY distance relays to provide forward-reaching Zone 1 and Zone 2 phase protection, and a reverse looking three-phase CEY distance relay for carrier start. Ground fault protection is provided by both a CLPG carrier ground distance relay, and a JBCG directional overcurrent relay. All lines include synchronism check for automatic reclosing, and a CHC relay for breaker failure.

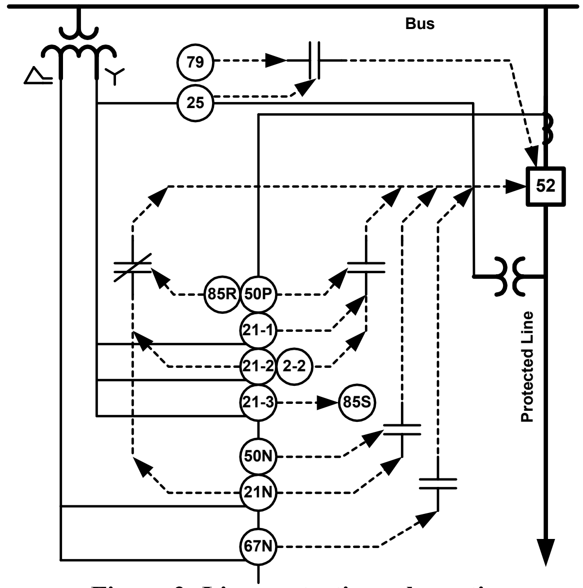

Figure 2: Line protection schematic

Currents for all protection functions come from a set of bushing CTs located on the line circuit breaker. Voltages for all protection functions are provided by a three-phase set of VTs located on the 161 kV bus. These VTs use a dual secondary, with 1 set wye-connected to provide 3 single-phase voltages for protection functions, and 1 set connected broken-delta to provide a 3V0 polarizing voltage for the electro-mechanical ground relays.

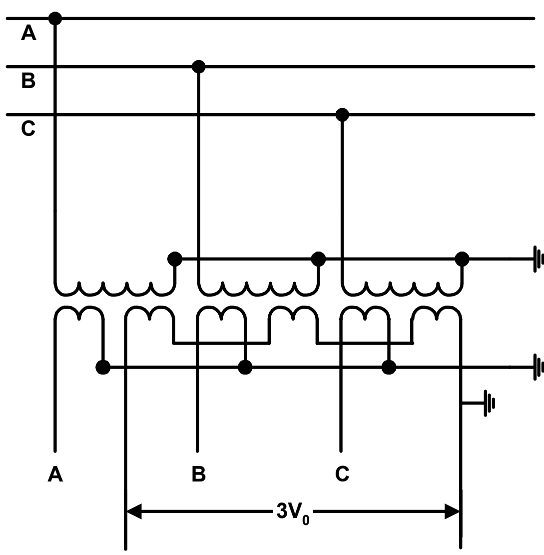

Figure 3: Dual secondary VT connections

Reclosing on these transmission lines uses 1 reclosing attempt, on ground faults only. Reclosing also checks synchronism conditions between the bus voltage, and a single-phase CCVT connected to A-phase of the protected transmission line. Reclosing is permitted when synchronism conditions are met, or when Hot Bus-Dead Line conditions are met.

Obviously, a relay that is applied to provide station-wide recording must also be able to meet these application requirements to be a practical choice.

The fault event that contributed to the mis-operation at Morrilton was a temporary A-phase-to -ground fault on the Pleasant Hill to Mayflower 500kV line at 2:18:28 a.m. on July 20, 2002. The 500kV line protection operated correctly, clearing the fault in 4 cycles, and then successfully reclosing.

During this event, the breaker B1288 (Morrilton to Pleasant Hill line), B2588 (Morrilton to Russellville East line), and B2388 (Morrilton to Conway West line) also operated, tripping and successfully reclosing for the fault. A complete investigation found no cause for the mis-operation. The investigation included end-to-end satellite testing of the protection on the B1288 Morrilton to Pleasant Hill line, checking for double grounds in the CT circuits, verifying correct phasing for the potentials to the carrier ground relay, and performing a directional ground test.

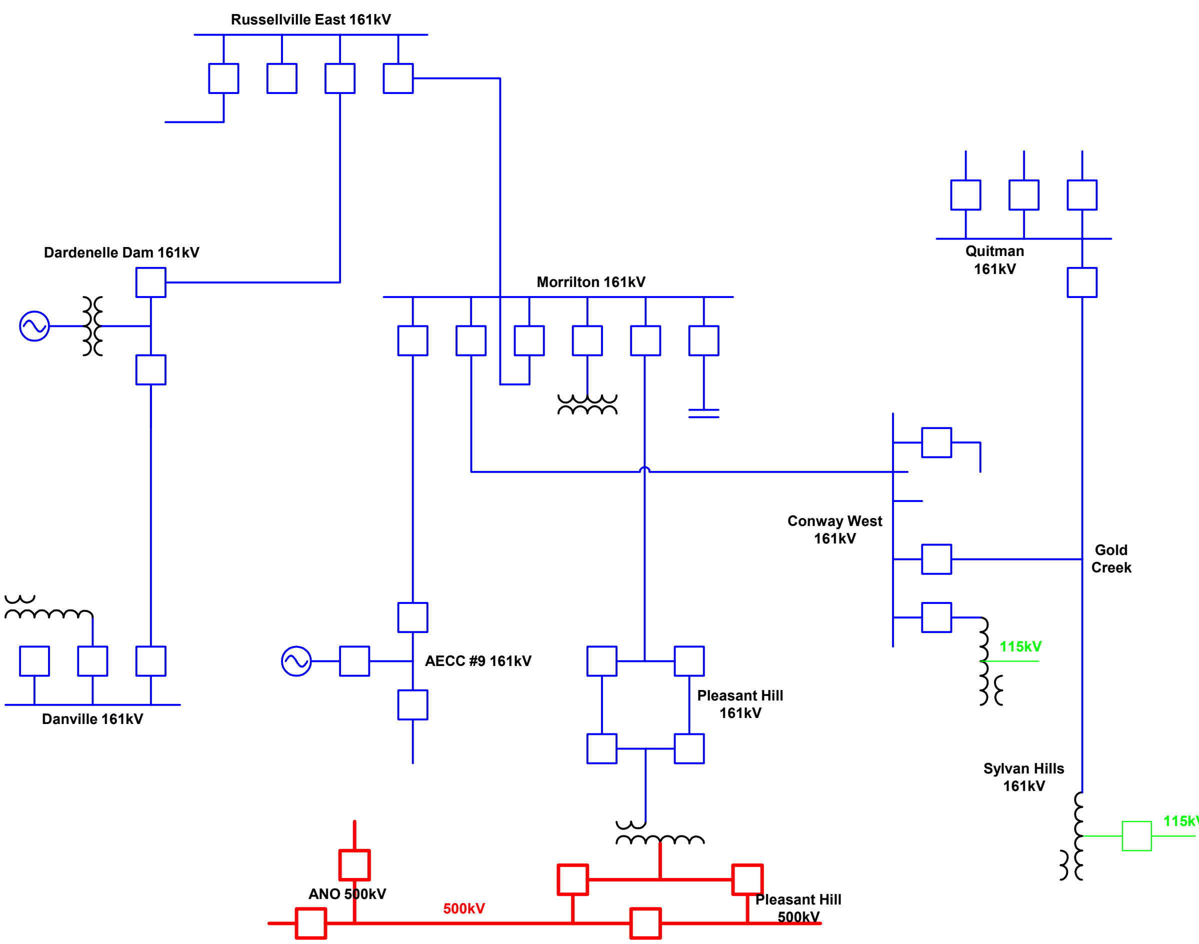

Figure 4: System oneline (simplified)

Capabilities of the L-PRO Line Protection Relay

THE L-PRO Line Protection Relay from NxtPhase is a full-featured distance protection relay. The L-PRO provides all the commonly available protection functions, including 4 zones of phase and ground distance protection, directional phase and ground overcurrent protection, logic for inclusion in pilot protection schemes, automatic reclosing, and synchronism check. These operation are little different than other commonly available distance protection relays.

The L-PRO, however, is designed as a protective relay, and as a platform for recording. The L-PRO has 18 analog channel inputs: 2 sets of three-phase voltage inputs, and 4 sets of three-phase current inputs. Recordings always include data on all 18 of these analog channels. The L-PRO also provide 2 types of recordings: high-speed fault recording and low-speed swing recording.

Fault recording in the L-PRO records raw, instantaneous data at DFR-quality 96 samples per cycle. Records can be from 0.2 to 2.0 seconds long, with 10 cycles of pre-fault data. Records can automatically extend for multiple triggers up to 2 seconds long. Swing recording captures data once per cycle. The data captured is positive sequence current, voltage, real power, reactive power, and impedance, along with system frequency. Records are from 60 to 120 seconds long, with 30 seconds of pre-fault data. Records can be automatically extended for multiple triggers up to 180 seconds.

Fault records and swing records can be triggered by any protection function in the L-PRO. However, the primary protection functions only operate on specific voltage and current inputs. The L-PRO provides 50LS definite-time overcurrent functions for each current input, additional undervoltage and overvoltage functions for each voltage input, and a positive-sequence impedance function, specifically to trigger fault and swing recording.

Installation of the distance relay

THE CLPG carrier ground distance relay operated unexpectedly during the event. Entergy decided to replace the carrier ground relay with a microprocessor distance relay. The distance relay will be the primary protective relay for the line, and is configured to exactly replicate the existing protection scheme.

The new distance relay is configured to replicate the existing protection of the 161 kV line exactly. The relay is set to operate in a DCB pilot protection scheme. For both the phase and ground distance elements, Zone 1 and Zone 2 operate in a forward direction, with Zone 4 reversed for carrier start. Carrier set signals are sent and received via contact input. Additional ground protection is provided by a forward directional ground overcurrent element. Automatic reclosing is configured to provide 1 reclosing attempt, with a 5 second reclosing interval, supervised by the internal synchronism check element. Reclosing is allowed on both synchronism conditions, and on Hot Bus – Dead Line conditions. The remaining electro-mechanical relays are maintained in place as backup protection for the line.

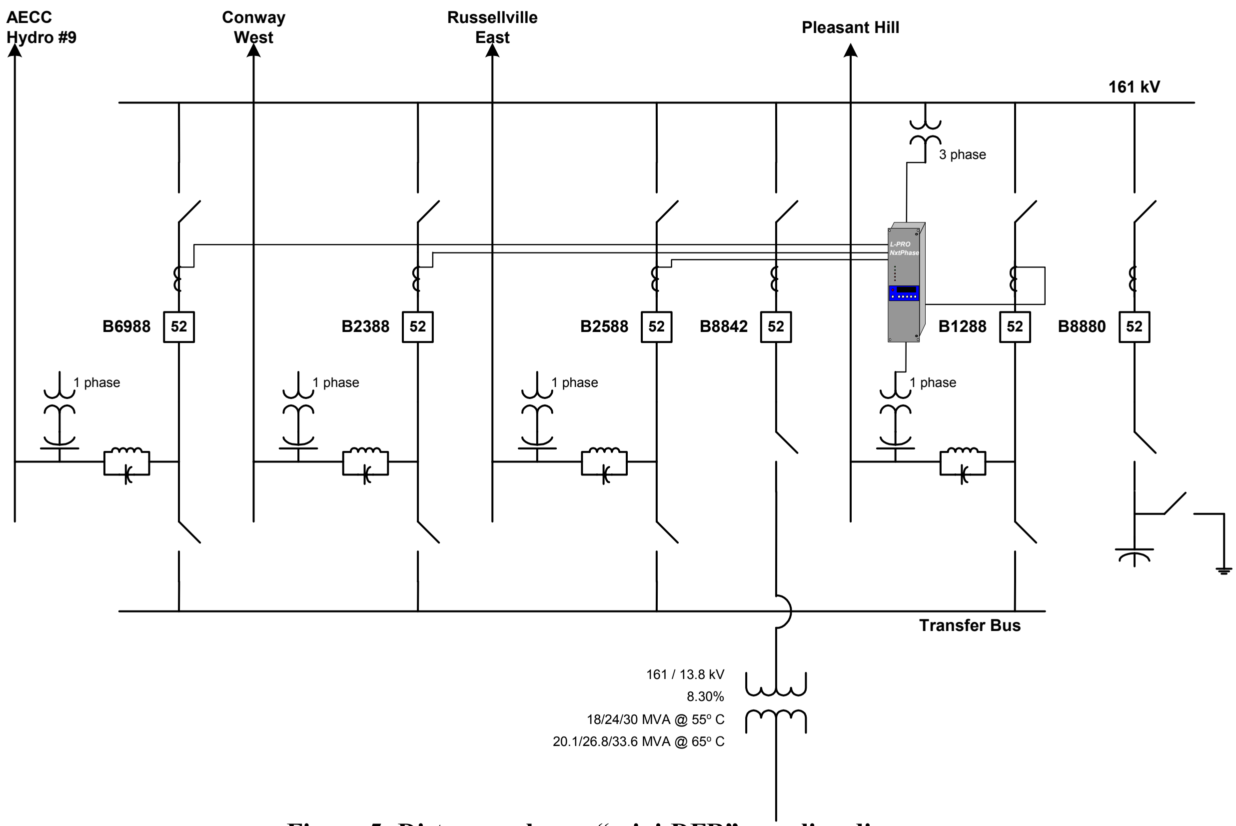

Figure 5: Distance relay as "mini-DFR": one line diagram.

Connections

THE distance relay applied has a three-phase voltage input "Main AC Volts", and a three-phase current input "Main AC Line Current", that must be specifically connected to voltages and currents used for the primary line protection. The output of the bus VTs is connected to the Main AC Volts input. The bushing CTs from breaker B1288 for the Morrilton – Pleasant Hill line are connected to the Main AC Line Current input. All the primary line protection, such as the distance protection and ground overcurrent protection, uses the values measured on these inputs.

The synchronism check voltage also needs to be connected to the relay. The synchronism voltage is taken from a single-phase CCVT connected to A-phase of the Morrilton – Pleasant Hill line. This voltage is connected to the A-phase terminal of the "Auxiliary AC Volts" input.

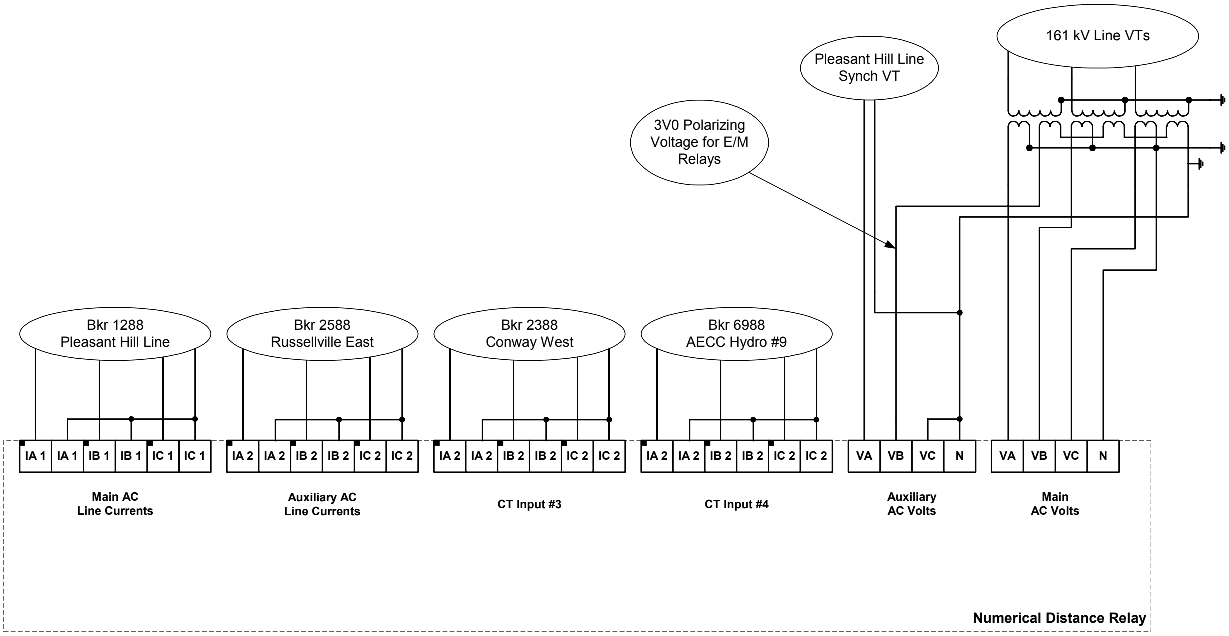

Figure 6: Analog channel input connections.

Beyond these required inputs, the relay used by Entergy includes 3 sets of three-phase auxiliary current inputs. The bushing CTs from B2588 (Morrilton – Russellville East line), B2388 (Morrilton - Conway West line), and B6988 (Morrilton - AECC Hydro #9 line) are connected to these inputs. These connections are made using slide-link terminal blocks that can short out the currents to the relay from maintenance purposes. This type of terminal block connection is the “fault recorder” connection at Entergy, illustrating how the application of this relay follows fault recorder concepts.

Entergy desired to capture the $3V_0$ polarizing voltage supplied to the electro-mechanical ground relays from the broken-delta secondary of the bus VTs. The broken-delta voltage is connected to the B-phase inputs of the Auxiliary AC Volts input. Measuring the polarizing voltage in the relay will have no impact on the correct performance of the synchronism check function. Polarizing voltage is only available when an unbalanced fault is seen by the 161kV bus, such as for a ground fault. When the breaker B1288 operates for a ground fault, the bus no longer sees the voltage unbalance, and $3V_0$ becomes 0. Therefore, the relay will only see synchronism voltage from the line itself.

Figure 7: Relay installed in protection panel

Configure the relay for recording applications

NUMERICAL distance relays are designed to trigger recordings on operation of protection functions. For the multiple analog input distance relay used at Morrilton, the protection functions only use the main current and voltage inputs as part of the protection algorithm processing. However, to act as a DFR, the relay must be able to trigger for fault events on the other connected lines, as well as for faults on the 161kV bus. In addition, the recording should have some flexibility as to record length and type of recording.

Set up recording

RECORDING provided by a DFR can include both high-speed and low-speed recording. High-speed recording is traditional fault recording at 96 samples per cycle or more, with a configurable record length. Low-speed recording is swing recording, capturing current and voltage phasors once per cycle, also with a configurable record length. Records are stored in a first-in, first-out buffer in non-volatile memory.

The distance relay applied by Entergy includes both of these types of recording commonly found in a DFR. Fault recording has a length of 0.2 to 2.0 seconds, with 10 cycles of pre-fault data. Entergy has set this record length to 0.5 seconds. Swing recording has a length of 60 to 120 seconds, with 30 seconds of pre-fault data. Entergy has set this record length to 120 seconds. The relay can store up to the last 30 recordings in non-volatile memory, depending on the type and length of the recordings.

This specific distance relay includes a unique feature for both types of recording: the ability to auto-extend the record length for sequential triggers. The relay automatically extends a record as required to capture consecutive triggers that are close together. If a trigger occurs while a recording is in progress, the record is stretched to include the full post-trigger time of subsequent triggers, up to a maximum length—2.0 seconds for transient records, 180 seconds for swing records. If a trigger occurs before the end of a record caused by a previous trigger, but too late to allow sufficient post-trigger time in a maximum extended record, a new overlapping record is created.

Configure the trigger events

THERE are three general trigger events that can be used to trigger recording: protection elements on the Morrilton – Pleasant Hill line, analog triggers for the other channels connected to the relay, and external contact triggers for other events. For the primary protection elements, Entergy has basically configured all the protection functions to initiate fault recording.

Table 1: Protection recording triggers

Element	Trigger	Fault Recording	Swing Recording
21P1	Pickup & Trip	•	
21P2	Pickup & Trip	•	
21P3	Pickup & Trip	•	
21P4	Pickup & Trip	•	•
21N1	Pickup & Trip	•	
21N2	Pickup & Trip	•	
21N3	Pickup & Trip	•	•
21N4	Pickup & Trip	•	•
67N	Pickup & Trip	•	
Carrier Send	Asserted	•	
Carrier Receive	Asserted	•	
DCB Trip	Trip	•	
Positive-sequence impedance	Pickup		•

For recording fault events on the other sets of current inputs, this distance relay includes a definite-time overcurrent function (50LS) for each of these current inputs. The 50LS functions in this relay are specifically designed as triggers for recording, not as protection functions for tripping.

When developing settings for the 50LS elements, Entergy used the same methodology they apply on DFRs for high magnitude triggers on current channels. Entergy sets these triggers at 5% above the maximum loading of the line. The settings for the elements at Morrilton Substation are:

Table 2: Auxiliary recording triggers

Line	Element	Setting	
		Secondary	Primary
Russellville East	50LS-2	4.88	1562
Conway West	50LS-3	4.03	967
AECC Hydro #9	50LS-4	3.66	878

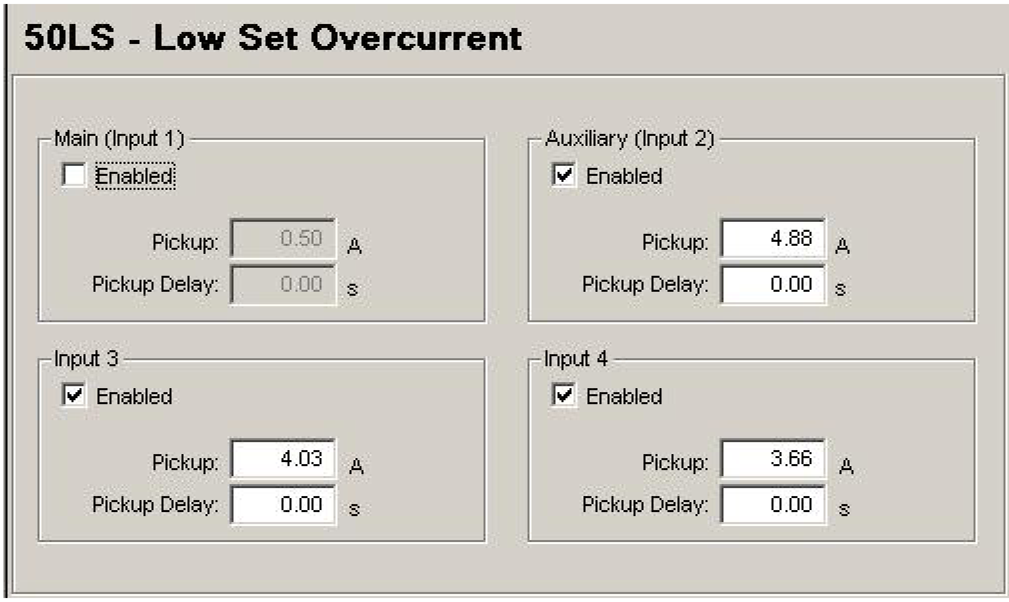

Figure 8: 50LS settings

IT may be desirable to include contact triggers from the other lines to trigger fault recording. Contact triggers could be trip contacts from protection relays, received signals from carrier sets, or any other device that can provide a contact to the L-PRO. Including these contact triggers ensures a fault record is created, even if the fault current in the line isn't enough to operate the 50LS elements. At this point in time, Entergy has chosen not to use external triggers to start recording.

Operating experience and examples

FAULT recording on the Entergy 161kV transmission system in Arkansas is a key part of the operations procedure for fault restoration. The protection system at 161kV contains a mixture of both electro-mechanical and numerical protective relays. There is no specific methodology or long-term plan to add recording capabilities to the 161kV system. Recording capabilities are added when numerical relays are installed for new installations, or for replacement of electro-mechanical relays.

Entergy uses fault records as part of the fault locating process. Fault records provide current and voltage information at a line terminal for the fault event. This information is then compared to fault studies performed by a system modeling tool. The overall method is to perform fault studies, moving the fault location, until the data from the model matches that from the fault record. This information is then used to suggest a fault location.

Since the installation of this relay in November 2003, there have been no faults directly on the transmission lines at Morrilton Substation. However, the relay acts like a DFR to provide valuable information about the operations of the system. The most basic information is real time metering for the station, showing the bus voltage, synchronism voltage, polarizing voltage, and the line currents on all 4 lines.

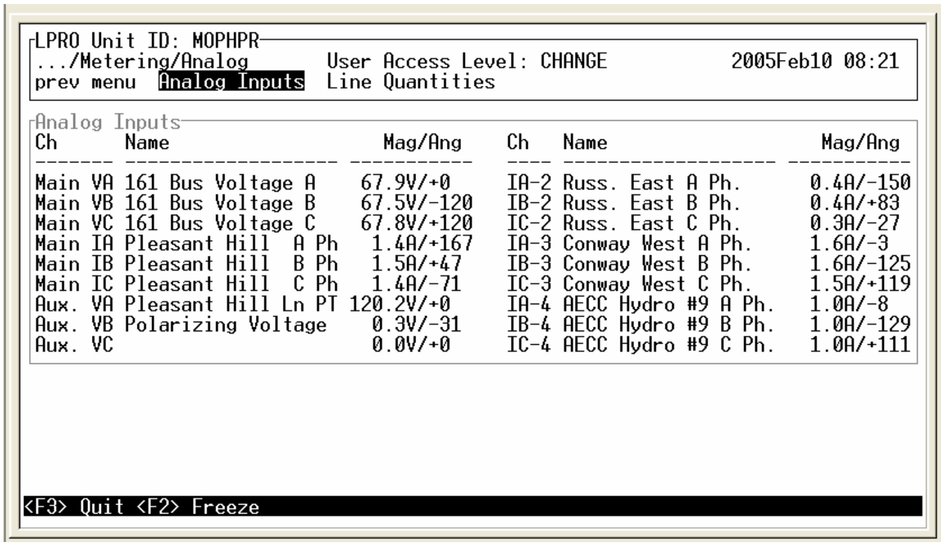

Figure 9: Relay metering display

While no faults have directly occurred on any of the lines at the station, the relay has captured records for many faults on the Entergy system. For example, the most recent fault recording was a fault and swing recording on December 8th of 2004.

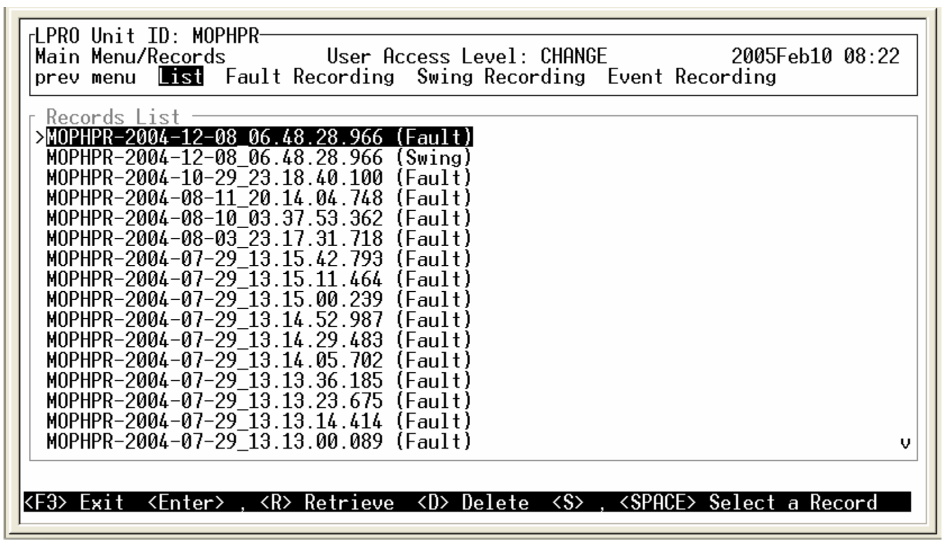

Figure 10: Stored fault records

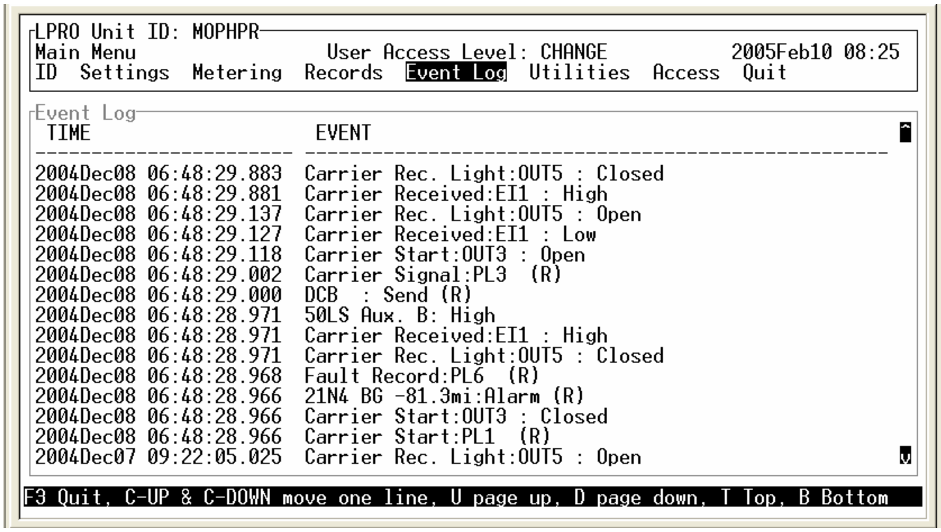

Figure 11: Relay event log

The relay also captures sequence of event information. The event log of the relay lists events associated with the fault of December 8th. The fault is a reverse fault relative to the Morrilton – Pleasant Hill line. Of note is that one of the 50LS functions operated for this fault. The 50LS Aux function is set to trigger for overcurrent events on the Morrilton – Russellville East line. This shows the efficacy of applying the relay also as a DFR.

THE key for Entergy is that the information from the distance relay may be used in exactly the same manner that information from a traditional DFR is used, which is to analyze fault events, be a key piece of the fault locating process, and verify the short circuit model of the transmission system. The multiple input distance relay has recorded data for many faults since its commissioning in November, 2003. There are 3 faults captured by the relay that are interesting to discuss, because these faults illustrate the use of the 50LS triggers, the ability to automatically extend fault records for multiple trigger conditions, and the ability to capture data for remote faults on the system.

50LS Trigger – 161kV fault of December 8th, 2004.

ON December 8th, 2004, Entergy experienced a B phase-to-ground fault on the 161kV line between Danville and Dardanelle Dam. The 50LS Auxiliary element asserted and triggered a recording. The 50LS element is set to trigger when the current in any phase of the Morrilton – Russellville East line exceeds 4.88 $A_{secondary}$. As seen from the fault record information of Figure 12, the RMS value of the fundamental current on Phase B is 5.6 $A_{secondary}$, which exceeds the trigger value.

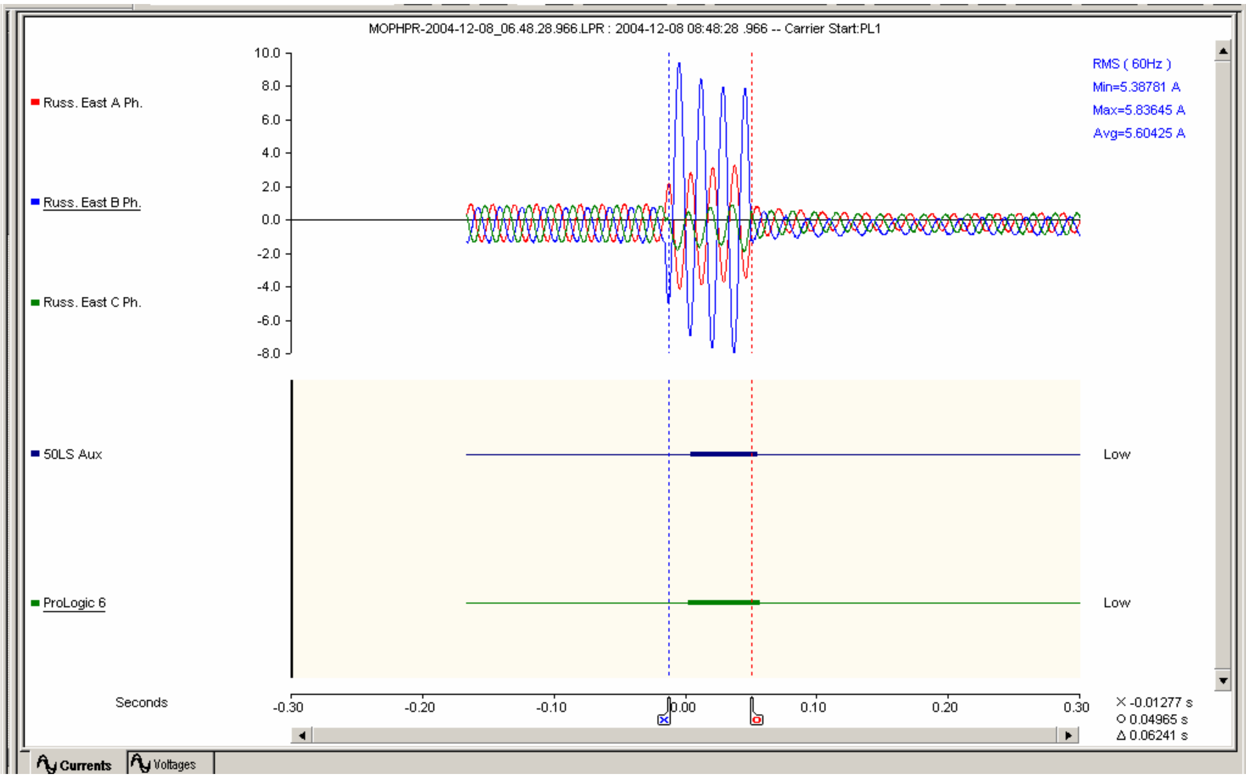

Figure 12: 50LS operation on Morrilton – Pleasant Hill line

This event clearly shows the distance relay acting like a DFR, triggering for an overcurrent condition on a current input separate from the protected line. Furthermore, Entergy uses this information in the fault location process in the same manner as information from a DFR. Analyzing the data in the fault record, the distance relay recorded fault currents as shown in Table 3. When the exact location of a fault isn't known from field observation, Entergy performs fault locating by placing theoretical faults on the system short circuit model at various points on the line, until the fault current from the model approximates that taken from a fault record. As shown in Table 3, a fault located at 10.35% from the Dardanelle Dam end of the line approximates the fault current shown in the relay.

Table 3: Fault data from December 8, 2004 (primary amps)

Line	B Phase Fault Current (Actual)	B Phase Fault Current (Model)
Morrilton – Pleasant Hill	1481	1474
Morrilton – Russellville East	1800	1789
Morrilton – Conway West	370	385
Morrilton – AECC #9	270	290

The actual cause of the fault was not determined. However, the data from the system model, which matches the data taken from the relay, indicates the fault was approximately 3.9 miles from the Dardanelle Dam end of the line. This distance to fault matches the fault location information from an IED located on the Dardanelle Dam – Danville line for the same event, verifying the system model.

Automatically extending fault records: remote fault of April 27th, 2004

On April 27th, 2004, a B phase-to-ground fault occurred on a three-terminal line between Conway West, Quitman, and Sylvan Hills. The fault was a permanent fault. The line protection operated and made one reclosing attempt before locking out. The distance relay triggered a recording on a ground overcurrent carrier start condition on the Morrilton – Pleasant Hill line. The record of Figure 13 clearly shows a reclosing attempt on the faulted line.

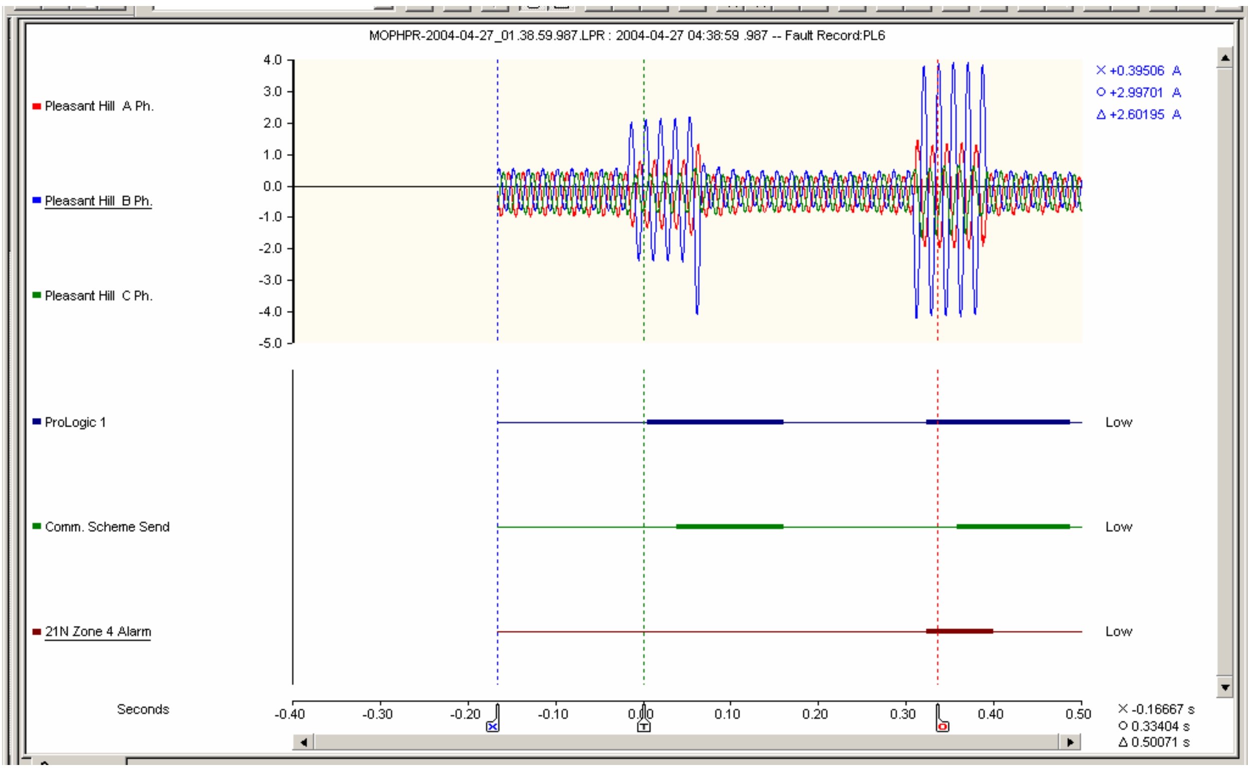

Figure 13: Automatic extension of fault recording

This recording illustrates the capability of the multiple analog input distance relay used by Entergy to automatically extend fault records for multiple trigger conditions, providing data similar to that of a DFR. The normal record length for this relay is 0.50 seconds, with 10 cycles of pre-fault data. The markers in Figure 13 are set to show a record length of 0.50 seconds, but the total record stored in the relay is actually 0.857 seconds long. While the initial 0.50 second record was still recording, the breakers on the faulted line reclosed, with the fault condition still in place. Both the ground overcurrent carrier start condition, and the pickup of the reverse-looking Zone 4, triggered a recording. This new trigger occurs before the completion of the initial 0.50 second fault record, and automatically extends this first fault record to capture all post-fault data for the second trigger. The relay, just like a DFR, shows the entire reclosing cycle for a line fault in one record.

As with all transmission faults, Entergy compares fault currents recorded in the relay to faults on the system model as part of the fault location process. The distanced relay captured the currents shown in Table 4 for this event.

Table 4: Fault data from April 27th, 2004 (primary amps)

Line	B Phase Fault Current (Actual)	B Phase Fault Current (Model)
Morrilton – Pleasant Hill	682	477
Morrilton – Russellville East	619	338
Morrilton – Conway West	1400	1375
Morrilton – AECC #9	300	561

The fault was known was known to be a shield wire that burned and fell into the Gold Creek Switching Station. The data from the system model compares relatively favorable to this currents measured by the distance relay for this fault event. The differences in the model may possibly be explained by the output of the hydro plant connected to the AECC #9 line, or by arcing fault resistance in the fault.

500kV Remote fault

On April 24th, 2004, Entergy experienced a B phase-to-ground fault on the 500kV line between the ANO (Arkansas Nuclear) Switchyard and the Pleasant Hill 500kV Substation. The distance relay on the 161kV Morrilton to Pleasant Hill line triggered a fault recording on the pickup of the 51N/67N overcurrent relay, and then on the pickup of the 21N3 forward reaching distance element. A similar fault on this line caused the mis-operation of the relays at Morrilton Substation in July, 2000. It is obvious from the record that the new distance relay operated correctly for this fault event. Backup protection elements saw the fault, but did not operate as the primary line protection cleared the fault.

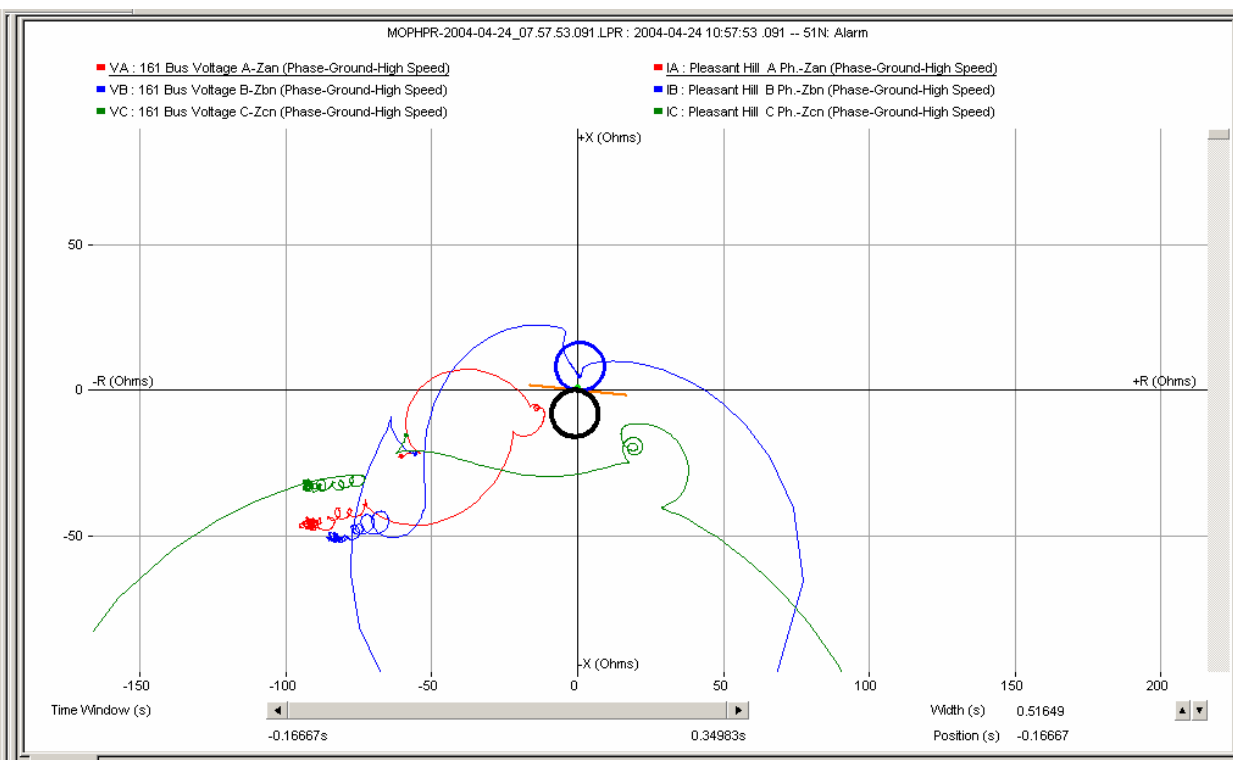

Figure 14: Remote forward fault on 500kV system

The impedance plot of Figure 14 shows that normal load flow is into Morrilton from Pleasant Hill, but during this fault event, the current flow reverses direction, to flow from Morrilton to Pleasant Hill. This plot also shows the B phase-to-ground apparent impedance moving into the Zone 3 ground distance element operating zone.

Once again, the data recorded in the relay was used to determine a fault location on the system model, as shown in Table 5. This fault location corresponds to approximately Structure #43 on the ANO to Pleasant Hill 500kV line. The FALLS lightning detection software used by Entergy indicated a -9KV lightning stroke at Structure #43 occuring at this time. Therefore the system model is proven to be accurate in this instance.

Table 5: Fault data from April 24th, 2004 (primary amps)

Line	B Phase Fault Current (Actual)	B Phase Fault Current (Model)
Morrilton – Pleasant Hill	1180	1182
Morrilton – Russellville East	260	299
Morrilton – Conway West	520	464
Morrilton – AECC #9	520	420

A fault on this 500kV line was the original reason for placing a recording device into Morrilton Substation. One valuable piece of information captured in the recording is the polarizing voltage used by the electro-mechanical ground relays in Morrilton Substation. Obviously, the ground relay mis-operations may be due to problems with the polarizing voltage. The distance relay is wired to capture the polarizing voltage in fault records. Figure 15 shows the polarizing voltage for this specific fault event. The actual polarizing voltage data could have proven useful in explaining the mis-operations that occurred during the July 2000 fault event.

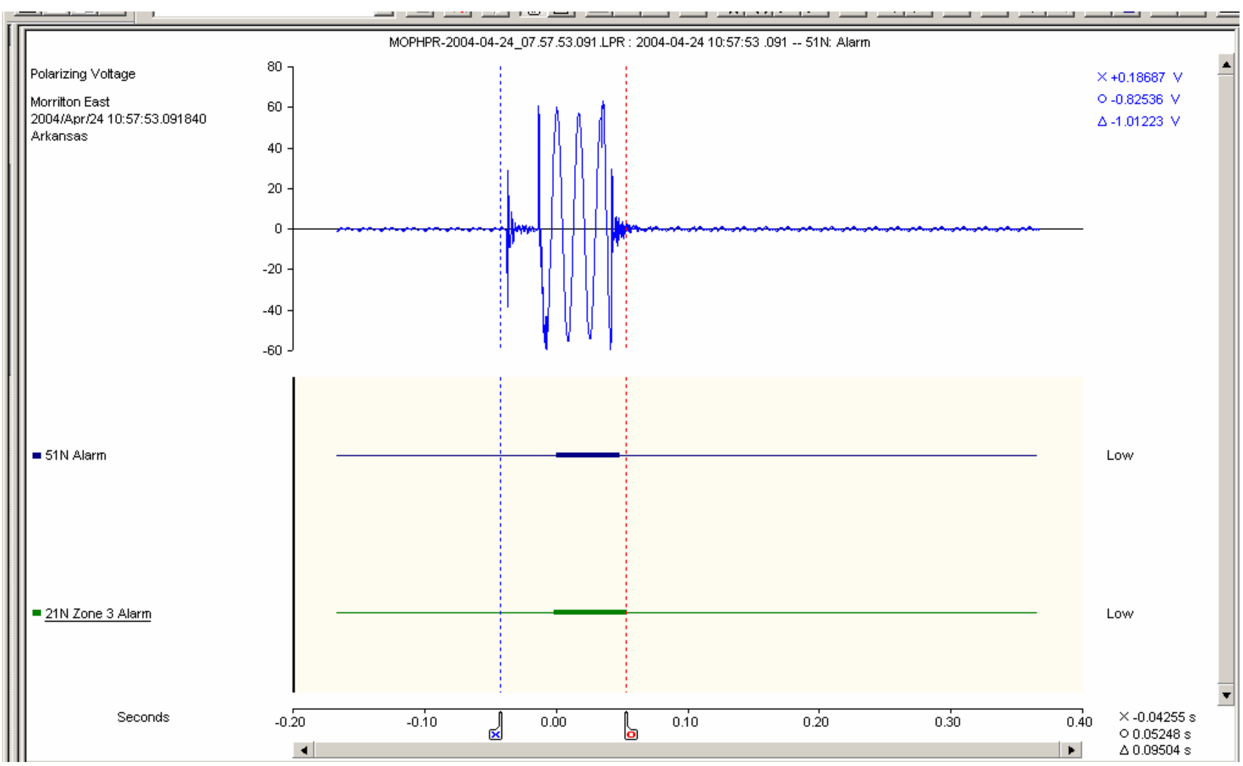

Figure 15: Polarizing voltage for forward fault on 500kV system

Comparing a relay to a DFR

USING a relay for protection, and as a DFR, is certainly a cost-effective solution for small substations such as Morrilton. However, even in a relay with multiple analog input channels and DFR-quality recording, there are some limitations when comparing the relay to a true DFR. The analog channels in a relay are fixed as current or voltage channels. This limits the ability of the relay to record and trigger on the measurements actually available in a substation. Relay triggers are based on specific protection function events, and are generally high or low magnitude triggers. There is little flexibility to apply different types of triggers for a specific measurement. Record storage is also very limited, typically storing only about 30 seconds of total record length. Relays may supply some pre-configured calculated, particularly zero-sequence current, but have no capability to provide user-defined calculated channels, or triggers on user-defined channels.

However, a relay with robust recording capabilities does provide the basics: fault recording for all lines in the substation, while triggering for the most common events. Providing quality recording at a station, for no additional cost, outweighs any limitations in the recording capabilities of the relay.

Other possible applications

THIS paper discusses a specific application of a distance relay used for protection and DFR recording purposes. There are a few other application possibilities to consider.

The first of these applications are for substations with more than 4 transmission lines, that still, due to voltage class or location, don't justify an independent DFR. For this case, it is possible to use 2 distance relays, and cross-trigger between the relays, just as with DFRs for large substations. When 1 relay triggers a recording, it closes an output contact that is wired to a digital input of the second relay, triggering both relays simultaneously for the same event.

This specific application is a substation that uses single-breaker transmission terminals. However, dual-breaker transmission terminals, such as ring bus and breaker-and-a-half terminals, are very common. It is possible to apply the distance relay to capture currents on 4 lines, by bringing in the electrical sum of the breaker currents of each line terminal into one of the current inputs of the relay. However, it will only be possible to capture voltage on one of the protected lines, because of the limited number of voltage channels.

While a distance relay is a very good choice to use as a protective relay and DFR, a bus protection relay may also be a good choice. Numerical low-impedance bus protection relays typically accept currents from up to 6 lines, and one set of voltages. If the bus protection relay includes overcurrent elements for each set of current inputs, then the bus protection relay can easily be used for the same application described here. However, the bus protection relay will only operate for faults close enough to the station to trigger the overcurrent elements for the individual inputs. Also, for a breaker-and-a-half substation, the relay will only record individual breaker currents, and not the actual relaying current.

About the Authors

Dennis Denison of Entergy and Rich Hunt of NxtPhase are both intelligent, experienced, and seriously thoughtful guys.

Rich Hunt, M.S., P.E., is presently a Senior Field Application Engineer for NxtPhase T&D Corporation, responsible for technical marketing, technical sales, and technical support of optical current and voltage sensors, and protective relays and fault recorders. Rich has over 10 years of utility experience at Virginia Power and the University of North Carolina, as well as over 6 years of industry experience. Rich is a member of the Main Committee of the IEEE PSRC, and is registered Professional Engineer in the Commonwealth of Virginia.

Dennis Denison is currently a Senior Transmission Specialist for Entergy Arkansas, working in the System Protection, Control, and Metering Reliability group headquartered in Little Rock, Arkansas. Dennis has 32 years experience in protection and control with Entergy.