Analyze Relay Fault Data to Improve Service Reliability

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ABSTRACT

Protective relays are at the core of maintaining electric service to as many customers as possible during a system disturbance. For this reason, an improvement in protection quality is directly reflected as an improvement in customer service. To improve protection quality, it is useful to identify and record performance measures that can be evaluated for system impact.

Using 18 months of data (January 1996–August 1997), detailing every relay operation on an anonymous utility system (1400 operations), this paper analyzes the faults and protective system operation to determine relay operation and performance of electromechanical, solid-state, and digital relays. Specific system quality measurements include relay misoperations; relay failures to operate; relay delayed operations; and accessory component failure, such as fault recorder, trip circuit, communications system, or targeting system. Results are compared to the values given by Working Group I17, Transmission Relay System Performance Comparison for 2000 and 2001 [1].

For each protection quality measurement, examples of negative responses and their power system impact are presented, as well as statistical values detailing the probability of a negative response. In conclusion, a discussion of reasonable mitigation techniques and their cost and benefits, based on the data, is presented.

INTRODUCTION

Looking at actual system events provides fascinating details in the life of a power system. A massive explosion at an industrial facility breaks windows a half mile away and causes electromechanical contacts to bounce closed. Pelicans fly into a subtransmission line and relays clear the fault after a time delay. Individual events are significant in that they form part of a pattern; the analysis of which can be used to improve relay operation.

The power system data used in this paper include electromechanical relays, solid-state relays, and microprocessor relays. The utility involved has an excellent service record for its customers and is committed to using technology to reduce system costs. Real-world resource limitations limit how much and how fast optimized solutions can be implemented. Analysis of system events can help prioritize updating of equipment to save the most money.

The operation of a protective relay can be measured by its security against false operation, its dependability to operate for faults in its zone of protection, its speed of operation, and its impact on control of the overall power system. In examining the success or failure of relays to perform to these measurements, choices can be made that improve, rather than degrade, the overall relay system performance.

Analysis of false operations, failures to operate, speed of operation, and general system operation make evident statistical and anecdotal information. This information supports possible changes in protective practices that can reasonably improve system protection and operation.

STATISTICAL MEASURES

One way to categorize the data from the selected utilities' relay operations is as follows:

1425 total events

- 1346 correct operations (94.5%)
- 66 incorrect operations (4.6%)
- 13 failures to operate 0.91%)

The IEEE Power System Relay Committee Working Group I17 Report, Transmission Relay System Performance Comparison [1], further breaks down statistical performance by voltage class and type of relay operation failure. The way this utility would report in the working group is shown in Table 1.

Table 1 IEEE Working Group I17 Incorrect Operation Reporting

			% INCORRECT OPERATIONS (DUE TO RELAYS) YEARS 1996/7							
Total Events	**K-Factor**	**Relay Misoperations**	**Voltage**	**Failure to Trip**	**Failure to Interrupt**	**Slow Trip**	**Unnecessary Trip During Fault**	**Unnecessary Trip Other Than Fault**	**Failure to Reclose**	**Total Misoperations**
20	Not Calculated	See Right	Above 400	0%	0%	Not Determined	30%	5%		35%
7			301-400	0%	0%		14%	0%		14%
49			201-300	2%	4%		4%	12%		22%
13			101-200	0%	0%		15%	31%		46%
5			51-100	0%	0%		0%	0%		0%
705			4.8-51*	1%	0.6%		2.5%	2.1%	0.14%	6.4%

* Not reported voltage in Working Group I17 Report

While these ratios are significant in making a relative measure of overall system performance, the individual events that make up each category better show how improvements in protective system design can be made.

SPECIFIC MISOPERATIONS (SEE APPENDIX 1)

Examining the reasonable percentage of misoperations (less than 5%) is difficult due to the large number of events. It can be made more manageable if the misoperations are divided into groups, based on cause. A quick read of the failures makes a few broad categories quickly apparent. These are:

- Relay component failure
- Relay design hole
- Accessory component failure
- Setting or coordination failure
- Human caused
- Force majoure

Looking at a Pareto categorization of causes for misoperations, we can see where a small effort can produce maximum improvement. There is some ambiguity in classifying these events. Is a false trip caused by a wiring error an accessory component failure, a human caused failure, or a relay design hole? Is a false trip caused by a shorted pilot wire relay an accessory component failure or a relay design hole? In both cases, I categorized them as an accessory component failure, although we can say it is the relay's fault for not detecting the problem. In the broadest sense, all failures could be called human caused in that piling enough systems on top of each other can prevent any error. For the sake of simplicity, these are categorized based on the first error cause.

By category, the misoperations are rated and ranked by percentage of failures:

- Setting or coordination failure: 18 instances (27%)
- Accessory component failure: 12 instances (18%)
- Human Caused: 12 (8 of these were due to one break-in by vandals) (18%)
- Relay design hole: 9 instances (13.5%)
- Induced Signal/Noise: 5 instances (7.6%)
- Force majoure: 5 instances (7.6%)
- Relay component failure: 3 instances (4.5%)
- Mystery: 2 instances (3%)

Drilling into the specifics of these categories reveals where protective design action can prevent misoperations.

SETTING OR COORDINATION FAILURE

Line differential relays had the most coordination problems (five), all due to fuses on taps on the lines. In some instances, a time overcurrent relay had been added to provide a level of coordination with tapped fuses. This seemed to eliminate the coordination problem at the cost of fairly long time delays and increased cost in material and wiring.

Four false trips, on three different protection schemes, were caused by system conditions that were not considered when applying settings. Delayed or repeated tripping of adjacent lines caused two false trips, one of them on a 345 kV line. Twice, frequency relays operated for transient conditions.

While most frequency relays are used with a time delay, system faults and switching operations can cause transients that fool a frequency relay under some conditions. These operations can cause a greater system problem than a false line trip because reclosing is not normally performed, but waits for operator intervention. Other settings-caused false trips were from incorrect echo signals, and in one case, from new settings that were not installed when a breaker configuration was changed.

None of the setting or coordination misoperations were the result of a missed calculation or the wrong curve selection. The combination of tapped loads on differentially protected lines and conditions not modeled made up the bulk of these cases. Both of these conditions can be addressed with modern relays. Tapped load coordination using the sum of both line end currents provides shorter coordinating margins than with a single end time overcurrent relay supervising the differential relay. Multiple settings groups can use external inputs to change to a setting that accounts for paralleling sources or other changed system conditions. Between these two solutions, settings-caused or coordination-caused false trips would be reduced by over 50%.

ACCESSORY COMPONENT FAILURE

Even though accessories are not a direct part of a relay, they are certainly part of a relay system. The 12 misoperations have only three root causes, all of which can be addressed with low-cost modern technology.

Six false trips were caused by copper pilot wires being shorted, which caused a false trip on an external fault. Three of these shorts appeared to be long-term failures, while three of them were caused when a fault on a nearby line brought down a phase conductor, damaging the pilot wires at the same time. This demonstrates the importance of both long-term monitoring of communication channels as well as high-speed supervision of trips with a loss of channel signal.

False trips caused by bad wiring were next, with five occurrences. Three of these were differential relays that had been miswired on initial installation. Using a relay capable of displaying phase rotation and steady state operating quantities provides a means of checking secondary CT and VT wiring.

One false trip was caused by an electromechanical auxiliary relay continually keying a permissive transmitter until an external fault caused a misoperation. Again, the use of a modern relay with a channel monitor and timer alarm could prevent this operation.

HUMAN-CAUSED MISOPERATION

With eight trips caused by vandals during one break-in, it is not difficult to determine the primary cause of human-caused misoperations. The station break-in occurred at 6:04 pm in an urban area on Thursday, May 8, 1997. This demonstrates that physical security may not be sufficient to prevent breaker operation by unauthorized persons. There are operational questions about routing all trips through password-controlled devices, but if cases like this one increase, the incentive to use the secure devices available will increase.

The other human-caused events were by either bumping relay panels and RTU racks or dropping wires. The bumping demonstrates the need for high seismic contacts. The bump of the RTU rack showed no targets of any kind following the operation. Routing through a relay with SER would provide a record of trips and their initiating device. Debounce timers on inputs can help prevent cascading a bump-caused event.

RELAY DESIGN HOLE

To some extent, any relay false trip can be described as a design hole. For this analysis, however, the definition is restricted to those cases where the relay clearly misoperated even though it tested as OK. Considering the system exposure, the low number of operations of this type is a credit to the qualification testing performed by relay manufacturers and utilities.

The most common (five occurrences) design-caused misoperation was distance relays operating on either a PT failure or a remote fault causing a low voltage on a radialized system. These misoperations were all on electromechanical relays. Solid-state and microprocessor relays had no recorded loss of potential operations.

The second greatest single design hole based on these 19 months of experience was three cases of electromechanical transformer differential relays (built by two different manufacturers) operating on inrush. Considering that inrush is itself a statistical phenomenon, with only about one out of 20 energizations producing maximum inrush, this number can be considered significant. Microprocessor relays provide improved setting ranges and operating principles [2]. Possibly of greater importance is the recorded waveform of all trip events to provide analysis without the time and expense of testing the transformer itself.

The only other false trip from a relay that tested OK was a solid-state phase comparison relay that operated for a fault on a parallel line. It is possible this is a settings error. The limited information available from a solid-state relay makes a detailed diagnosis impossible.

INDUCED SIGNAL/NOISE

Four of the five instances of induced signal-caused or noise-caused trips were in communications circuits, not in the relays themselves. The use of communications-dependent schemes for EHV protection makes these events even more significant. At 500 kV, one event was with phase comparison and one was with differential. This demonstrates the problems with using a communications system subject to noise, such as microwave, with a protection scheme dependent on accurate communication. Direct or multiplexed fiber systems would be more appropriate for communication-dependent protection schemes.

The other instance, by itself, continues to illustrate the problems with having unrecorded trip paths. A circuit breaker operated during a dc ground search with no relay targets recorded. With no record of a device operation, any corrective action is by guesswork only.

FORCE MAJOURE

These may be the only five instances of false trips that defy a reasonable corrective action. The industrial explosion that caused the three line relays to operate broke windows a half mile from the facility and the substation was across the street. A reasonable case could be made that the trips were correct.

The other two events were caused by water gaining access to transformer-mounted relays. Proper maintenance of gaskets could help, but the relays were mounted where they need to be.

RELAY COMPONENT FAILURE

At almost the bottom of the list of false trips, we arrive at relay component failure. Of concern is that in all three instances, the component failure in an electromechanical or solid-state relay system was found as a result of a system fault. The implication is that more quietly failed components are sitting out there waiting for a nearby event to trigger a false trip. In this case again, a relay with self-checking diagnostics does not need to wait for a false operation to determine that there is a problem.

MYSTERY

The last two false trips could almost certainly fit into one of the categories listed above, but there is no data to draw from. No targets, test failures, or event records indicated the guilty devices. Again, the importance of recording relays is indicated.

FAILURE TO OPERATE (SEE APPENDIX 2)

In terms of equipment damage, if not system damage, the failure to operate for a fault is of great concern to the relay engineer. Local backup can limit damage and the spread of tripping, but loss of service will certainly be greater than if the relay operated correctly. By the time remote backup takes place, numerous lines must be cleared. Because fault current is divided between these lines, the delay in clearing is significant.

The fault shown in Appendix 2 (which occurred on 5/5/96) lasted at least 82 cycles (the fault recorder stopped recording at that point; more on this topic later). Six lines connecting to six different stations cleared to remove the fault current. Murphy's law was strongly evident, as it took a dispatcher five tries to find the correct breaker to open in order to restore the system. With minimal fault data available, problems compounded, and it took 35 minutes before lines tripped on backup could be closed.

Using the same categories and rankings as listed for misoperations, we can group the failure to trip events as follows:

- Setting or coordination failure: 1 instance (7.7%)
- Accessory component failure: 10 instances (76.9%)
- Human-Caused: 0 instances
- Relay design hole: 0 instances
- Induced Signal/Noise: 1 instance (7.7%)
- Force majoure: 0 instances
- Relay component failure: 1 instance (7.7%)
- Mystery: 0 instances

SETTING OR COORDINATION FAILURE

The only event caused by a settings problem was a fault below set pickup in a time overcurrent relay.

ACCESSORY COMPONENT FAILURE

Accessory component failure, including wiring, was responsible for ten times more failures to trip than any other cause. Clearly, attention needs to be paid to the root cause and detection of these errors. For convenience in analyzing the data, it is fortunate that for the ten failures to trip there were only three basic causes.

For five of the failures, the circuit breaker failed to trip. The failures were caused by both trip coil failures and mechanical or electrical failure of the breaker itself. While trip coil monitoring has been available for years in solid-state and microprocessor relays, it is not used in all applications. More complete monitoring of actual circuit breaker interruptions has only recently been available in microprocessor relays. Even using a simple breaker history report (see Figure 1) can provide information on the "health" of a circuit breaker before a failure to trip clears at least a system bus. The utility presented did not use breaker failure protection at subtransmission levels, and remote clearing was typically delayed.

```
=>BRE 1 H <Enter>
Breaker 1 History Report

Relay 1                              Date: 03/15/2001                            Time: 07:19:27.156
Station A                            Serial Number: 01001234

No.   Date          Time             Bkr.Op        Op   Time(ms)       Pri I       VDC1        VDC2
                                     Elect Mech    (A)  (V)            (V)
1     06/01/2000    12:24:36.216     TRP A         26   28             5460        119         118
2     06/01/2000    12:24:36.216     TRP B         26   28             5260        119         118
3     06/01/2000    12:24:36.216     TRP C         26   28             5160        119         119
4     09/26/1999    16:24:36.214     Cls A         39   35             1020        118         118
5     09/26/1999    16:24:36.214     Cls B         39   35              990        118         118
6     09/26/1999    16:24:36.214     Cls C         39   35             1010        118         118
7     03/26/1999    11:24:36.218     Cls C         39   35             1100        117         115
8     03/26/1999    11:24:31.218     Trp C         26   28             3460        116         112

128
=>
```

Figure 1 Breaker History Report

Four failures were caused by shorted or miswired pilot wires. Combined with the false trips detailed above, this is the greatest single failure mode. This amounted to almost a 1% chance of failure for all events. Pilot wire relays were on only a little more than 10% of feeders. With roughly one chance in ten of a misoperation or failure to operate, the pilot wire failure rate seems unacceptably high. Monitoring of differential communications or replacement of copper wire with optical fiber should be a very high priority for any system.

One failure to trip was caused by CT wires being reversed for a directional overcurrent relay. A three-phase fault had current of 5200 amps at 34.5 kV for 15 seconds. From an energy standpoint alone, this is 1.29 Megawatt hours! This was a new electromechanical installation at the time. A microprocessor relay would have shown reversed CTs with a glance at the meter report.

INDUCED SIGNAL/NOISE

One instance is a data point, not a trend. Arcing noise blocked a power line carrier signal in a POTT scheme at 230 kV. This resulted in tripping by a backup system in 24 cycles. If it were a trend, switching to a blocking scheme or changing a permissive window would be reasonable.

RELAY COMPONENT FAILURE

Of over 1400 events, only one failure-to-trip event was caused by component failure. The statistic is of more interest than the specific component failure.

SECURITY/RELIABILITY TRADE-OFFS

The one event of component failure in a 55-year-old relay shows the exemplary reliability of relay systems in the past decades. This should make us think about the traditional use of two different relay systems for increased reliability. The data provided by this utility indicate that almost all failures to trip are caused by connected wires or circuit breaker problems, not relay construction or design. This indicates that adding a second, dissimilar, relay system produces virtually no increase in protection system reliability. On the other hand, because a second, dissimilar, relay system increases the probability of settings errors, the probability of a false trip roughly doubles with the added relay. Where two relays are desired for maintenance or testing purposes, this data shows that having similar wiring and settings will provide the least security degradation.

Using fault tree analysis methods [3] provides a way to quantify these trade-offs and explain the significantly higher incidence of misoperations than failures to operate. Misoperations are the logical "OR" of trip outputs from each scheme. Failures-to-trip are the logical "AND" of the trip outputs; all schemes must fail to prevent a trip.

PROTECTION SPEED

After security and reliability, the next measure of protection system performance is speed. The data sourced for this paper indicates EHV protection times of 2–4 cycles for most faults. There are numerous papers discussing protection speeds at EHV levels, so this paper will not go into further detail [4] [5] [6].

At subtransmission levels (34.5 kV) there is a large amount of data provided by the utility. This can be analyzed statistically to examine the performance of these relays and the system impact of this speed.

Figure 2 shows the subtransmission TOC clearing times versus fault duty. While this has a "shotgun" look, and clearing times that do not change a lot with increased fault duty, there are other ways to look at the data that is even worse. Removing reclose tries from the plotted data more clearly demonstrates the lack of relationship between fault magnitude and clearing time (Figure 3). For comparison, a moderately inverse TOC curve is included (Figure 2 and Figure 3) to show the relationship that current and time could reasonably be expected to have for a protected system.

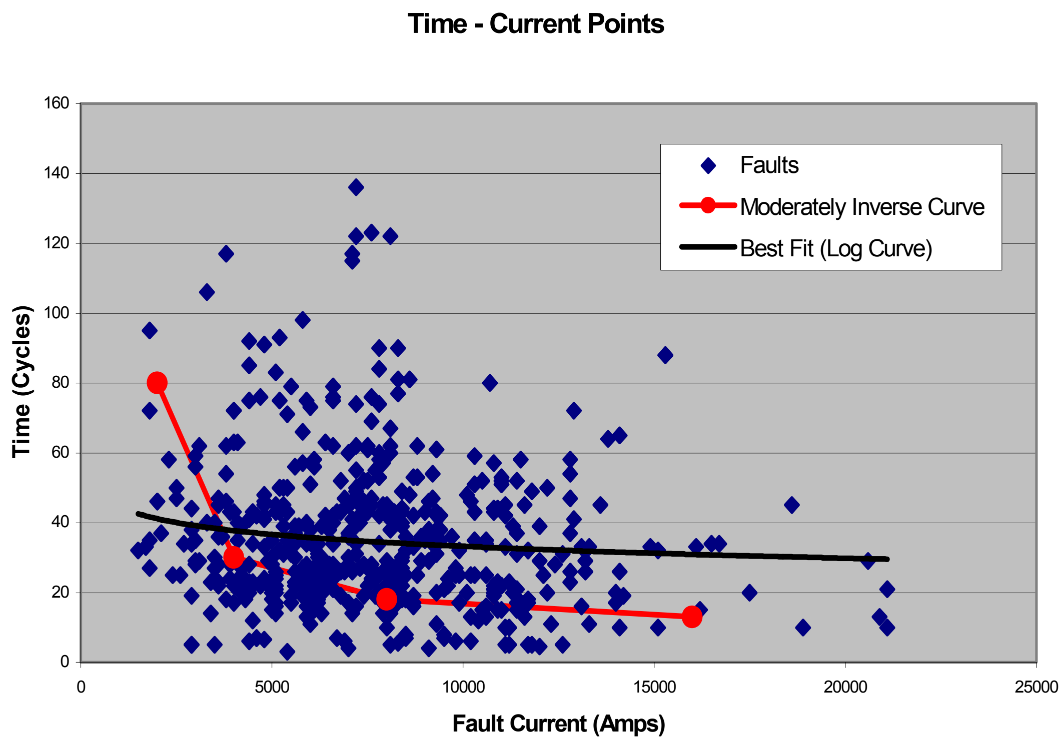

Figure 2 Time Current Points Chart

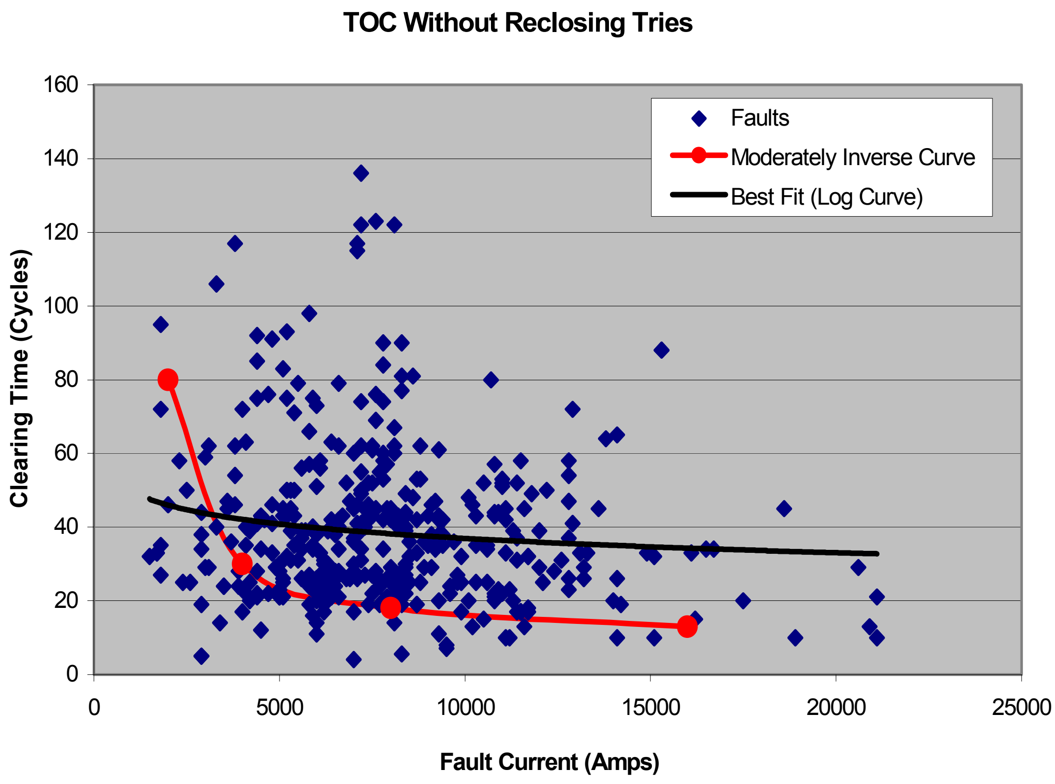

Figure 3 TOC Without Reclosing Tries Chart

Of course, a single TOC curve is applicable only to a single line. Stacking curves for coordination results in clearing times actually increasing as a fault moves closer to the source. This tradeoff of higher speed for higher currents—and lower speed as a fault moves closer to the source—is what results in the scatter plots shown. The negative results of this are clearly seen in the minimum clearing speeds as a function of fault duty. At 7000 Amps of fault duty there is a minimum clearing time of 5 cycles. At 10,000 Amps that has gone up to 7–8 cycles, and at 20,000 Amps it has increased further to 10 cycles.

By comparison, some of the utilities' lines are protected with differential relays. For all of their lack in security and dependability, these differential relays are unarguably fast.

Figure 4 shows the clearing times for faults on a differentially protected line. Note the difference in scales from the TOC curves.

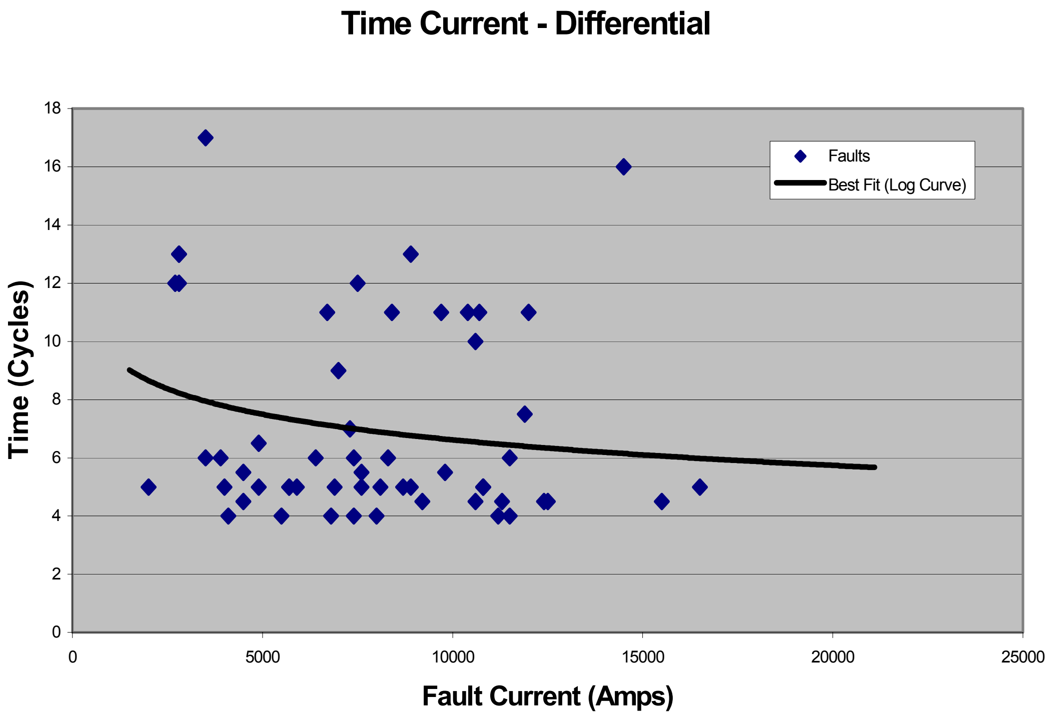

Figure 4 Time Current Differential Chart

One of the advantages of microprocessor relays is that high-speed protection does not require expensive relays. The same relay that is used for directional time overcurrent protection can be used in a high-speed protection scheme with the simple addition of low cost communication [4].

IEEE standard C57.12 for Liquid-Immersed distribution, power, and regulating transformers states that "… the duration of the short-circuit current as defined in 7.1.4 is limited to 2 s, unless otherwise specified by the user." This standard also states that this time includes all reclosing operations. It is well understood that fault current and time will damage transformers, with each event taking a piece of life out of the unit. The passage of through fault current is a leading cause of transformer damage [7]. One of the elements of a high quality protection system is that equipment damage is limited, as much as reasonable, given the overall economics of the protection.

In addition to limiting equipment damage, reclosing was more probably successful with higher speed tripping. In addition, the likelihood of damage to nearby lines was limited by faster tripping. Specifically, in TOC protected lines there was a 31% probability of a failed first reclose, compared to a 25% probability for differentially protected lines of the same class. Also, in 5% of the faults, a second fault was caused by the first. These were all on TOC protected lines, with the second fault occurring at least 6 cycles after the first with a typical time of 30–60 cycles after the first fault started.

An example of how fault times add up is a storm event that occurred on January 6, 1997. Numerous lines experienced multiple temporary faults, followed by a high-speed reclose operation. One, not exceptional, example is the 34.5 kV line (identified as the V-P3 line). It experienced 15 faults over an eight-hour period, with an average magnitude of over 7000 Amps and a duration of each fault of 45 cycles. This is 11 seconds of fault duty. The transformer feeding this line survived the day, but it could not have felt good.

This type of event can be improved in two ways: 1) Fault-clearing time can be reduced with relay-to-relay communications; this average clearing time of 45 cycles could reasonably be reduced to 6 cycles. 2) Microprocessor relays can also improve the system operation by counting operations in a given time and limiting relatively long term events to a “reasonable” level. If a slack span is causing numerous trips in a storm, it might be a better idea to trip off the line until the span can be repaired than to continue hammering it with fault after fault.

CONCLUSIONS

Based on the data from this utility, we can make some general conclusions. Because the data is from only one utility, care should be taken in its unquestioned application; however, the large number of events sampled increases confidence.

1. False trips outnumber failure to trips by a factor of about five to one. Protection quality improvements should be focused with this ratio in mind.
2. Failures to trip are rarely caused by relay failures or design flaws. Doubling overall protection scheme complexity can decrease security without improving reliability, unless steps are taken to minimize the possibility of setting or accessory problems.
3. Relay communications are the number one cause of both security and reliability problems. Improving the quality of communications will have a direct benefit to protection system quality.
4. Measured protection speed at all voltage levels should be examined for suitability and reasonability to limit equipment and system damage.

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BIOGRAPHY

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as Market Manager for Transmission System Products. Prior to that he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in Pennsylvania.

APPENDIX I: FALSE OPERATIONS

Relay Component Failure	
4/8/96	Reclosing relay with shorted diode, closed in three times, loss of air pressure in circuit breaker caused trip times to increase until backup relay (on 230 kV bank) cleared fault on 34.5 kV feeder.
3/15/96	Staged fault caused adjacent 500 kV line to trip by “finding” a faulty component that removed restraint and caused operation on reverse fault. This sent a direct transfer trip to the other end.
6/29/97	230 kV line tripped due to leaking capacitor in electromechanical distance relay.
Relay Design Hole	
1/30/96	Two electromechanical distance relays operated for remote bus fault: “the relay contacts have a history of drifting closed when the line voltage goes dead.” They did not cause outage. The line was already dead.
8/11/96	Solid-state phase comparison relay tripped for a fault on parallel line. Relays were tested with no problems found.
9/11/96	Electromechanical distance relays tripped on PT failure; line did not trip.
9/23/96	Electromechanical transformer differential misoperated during inrush. Relay tested OK.
9/25/96	E/M DCB scheme misoperated at one end of line due to fault detector operating for external fault and forward looking distance relay “drifting” closed on low voltage (two occurrences on separate lines for same fault).
10/17/96	Electromechanical transformer differential misoperated during inrush. Relay tested OK.
11/6/96	Electromechanical transformer differential misoperated during inrush. Relay tested OK.
Accessory Component Failure	
1/27/96	9:41 Electromechanical pilot wire differential false trip on bad pilot.
1/27/96	9:48 Electromechanical pilot wire differential false trip on bad pilot.
8/1/96	E/M POTT scheme false tripped on external fault due to e/m aux failure causing transmitter to stay keyed on.
8/1/96	Solid-state bus differential tripped on external fault due to a ground return wire not installed during addition of new equipment to station.
9/18/96	Three transformer banks tripped due to false transfer trip during test of breaker failure relays. Blocking switches were mislabeled on newly installed equipment.
11/20/96	Directional overcurrent relay opened while switching a capacitor, due to a control wiring problem.
1/6/97	Fault on adjacent line damaged pilot wires, causing electromechanical pilot wire differential relays to trip three lines.

5/6/97	Electromechanical pilot wire differential tripped on external fault. Apparently shorted pilot.
6/24/97	Transformer false tripped on first load because CT wired backwards.
7/8/97	Same transformer tripped again due to one phase wired incorrectly.
Setting or Coordination Failure	
1/16/96	Electromechanical pilot wire differential operated on fuse-cleared fault. Electromechanical pilot wire differential cannot coordinate with fuse, cleared faults.
3/15/96	500 kV staged fault caused an echo-tripping permissive echo that eventually caused a false trip on that line. Line tripped again on second staged fault test on adjacent line.
3/18/96	Overfrequency relay tripped on transient caused by line tripping. Relay operated correctly, given its settings, but incorrectly, given its application.
3/25/96	Relay operated for a repeated fault on an adjacent 345 kV line. This was a “correct” incorrect operation. Could be described as a coordination failure.
4/5/96	Transfer trip inadvertently sent during disconnect switching 230 kV line.
4/5/96	Electromechanical pilot wire differential tripped after fuse-cleared fault—lack of coordination.
5/17/96	Electromechanical pilot wire differential tripped after fuse-cleared fault—lack of coordination.
7/4/96	Electromechanical pilot wire differential false tripped due to circulating current when transformers were paralleled.
9/19/96	4.8 kV bus tripped on backup due to slow trip of downstream fault (coordination failure).
12/12/96	Overcurrent relay on transformer tripped on back-up when a fault on a feeder did not clear; coordination error.
1/16/97	Underfrequency relays tripped on the transient when a breaker tripped on low SF6 pressure. Settings error (in my opinion).
2/27/97	EM TOC relay tripped on circulating current when bus tie closed for routine work.
3/21/97	Electromechanical pilot wire differential overtripped on fault cleared by fuse tapped on line.
4/4/97	Electromechanical pilot wire differential tripped due to circulating current when lines paralleled.
5/19/97	EM directional overcurrent tripped when line was paralleled.
5/23/97	Electromechanical pilot wire differential overtripped on fault cleared by fuse tapped on line.
7/3/97	Transformer relay false tripped on new energization because new settings had not been applied.

Induced Signal/Noise	
3/15/96	Staged fault at a 500 kV line caused false trips due to noise induced into phase comparison relay at same station, which sent a transfer trip to other end.
7/23/96	Breaker tripped due to a spike in the dc circuit during a dc ground search. No relay targets were reported.
10/16/96	Electromechanical pilot wire differential relay misoperated due to external 230 kV fault sending “noise spike” into pilot wires, which tripped one end of 34.5 kV line.
12/17/96	Fault on nearby line created a voltage spike, causing a pilot wire relay to operate (line did not have drainage reactor).
8/23/97	500 kV false trip due to microwave noise, causing current differential relay to operate.
Mystery	
3/18/96	230 kV line tripped for fault on reverse line. No targets found on any relay.
8/27/96	230 kV bus tripped during transfer of station service. No targets, no cause found.
Human Caused	
4/25/96	500 kV line tripped on transfer trip accidentally sent during maintenance.
11/4/96	Electromechanical pilot wire differential false tripped when “a construction crew was drilling on the adjacent relay panel when the relay was jarred closed.”
12/31/96	Transformer tripped when RTU was bumped, causing it to operate. No relay targets (shows advantage of using relay trip contacts for operation).
3/8/97	False trip of transformer due to wiring being dropped into a pool of water during work on transformer pressure relay.
5/8/97	Vandals broke into substation. Tripped 8 breakers. No relay targets. Another reason to use relays to operate breakers. Break-in at 6:04 pm in May.
Force Majoure	
2/20/96	Water leaked into Buchholz relay.
11/11/96	“Concussion from a large explosion at X caused the relay contact to close” EM directional overcurrent relay (3 lines).
1/13/97	False trip due to rain water leaked into the pressure relay on a LTC.

APPENDIX II: FAILURE TO OPERATE

Setting or Coordination Failure	
2/16/96	Electromechanical TOC relay did not operate for fault 1000 Amp. Cleared other end after 63 cycles. Fault self-cleared at 125 cycles.
Accessory Component Failure	
1/29/96	6:36, CB failed to trip (reported as relay failure to trip)
5/5/96	Electromechanical pilot wire differential at 34.5 kV failed to operate due to miswired ground lead, which allowed an induced voltage to counteract the tripping voltage. This caused 6 line trips followed by 5 reclosing & trips. Dispatcher could not determine where the fault was and closed in repeatedly to test lines.
12/28/96	Breaker failed during trip for line fault (E/M POTT). Failure caused a bus fault to be detected. Breakers on the bus were blocked from tripping due to a large pump being started causing breaker failure of all incoming 230 kV feeds.
12/28/96	After clearing of the breaker fault, station was attempted to re-energize. Fault was re-initiated and same problems happened again.
1/6/97	E/M directional OC relay failed to trip due to CTs being reversed. Backup tripping cleared 5 incoming lines at 34.5 kV. Fault took approximately 15 seconds to clear.
1/6/97	Failure to trip electromechanical pilot wire differential due to shorted pilot wires. Line cleared on time overcurrent backup.
1/6/97	Failure to trip electromechanical pilot wire differential due to shorted pilot wires. Line cleared on time overcurrent backup. This was a repeat event 2 minutes following a successful reclose. It could be argued that if the pilot wire relay had tripped, the damage would have been limited and reclose would have held … maybe.
1/6/97	Failure to trip EM TOC due to bad breaker. Breaker would not open until all current flow was interrupted elsewhere. Cleared 2 other lines.
1/6/97	Pilot wire shorted caused failure to trip of electromechanical pilot wire differential. Two lines were cleared in backup.
8/5/97	Failure to trip due to burnt trip coil (EM relays); two lines cleared on backup.
Induced Signal/Noise	
1/6/97	Failure to trip of 230 kV E/M POTT primary protection scheme for the line caused by excessive noise from an arcing conductor swamped out the power line carrier receiver. Line tripped on backup after 24 cycles.
Relay Component Failure	
5/24/96	Electromechanical pilot wire differential failed to trip due to bad “rectox unit” in 55-year-old relay. After failure relays were replaced by similar vintage relays. Six lines tripped as a result of failure to trip.

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