The Answer to the Relay's Misoperation is in the DFR Data

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Abstract - This paper discusses the common problems in using DFR records to reconstruct the test cases needed to prove a relay's or protection scheme operation (or misoperation). It first discusses the testing tools and methods commonly used and also requirements for proper analysis. It uses an actual case study to demonstrate the steps taken, techniques used and tools required to manipulate the DFR data and reconstruct usable COMTRADE test files to investigate the problem relay.

Index Terms— Protection scheme, DFR, analysis, protection testing, COMTRADE

I. INTRODUCTION

Testing of the protection system should provide the right kind of results where by a proper analysis can be performed and establish a baseline of how it should respond to the power system.

The analysis of the actual operations of protection relays during short circuit faults or wide area disturbances plays a very important role in detecting real problems with the settings of the relay, the electric power system model used to calculate them or with the protection relays interface to the substation apparatus.

A Proper Set of Analysis Tools is required to:

- Create/Understand the Phenomena
- Properly indentify/classify the event(s)
- Verify system devices and operations
- Reconstruct key data for trouble shooting
- Determine corrective actions

In the past few decades however, changes in the industry caused by deregulation, economic pressures, reduction of work force, and subsequent loss of protection knowledge and field expertise has resulted in many utilities and grid operators to omit detailed investigations of relay and system misoperations. However, with proper training and retention of event and relay operations, analysis of these misoperations can be a quick and beneficial exercise.

II. TESTING TOOLS

What are the general requirements of tools that not only test protection systems but also support the analysis of the protection system?

- There is one common element that all tools should have, the ability to generate/display the waveforms used for testing and capture of the relay's I/O response.
- The ability to record waveforms that are either injected or connected to the protection device.
- The ability to use industry standards for data exchange – e.g. COMTRADE.
- Modify captured data as needed into other system or engineering quantities or visual displays.
- Flexibility to reconstruct events from various data sources and combine them into usable test files and test cases.

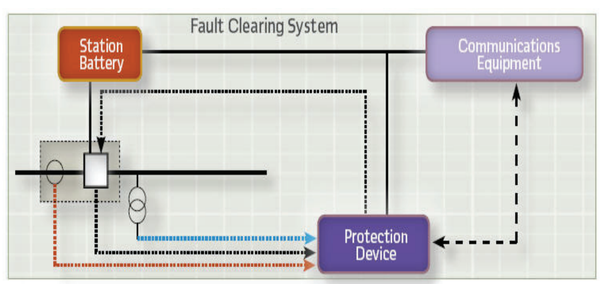

Figure 1: Fault clearing system

Modern test equipment must be able to be used with these various tools and perform injection, simulation, and monitoring for all types of relay systems, legacy E/M relays, static designs, and multifunctional digital IED's. Today, that simulation requirement extends to the newest technology of IEC 61850 enabled devices. For optimization of analyzing relay operations in the future, Network Simulation Tools will have to support the communications and networks too in order to again establish proper baseline performance. Present standards like COMTRADE may not be adequate for such future communications based testing requirements.

From a system or scheme testing perspective the test equipment or synchronized multiples of them must also be capable of simulating the entire Fault Clearing System; (see Figure 1) this is also an advantage for other protection systems like a PMU/PDC system or SIPS/WAPS. But as noted, this may be far from present testing methods, equipment, and common software tools being utilized now.

III. TRADITIONAL TESTING METHODS

Can traditional relay testing methods be used to establish proper baseline performance data for protection systems? By that I mean the separate test of each relay element to a given setting as a manufacturer does for a design verification test? Or, as performed for an acceptance test, commissioning test, or routine test? (See Figure 2)

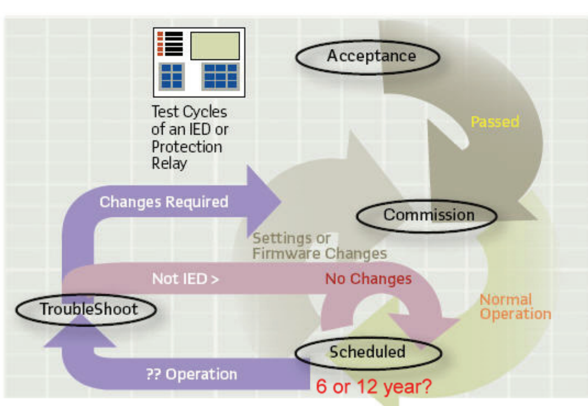

Figure 2: Traditional IED/Relay Testing Cycle

The answer is no. The only way to establish a performance baseline is to use a system testing approach with near real power system conditions. Using a model of the power system, parameters of the application, and understanding of the relay design or protection system is the cornerstone to achieving a performance baseline. The application defines the test cases of both positive and negative expectations. But, the power system operations and events determine the limits of the parameters validity and create the scenarios we often do not anticipate.

IV. TYPES OF EVENTS

- Shunt (short circuit) faults
- Series (open conductor) faults
- Parallel (mutual coupling)
- Breaker switching
- System parameter variations
- Equipment failure
- Protection settings and operation
- Control system operation
- Operator action

Performance testing requires consideration of all event types and this generates hundreds of variables. Events do not occur singly, they are a cascade of actions that must be sorted through and identified. Analysis requires identifying the Primary event and the following resultant Secondary events that stem from it.

Failure to operate

Failure to operate under fault conditions may have severe impact on the stability of the electric power system due to the increased duration of the fault caused by the operation of backup protection functions or the switching-off of healthy system components. An example (see Figure 3) of this would be a fault occurring during a power swing when the protection system is set to block tripping, but when the fault occurs it should then trip, but does not.

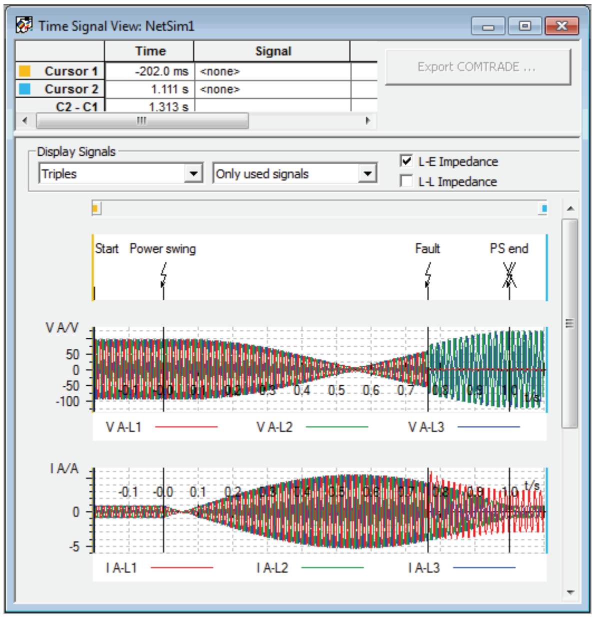

Figure 3: Asynchronous power swing w/fault

Undesired operation

As many system disturbances and blackouts have shown, one of their main causes has been operations of the protection system under non-fault conditions. These failures also need to be prevented since they may also have a negative impact on the stability of the grid and result in deterioration of the conditions that promote a wide area disturbance.

The problem operation needs to be analyzed in order to determine what happened and some corrective action taken to prevent future incorrect operation of the Protection System. Further, if we reference reliability standards such as NERC PRC-005-2 (pending) and if this misoperation involves a "Segment" which is defined as a group of at least (60) individual "components" of a particular model or design on this system; then a required change to one such Component (say a firmware update to correct the problem) may have to be implemented to the entire Segment to stay in compliance. Documentation and tracking of this would be a critical point of compliance. So failure to properly analyze the problem operation could lead to additional system protection failures in the future.

A key requirement for doing any testing is the reason for the test and accuracy of the test data obtained. Simply performing an element check will not identify the relay's reason for misoperation.

Sequence of Events Example:

Primary event: Single phase-to-ground fault in phase A.

- Secondary event 1: Voltage variation (sag) in phase A
- Secondary event 2: Voltage variation (swell) in phase B
- Secondary event 3: Voltage variation (swell) in phase C
- Secondary event 4: Protection operation
- Secondary event 5: Breaker trip
- Secondary event 6: Autoreclosing relay operation
- Secondary event 7: Breaker failed to close

What information from this SOE are important and to whom? Which part of the protection system or FCS should be tested?

In many cases the Event Log cannot identify the root cause of the misoperation, but it can zero in on the problem part of the FCS that failed its task or show coordination problems spanning the system. All data must be time tagged to be of use, and having a system wide definition and time reference is critical. For event data it would ideally be in the format of IEEE C37.239-2010; (COMFEDE). This IEEE standard was developed for the purpose of easily merging event data from multiple sources and having the time tags automatically align the events. In order to test the system properly we need to re-create the conditions under which it failed. This requires both SOE status data and the system waveforms during the events. The Disturbance Fault Recorder is the ideal tool for capturing all of the information we need as synchronized data.

However, it must be properly configured and have all the voltage, current, and status channels for each protection system being monitored. In reality, economics often dictates that this is not the case.

V. TOOLS FOR ANALYSIS / RECONSTRUCTION

In order to analyze and reconstruct the test files needed for an investigation into a protection issue, we need an excellent software tool or suite of tools that can as a minimum:

- Import/Export COMTRADE/PL4 files,
- Import and synchronize multiple files,
- Display recorded waveforms,
- Provide sample by sample analysis,
- Display Vector, Phasor, Impedance, and Harmonics Diagrams,
- Display RMS and peak values in Primary/Secondary units,
- Allow channel assignments by network model,
- Identify fault inception angle,
- Measure DC offset and harmonics,
- Identify evolving faults and phase rotation,
- Perform single and double ended Fault Location calculations,
- Current reversal on double circuit lines,
- Show system transients up to 50th harmonic,
- Display/modify digital status of protection functions as needed.

To demonstrate the importance of having the right tools we can take the following example of a relay misoperation and the effort needed to reconstruct the system event that brought the problem to light.

VI. RECONSTRUCT THE EVENT

Actual event investigation: static design distance Relay 1A on Line 1misoperates for out of segment C-A fault on Line 2. Results in loss of Line 1 and interrupts normal restoration logic. Relay 1A data and event conditions are:

- Relay 1A is static design and has no event memory or oscillographic data, only some element flags.
- Local DFR is at Line 1, 2, 3 Bus: only Line currents recorded; voltages at this location are not recorded and missing.
- However – Local DFR digital channels have key POTT scheme data for Line 1.

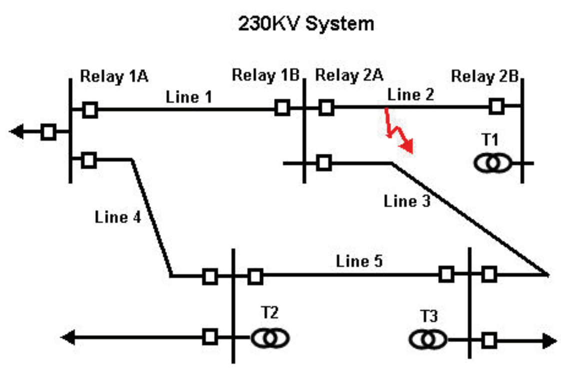

Figure 4: 230KV system – fault Line 2

So the challenge is to use the available data and our test tools to reconstruct the event with the goal to produce a COMTRADE file to use in playback to the relay and verify the misoperation to find the problem.

Process involves using several analysis steps:

1. Gather any additional data: review adjacent substation DFR and Relay data and find usable bus or line voltages as substitute for

missing Line 1 voltages taking system constants into consideration to reflect them at the Relay 1A location.

2. Ensure time sync of current and voltages with start of Line 2 fault by aligning collected data.

3. Extend Prefault time from 200mS to 2.0 S to allow proper initialization of Relay 1A.

4. Verify and adjust secondary values to used CT/VT ratios of Relay 1A.

5. Use phasor & symmetrical components analysis to verify Prefault & Fault relationships of the collected data and the reconstructed file.

6. Add key digital channels (POTT) and CB operations for replay simulation to Relay 1A.

7. Export data reconstruction as new COMTRADE file for playing back to Relay 1A.

VII. INVESTIGATION RESULTS

The result of the reconstructed COMTRADE file is shown in Figure 5. When the file was replayed to Relay 1A – it resulted in operating conditions that verified the misoperation per the original flagged elements and recorded POTT scheme timing.

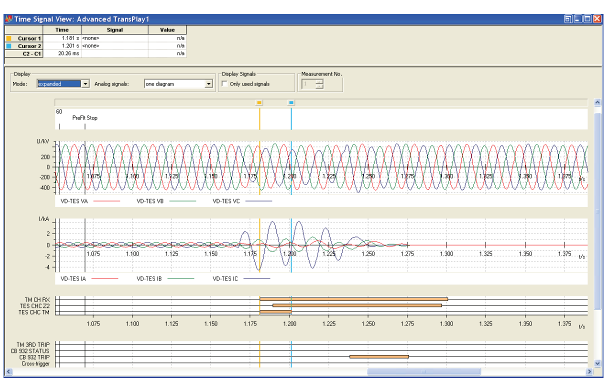

Figure 5: Reconstructed COMTRADE file

Relay 1A operated similar to the original fault, tripping for the Line 2 out of section fault. By monitoring additional timer elements during replay, the problem of the POTT scheme coordination was discovered.

POTT scheme reclaim timer for loss of channel not set correctly. The Zone 2 setting allowed overreaching to 170% of Line 1, but the desired setting was 140%, after additional test cases were created to verify setting limits, the setting multiplier was found to be marked incorrectly.

We can quickly review the steps that created the reconstructed fault file and how the test/analysis tools provided key capabilities.

Step 1: Identify fault currents of Line 1 and 2. In Figure 6, Line 1 operates due to POTT scheme.

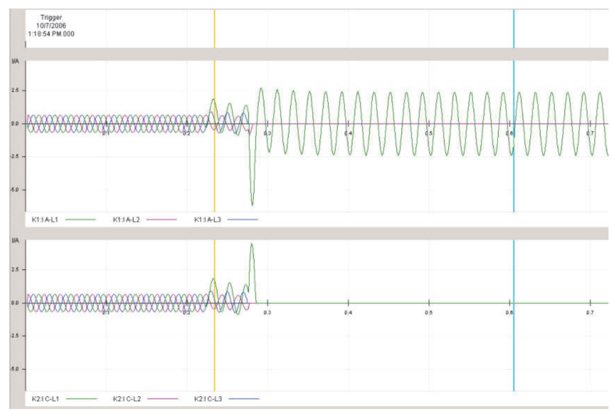

Figure 6: Waveform Display Fault w/Reversal to Line 1

Step 2: Phasors & Sequence Components are used after the various voltage traces are brought together with the currents to verify the alignment of samples. Values are adjusted to reflect the currents and voltages to the Relay 1A position. Figure 7 shows the Phasor display after alignment.

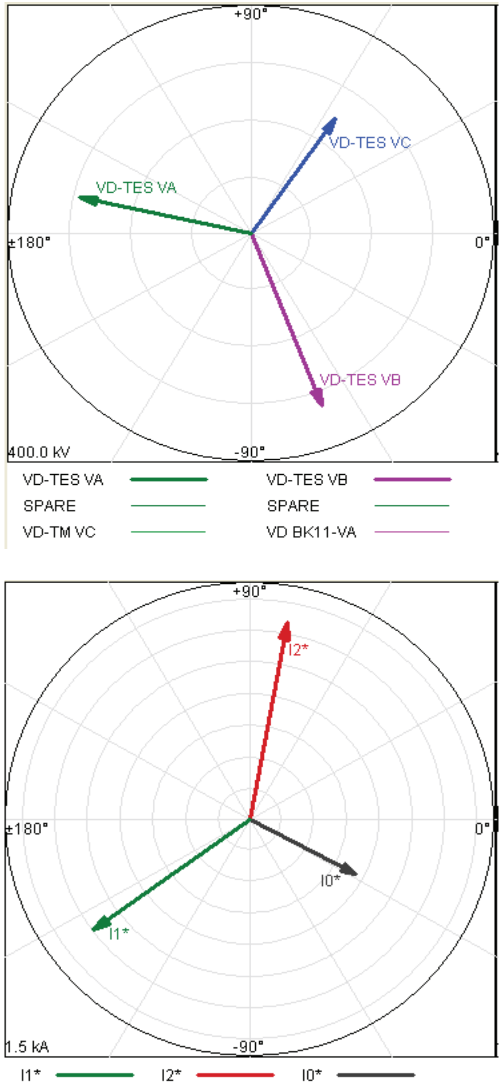

Figure 7: Phasor display of Relay 1A signals.

Step 3: Verify Harmonics are not excessive.

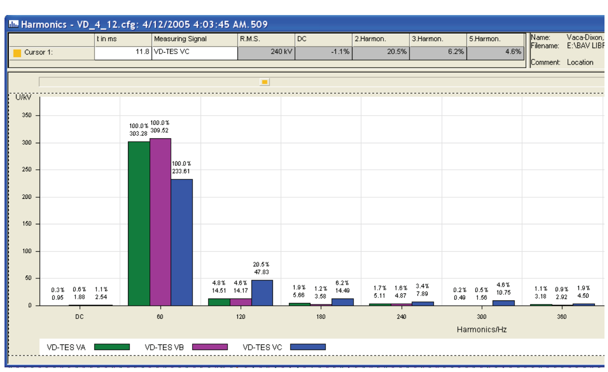

Figure 8: Harmonic content at fault inception.

Step 4: Use the reconstructed file and verify the fault sequence and values using Impedance Plots of the impedance locus of each fault loop.

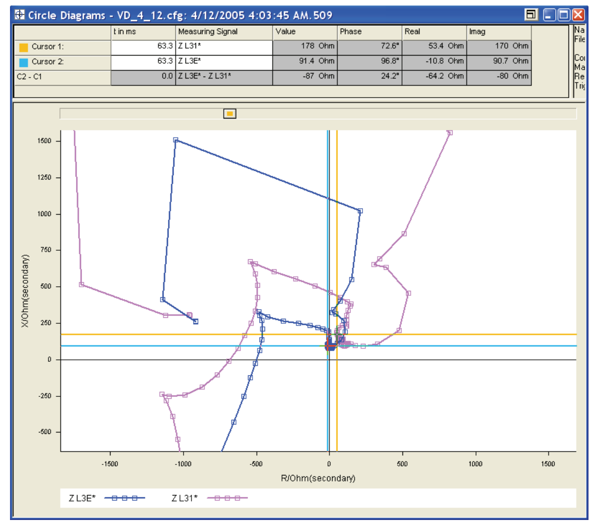

Figure 9: Impedance Plots of Fault Loops

Step 5: Verify the Primary and Secondary values of the file before playing to Relay 1A.

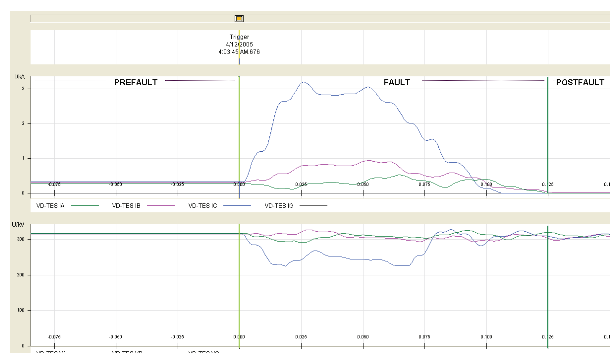

Figure 10: RMS Values (in both Primary & Secondary Values)

The example makes the point that it would be better to know such issues, deficiencies, or limitations prior to system wide implementation of this relay. And this makes the point for improved and more detailed system testing both in the lab and in the field. If such testing is performed – say in the lab – to prove a device or scheme as suitable for the system, then a subset of these lab test cases would be appropriate as part of the End-to-End test case portfolio for routine testing, particularly when other modifications or updates of the FCS are made.

VIII. CONCLUSIONS

The following tools are essential in the analysis of electric power system events and allow for any possibility of reconstructing the fault data:

- Visualization tools – allow the user to see the disturbance record as a waveform, vector diagram or in the impedance plain
- Fault location tool – calculates the location of the fault based on a single or two-ended method (when disturbance records are available from both ends of the protected line.
- Harmonic analysis tool – calculates the different harmonics and displays the amplitudes of measured variables as a bar chart
- RMS calculation tools – calculate and display the profile of currents and voltages

Proper consideration for test cases is required to establish performance benchmarks that confirm the FCS design and operation. When misoperations occur, the data is often in the DFR records, but proper tools are needed to ensure that it can be utilized to troubleshoot and analyze the system's operation or relay's problems.

IX. REFERENCES

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X. BIOGRAPHIES

Alexander Apostolov received a MS degree in Electrical Engineering, MS in Applied Mathematics and Ph.D. from the Technical University in Sofia, Bulgaria. He has more than thirty years experience in the field of electric power systems protection, control and communications.

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He is member of IEC TC57 and Convener of CIGRE WG B5.27 and member of several other CIGRE B5 working groups. He is Chairman of the Technical Publications Subcommittee of the UCA International Users Group. He holds three patents and has authored and presented more than 300 technical papers. He is also Editor-in-Chief of the PAC World magazine.

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He was with Houston Lighting & Power for 14 years and Multilin Corp. for 4 years before joining OMICRON electronics in 1995 where he is currently Technical Director in Houston, TX. A registered Professional Engineer in TX, he is also an IEEE / PSRC member, USNC member, CIGRE corresponding member. He holds a US Patent for “Communication-based Testing of IED’s” and has authored, co-authored, and presented over 90 technical papers.