ADVANCED APPROACHES FOR MONITORING, TESTING AND TROUBLESHOOTING THE PROTECTIVE RELAY OPERATION

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ABSTRACT

This paper introduces new developments in the area of monitoring, testing and troubleshooting the protective relay operation. The relay monitoring has recently been enhanced by automating the analysis of relay operation using data files from digital fault recorders (DFRs). The relay testing has been extended and further automated using recent developments of digital simulators. The simulator developments have also enabled extensive simulation and evaluation of relay operation, in particular for the cases when a misoperation has been identified. This paper gives a brief description of each of the new developments. It also gives an assessment of the existing practice, as well as future trends in the area of monitoring, testing and troubleshooting the relay operation.

INTRODUCTION

Protective relaying of power systems is a well established field with over 50 years of practical experience. The major advancements in this field have been made with the introduction of digital computer technology in the late seventies. An extensive development of new digital relays and digital communications took place in the early eighties. By the end of the eighties, the use of digital technology became an established practice [1].

In the area of monitoring, testing and troubleshooting the relay operation, three major developments have dominated the last fifteen years. Introduction of digital fault recorders (DFRs) in the eighties has enabled recording of analog waveforms "seen" by the relays, as well as contact changes such as relay trip signals, circuit breaker 52b contacts and communication channel signals for the relay scheme operation. Skillful operators have used DFR records to analyze relay operation quite successfully and this has become a well established practice [2]. The second major development was introduction of programmable test sets for relay testing. These instruments are produced today in a compact easy-to-carry form, and as such, have been extensively used for field testing of protection relays [3]. Yet other developments are electronic power system simulators aimed at replacing the costly solution of a physically scaled model of a power system. The new electronic simulators were built by the relay vendors and used primarily for testing new relay designs and occasionally for troubleshooting the operation of the existing designs as well[4,5].

Most recently, some new advances in the mentioned areas have been introduced. Software packages for automated analysis of DFR files are commercially offered by several vendors [6,7,8]. New digital simulators with an extensive transient waveform replay capabilities have been offered for both field and laboratory testing of protection relays [9]. In addition, elaborate digital, real-time simulator configurations have been recently developed for troubleshooting complex operations of protective relays and relaying schemes [10,11,12].

This paper gives a summary of the new developments in the area of automated DFR data file analysis using expert systems, as well as relay testing and relay operation troubleshooting using various designs of digital simulators. First, the need to improve the existing practice is discussed providing rationale for recent introduction of the new developments. After that, three sections are devoted to the advances in the following three areas: relay monitoring, testing and operation troubleshooting. The final section discusses future directions in the new practice that may be adopted by utilizing the new developments. Conclusions and references are given at the end.

EXISTING PRACTICE AND NEEDS

Analysis of DFR Records

Typical practice in the U.S.A. is to set digital fault recorder (DFR) triggers to be very sensitive to the disturbance on analog waveforms and the change of various contacts. This practice results in a large number of DFR records representing events that are not faults being captured. On the other hand, the ability to analyze fault events is quite enhanced since DFRs are sensitive enough to capture not only waveforms corresponding to nearby faults, but also waveforms of the faults occurring several buses away from the location of the DFR. The abundance of information contained in the DFR records is often sufficient to monitor operation of relays and related switching equipment and to analyze correctness of the operation [13]. The problem, however, is created by the volume of data being captured.

Most of the DFRs in the U.S.A. are connected to a Master Station via telephone lines. The large amount of data captured by DFRs needs to be communicated from DFRs to the Master Station for further analysis by the operators. This introduces an additional delay in analyzing the records. Finally, once the records are received by the Master Station, operators have a chance to perform the analysis. Again, the large number of records slows down the ability of operators to perform the analysis quickly.

The final outcome of the mentioned scenario for monitoring of the relay operation using DFRs is a post-mortem analysis that may take several days to complete. An alternative would be an automated analysis that can be performed in real-time. In this case, the results of the relay operation can be made available to the dispatchers in time to be of practical use in the remedial switching actions. Hence, automation of the analysis may be beneficial for both dispatchers and protection engineers where the dispatchers did not have this information readily available in the past and the protection engineers did not have an efficient way of obtaining this information quickly.

RELAY TESTING

A typical practice in the U.S.A. regarding relay testing is to perform setting calibration tests in the field. This practice assumes that a set of phasors representing voltage and current can be generated to perform steady-state testing of the relay operating characteristic. The most common examples of testing distance relays is by using a fixed voltage signal and ramping a current. This method of relay testing has been suggested by the relay vendors. The utilities have clear instructions how this testing is to be performed, and test sets suitable for carrying out such tests quickly in the field are readily available.

The complexity of some new relay designs, as well as a need to replace the "old" electromechanical relays with new digital relays have created a need for more detailed testing. As a result, several professional organizations have recommended more detailed relay testing that will be aimed at checking dynamic behavior of the operating characteristics, as well as relay behavior for a given set of application conditions [3,14]. This leads to a new requirement that both design and application testing of relays can be performed using phasor and transient waveforms as deemed appropriate [15,16].

Again, the need for additional testing may only be justified if the overall time to perform tests is not significantly longer. This implies that most of the additional tests can be performed automatically. To be able to provide for the new tests and required automation, new developments in the test equipment are required. Some recent commercial equipment offering in this area is aimed at meeting these needs [12].

TROUBLESHOOTING RELAY OPERATION

It is well known that relay misoperations do happen, and may cause major disturbances in the power system operation. Today's tools, readily available for analysis of such events, are rather limited. It is desirable that the overall power system event and related relay operation can be repeated for the purpose of the analysis. Existing test sets are not suitable for performing such a task. Designs of electronic simulators may be suitable, but their cost and availability are quite prohibitive for carrying out such a task as an everyday practice.

A need for advanced simulation tools capable of recreating power system disturbances and interacting with relays to mimic actual events is quite real. Recent studies aimed at troubleshooting relay misoperations performed using advanced simulator designs have demonstrated that such tasks can be performed at a relatively low cost [17]. Again, a cost effective solution is needed that will not only ask for an affordable capital investment in the equipment, but also for highly automated procedures for performing such tests [12].

ADVANCES IN RELAY MONITORING

Introduction of the software for automated analysis of DFR files is fairly recent. This software utilizes an advanced concept of intelligent system applications. These solutions may be implemented in various system configurations.

The simplest solution is to provide the analysis software locally at a substation. A PC may be installed next to the recorder(s) in a given substation as shown in Figure 1.

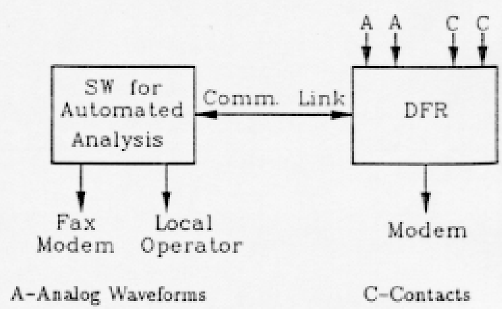


Fig. 1. Substation Configuration

In this case, DFR files are transferred to the PC each time a new record is captured. Once the file is transferred, the software for the analysis is automatically executed producing an abbreviated summary of the event. An example of a summary report is given in Figure 2.

It is important to note that the original DFR file can also be sent to a Master Station by using a modem link between the DFR and Master Station. The abbreviated event reports can be faxed to a designated location. At present, in one of the commercial solutions, such a report can be generated in less than 30 seconds after an event is recorded by a DFR [8].

Yet another solution is to automate the processing of the overall system data captured by different DFRs and ısmitted to the Master Station. A typical solution is wn in Figure 3.

EVENT DESCRIPTION USING ANALOG DATA**

ma is the circuit with largest current disturbance.
: disturbance is a phase A to ground fault.
: Fault is cleared by the protection system at this substation.

'refault Values:	Fault Values:	Postfault Values:
f = 0.0178 [kA]	;I0f = 3.7900 [kA]	;I0f = 0.0029 [kA]
f = 0.03911 [kA]	;Iaf = 3.7450 [kA]	;Iaf = 0.0010 [kA]
f = 0.3757 [kA]	;Ibf = 0.2886 [kA]	;Ibf = 0.0030 [kA]
= 0.3968 [kA]	;Icf = 0.4417 [kA]	;Icf = 0.0023 [kA]

'refault Values:	Fault Values:	Postfault Values:
of = 0.0006 [kV]	;V0f = 0.0112 [kV]	;V0f = 0.0005 [kV]
f = 294.90 [kV]	;Vaf = 255.60 [kV]	;Vaf = 294.60 [kV]
f = 295.60 [kV]	;Vbf = 290.80 [kV]	;Vbf = 294.70 [kV]
f = 294.90 [kV]	;Vcf = 288.70 [kV]	;Vcf = 294.80 [kV]
pf = 511.20 [kV]	;Vabf = 472.90 [kV]	;Vabf = 510.00 [kV]
pf = 512.00 [kV]	;Vbcf = 510.60 [kV]	;Vbcf = 511.00 [kV]
pf = 510.30 [kV]	;Vcaf = 463.90 [kV]	;Vcaf = 510.30 [kV]

ibove values are peak values.

*PROTECTION SYSTEM OPERATION ANALYSIS*****

ıary relay operation starts at 0.0878 sec [5.2698 cycles]
d ends at 0.1045 sec [6.2700 cycles].
middle 52b contacts operate at 0.1142 sec. [6.8520 cycles].
bus 52B contacts operate at 0.1162 sec. [6.9720 cycles].
bus breaker status change.
er trip is applied at 0.0284 sec [1.7022 cycles].
n e breaker status change
er trip is applied at 0.0264 sec [1.5822 cycles].

Fig. 2. Expert System Text Report

AASW – Automated Analysis Software

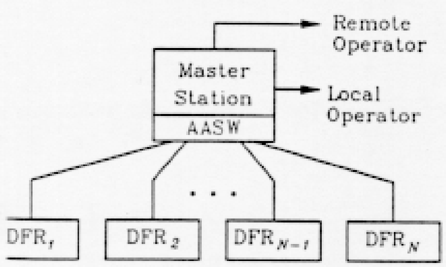


Fig. 3. Centralized Solution

s case, the analysis software is located at the Mas- ation. This solution is more cost effective since it ıot require separate PCs. However, this solution ıot provide the report as quickly since all of the 'rom DFRs has to be transferred to the Master Sta- efore the required processing can be completed. A t the centralized solution is the availability of the overall system data. Based on this data, analysis of various events can be enhanced based on the related data obtained from different substations.

A variation of the centralized solution is needed when a utility uses DFRs and Master Stations from different vendors. An example of this case is shown in Figure 4.

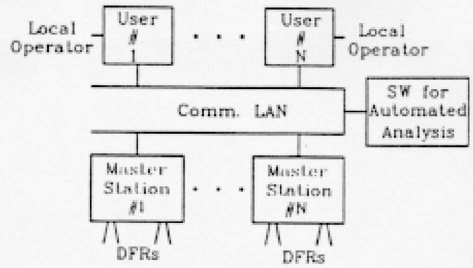


Fig. 4. Multiple Masters Configurations

This solution may utilize a Local Area Network (LAN) to connect all DFRs with a server that hosts the software for automated analysis. Once the analysis is performed, the results can be stored in a database on the server. All other users (local operators) may access this data via the LAN. This solution is the most convenient one since the analysis data may be shared among a number of different users as long as they are connected to the LAN.

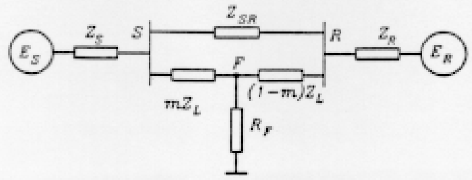
ADVANCES IN RELAY TESTING

The major advances in relay testing come from the new developments of digital simulators. Two basic designs have been introduced so far, namely open-loop and real-time [12]. These systems provide extensive hardware and software capabilities for relay test enhancements.

As a result, relay testing has been enhanced in the areas of design and application testing. Design testing is aimed at verifying relay operating characteristics, while application testing is related to assessing of relay selectivity and trip times. Both design and application tests can be performed using either phasors or transients. However, a typical scenario is the use of phasors for design testing and transients for application testing.

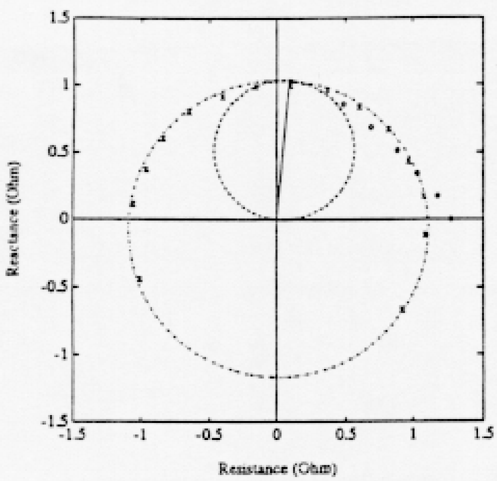
In the design testing, the flexibility in generating power system fault conditions using both single and two terminal cases using the two machine equivalent model is required. A typical power system model and related test conditions are indicated in Figure 5.

Using the model given in Figure 5, the test signals can be generated for testing of both steady-state and dynamic behavior of the relay operating characteristic. As a result, several different types of tests can be defined. Some examples of the test results obtained by using test signals generated by single- and two-terminal equivalent models, as well as test results obtained for different test conditions, are given in Figures 6 and 7, respectively.



Case I : Prefault Voltage = 0
Prefault Current = 0
Case II : Prefault Voltage = Rated Value
Prefault Current = 0
Case III : Prefault Voltage = Rated Value
Prefault Current = Selected Value

Fig. 5. Two Machine Equivalent Model and Related Test Cases

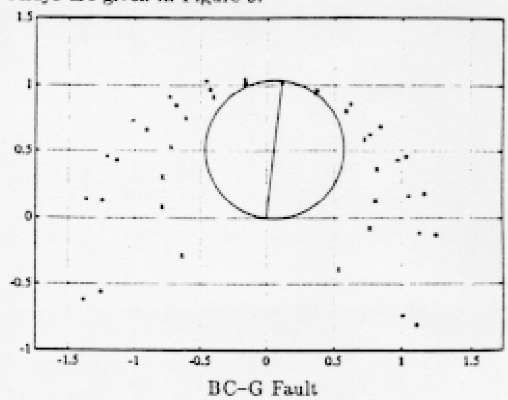


'- - - -': Theoretical Steady-State Characteristic
'-.-.-.-': Theoretical Dynamic Characteristic
'x': Test Results Using One-Terminal Model
'o': Test Results Using Two-Terminal Model

Fig. 6. Comparison of One-Terminal and Two-Terminal Test Results

The application tests are typically carried out using transient waveforms. These tests are conducted using test waveforms generated by an electromagnetic transient program (EMPT). A variety of such programs is present! available on the market. These software packages enab detailed modeling of the power system section of inte est, as well as instrument transformers and other powe system components of interest [18,19].

An example of a digital simulator configuration to b used for open-loop replaying of test cases is given in Fig ure 8. Examples of test results obtained by running number of application tests on several different distanc relays are given in Figure 9.



x: for Case I; o: for Case II; *: for Case III

Fig. 7. Comparison of Test Results for Different Test Cases

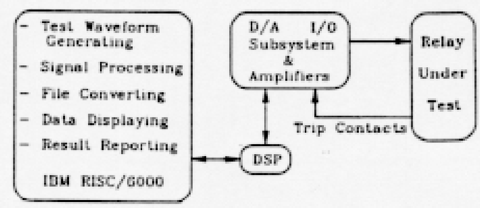


Fig. 8. Open-Loop Digital Simulator Set-Up

The real-time simulators are also utilized in relay testing to perform more involved tests in complex power systems. A typical example of a complex power system section used for evaluation of the protection relay operation on series compensated lines is shown in Figure 10 [20]. In this case, it is possible to simulate interaction between the relay and the system in the case of faults, MOV operations and sympathetic trips.

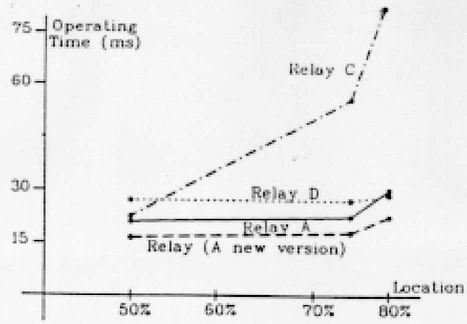
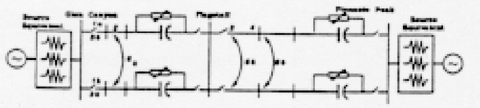


Fig. 9. Test Results from an Application Study of Distance Relays



ig. 10. Power System Model for Testing Relay Behavior on the Compensated Lines

ı all of the mentioned relay testing applications, it is ·itical that test sequences are automated and test re- ılts are conveniently presented to the operators using ·aphical user interfaces [12].

DVANCES IN TROUBLESHOOTING RELAY PERATION

·oubleshooting of the relay operation is an important proach in verifying and further improving the reliabil- ' of operation. The troubleshooting task requires an ility to recreate power system disturbances that have ısed the relay misoperation. Once the power system is ›deled, then a variety of the fault event scenarios can generated and repeated as many times as needed to duate relay operation. The use of digital simulators critical in achieving this flexibility. Both open-loop l real-time simulators can be utilized for this purpose ,17].

example of such a study is illustrated in Figure 11. A del of the power system given in Figure 11 is used to dy misoperation of the generator relay (Relay #87 on it #2) that has tripped under heavy inrush conditions sed by energizing a power transformer connected to generator Unit #1. The problem was difficult to as- ᵢ due to the use of different CTs on two sides of the erator terminals on the Unit #2. This situation oc- red because the unit breaker was installed at a later e and had a different CT in its bushings from what ᵢ available on the generator terminals.

: current differential relay misoperation was not eas- ᵢy· '·inable based on an intuitive understanding of the steady-state analysis. The complexity of the compound effects of the nonlinear phenomena of the inrush and CT saturation can only be represented and fully understood using transient simulations. After the simulations were performed, harmonics shown in Figure 12 were discovered in the differential current. These waveforms show a slow build up of the harmonic current, which has caused the relay misoperation. This scenario could be repeated several times to see how different power system operating and design conditions affect this misoperation. The generated waveforms were replayed into the relay to recreate, and verify, the misoperation conditions. Furthermore, these waveforms were used to test other differential relays in order to find the one that is not sensitive to the harmonic build up in the differential current.

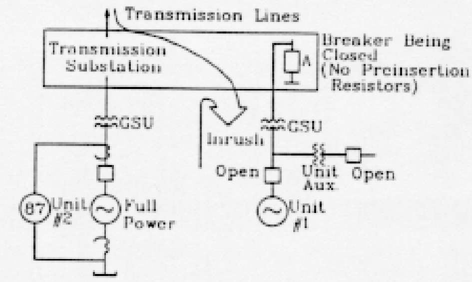


Fig. 11. Power System Model for a Troubleshooting Study

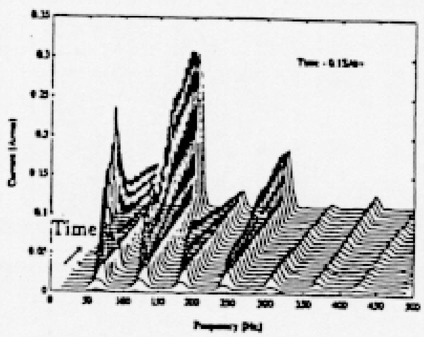


Fig. 12. Differential Current Waveform (Frequency Domain Representation)

FUTURE PRACTICE

Based on the discussion of the new developments, it is possible to adopt a new practice for monitoring testing and trouble shooting the relay operation with the following practical steps:

- All of the relay types used in the system are extensively tested for both design and application features using new digital simulator.

- Operations of all existing relays are monitored using the software for automated analysis of DFR files.
- As soon as a problem in relay operation is detected, an extensive trouble shooting study using digital simulators is performed to explain the reasons for the misoperation.

Even though the above mentioned practice may imply an additional investment in the new equipment and extensive use of additional man power, a detailed analysis of the new requirements will reveal that the equipment cost is quite affordable and automation of the procedures is reducing the need for the additional man power required. In any case, the final judgment needs to be made based on the overall benefits that can be obtained by improving the overall power system operation as a result of the adoption of the new practice.

CONCLUSIONS

The discussion given in the paper leads to the following conclusions:

- The existing practice for monitoring, testing and trouble shooting the protective relay operation can be improved.
- New developments in the use of expert systems for automated DFR file analysis, as well as digital simulators for relay testing and trouble shooting, are needed to improve the existing practice.
- A new practice may be adopted in the future based on the new developments.

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