Testing of the Fault Location Function in Devices and Disturbance Analysis Systems

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I. INTRODUCTION

Fault location functions play a very important role in the analysis of various disturbances. The built-in fault locators in multifunctional protection IEDs are typically based on a single ended algorithm, but more and more we see the implementation of double ended algorithms in protection devices that provide communications based schemes such as line differential.

The performance of the fault location functions is quite different and depends on many factors, such as:

- Algorithm used
- Fault location
- Fault type
- Fault resistance
- Source and line impedance
- Mutual coupling
- Load current

The paper discusses methods and tools for the testing of the fault location function and determining the impact of all of the above factors on its performance in single line or double circuit applications. Examples of different use cases are presented. The requirements for tools selected for the testing depending on the purpose of the test are also discussed.

Testing the performance of fault location functions during wide area disturbances is also discussed in the paper.

Testing of off-line fault location functions integrated in fault analysis systems is described later in the paper.

II. FAULT LOCATION FUNCTIONS

Multifunctional Intelligent Electronic Devices have a range of auxiliary functions that are designed to take advantage of the different function elements supporting the main protection function of the device. The analog input modules convert the current and voltage signals to sampled values that are used typically to calculate phase or sequence current and voltage phasors that are then used by the protection algorithms of the IED.

Since the very beginning of the era of microprocessor based protection devices measurements, fault location and waveform recording were some of the essential auxiliary functions in the IEDs.

The location of the fault has been typically based on a single end data – the data available to the relay. These single ended methods provided some estimate of the location of the fault that can be relatively good in the case of radial transmission lines or distribution feeders. However that is not the typical case at the sub-transmission and transmission level, and now with the wide spread use of distributed energy resources – even at the distribution level of the system.

In the typical cases of transmission or sub-transmission lines with sources at each end of the line multiple factors have an impact on the accuracy of the fault location. Some examples of such factors are:

- location of the fault
- type of fault

- fault resistance
- sources at the local and remote end of the protected line
- line configuration
- mutual coupling

Because of the impact of the accuracy of the fault location on the overall duration of an outage, the industry has been trying to improve the methods for single ended fault location. At the same time with the availability of communication interfaces between the devices at both ends of the protected line more and more manufacturers are implementing double ended fault location algorithms that are using data from both ends of the line, thus achieving a much better accuracy of the fault location function.

Considering the significant economic impact of the accuracy of the fault location function, it is important that it is properly tested in order to ensure that when this function operates under actual fault conditions the operator is going to send the crew as close as possible to the actual fault location, thus reducing the time to find the fault and put the circuit back in service.

III. REQUIREMENTS FOR TESTING OF THE FAULT LOCATION FUNCTION

The testing of the fault location function has three aspects:

- Determining the accuracy of the fault location algorithm being used
- Determining the accuracy of the components of the fault location function
- Determining the overall accuracy of the implemented fault location function

The requirements and tools to be used for the testing of the fault location function depend on which of the above aspects of the testing we are focusing, as well as where the function is implemented – in an IED or on a computer.

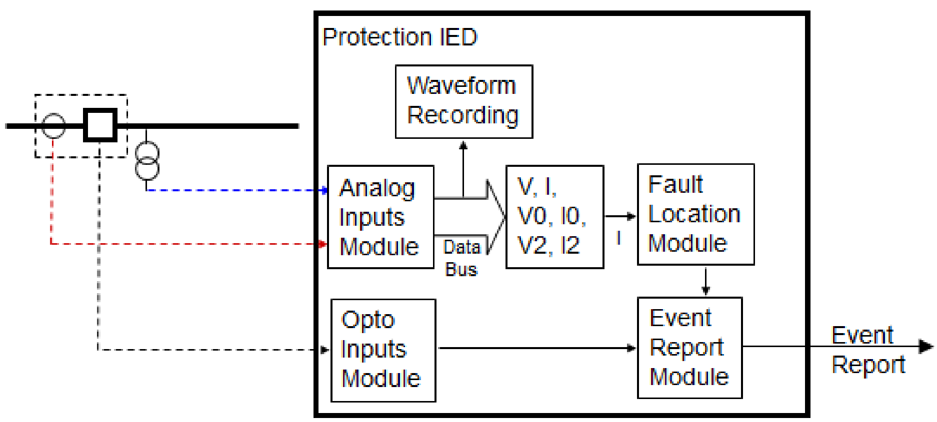

Fig. 1 Fault location function block diagram

The fault location function in an IED is not a stand-alone function – it is at the top of the hierarchy that needs to be considered for the testing (see Figure 1).

First of all, the secondary currents and voltages that are applied to the IED are filtered and processed in the analog input module and provide instantaneous sampled values to the internal digital data bus of the IED. These sampled values can be logged when an abnormal system condition is detected or used to calculate various measurements (e.g. current and voltage phasors or superimposed components) used by the different IED functions.

The outputs of the measurement elements become inputs to protection or other functional elements of the device. The fault location calculation is based on a specific set of measured value depending on the algorithm used – phase or sequence currents and voltages.

When a protection element detects an abnormal condition, it may operate and issue not only a trip command to clear a fault. It will also trigger the fault location function.

The accurate calculation of the fault location is affected not only by the system parameters and configuration - it also needs healthy secondary current and voltage circuits. This requires the IEDs to also perform monitoring functions, such as current and voltage circuit supervision.

In case of double circuit transmission lines the IEDs may have mutual current compensation that improves the performance of the fault location functions.

The interaction of different functional elements needs to be well understood, since there are differences between the implementation of some functions, especially when comparing single-ended with multi-ended fault location functions. For example, a multi-ended fault location function may be affected by the loss of synchronization between the IEDs at one end of the line.

IV. TESTING OF FAULT LOCATOR IN MULTIFUNCTIONAL DEVICES

When we analyze the complexity of modern multifunctional protection devices it is clear that their testing requires the use of advanced tools and software that can simulate the different system conditions and status of primary substation equipment and other multifunctional IEDs.

The test system should be able to simulate and apply to the device under test analog signals that represent the different system conditions that may have an impact on the accuracy of the fault locator. Several different methods can be used to provide the current and voltage signals:

- Using a state sequence simulation by allowing the user to define pre-fault, fault and post-fault magnitudes and angles of the phase currents and voltages applied to the IED under test based on the results from a steady-state fault analysis program
- Using transient simulation based on a simplified system model
- Using transient simulation based on a detailed system model
- Using waveform recording from actual events

The first two methods can be used for testing of the accuracy of the fault location function to determine the impact of several different factors on its performance:

- location of the fault
- type of fault
- fault resistance
- sources at the local and remote end of the protected line
- mutual coupling

This is due to the fact that these simulations are based on a sequence components system model that assumes a balanced three phase system. If we need to evaluate the impact of the line configuration, which in most of the real-life cases is unsymmetrical and untransposed, then we need to use the last two methods mentioned above.

Since the fault location function is triggered by the operation of a protection function or a fault detector and is executed after the clearing of the fault, closed-loop testing is not required to perform this kind of test. There are several methods that can be used to perform the testing:

- The test system can calculate the current and voltage samples for the pre-fault, fault and post-fault conditions configured in the testing software and then apply them to the IED under test.

- The fault simulation is performed off-line by transient simulation software such as EMTP or ATP. The results from the simulation are saved as a COMTRADE file which is then replayed by the test equipment.
- An actual fault record saved as a COMTRADE file is replayed by the test equipment.
- A closed-loop transient simulation test is executed

A simplified block diagram of the fault locator function in an IED is shown in Figure 2. The efficiency of the testing can be improved by simultaneously testing protection and fault location functions..

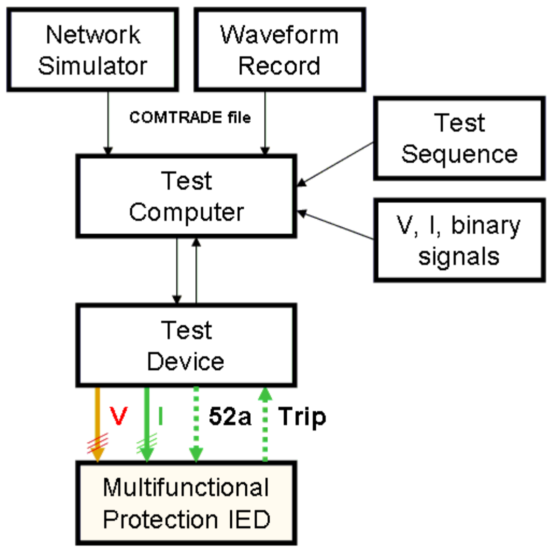

Fig. 2   Test system block diagram

The testing of the different IED function elements has to start from the bottom of the functional hierarchy and end with the functions at the top of the hierarchy, such as the fault locator.

A. Testing of the analog signal processing and measuring functions

The analog signal processing is the first critical step in the testing of a multifunctional IED that includes a fault location function, because if any problems exist at this level, they will be reflected at any other step up the functional hierarchy.

The only problem is that the data bus of the IED is usually not directly accessible or visible through the relay communications or user interface. That is why an indirect method is recommended. Since any problem in the analog signal processing will be reflected in the measurements, both can be combined in a single test.

If we configure the testing software to generate pure sinusoidal waveforms of balanced currents and voltages with their nominal values and no phase shift (zero degrees) between the currents and voltages in the same phases (as shown in Figure 3), the measured phase currents and voltages in this case need to be as close as possible to the nominal balanced values applied to the relay by the test device (within the accuracy range specified by the relay manufacturer).

The positive sequence measurements should be within tolerance of the phase values. Since the applied phase currents and voltages are balanced, the measured negative and zero sequence values should be close to zero (again within the expected tolerance range). At the same time the power factor should be close to 1 and the frequency close to the nominal frequency of the applied signals to the relay.

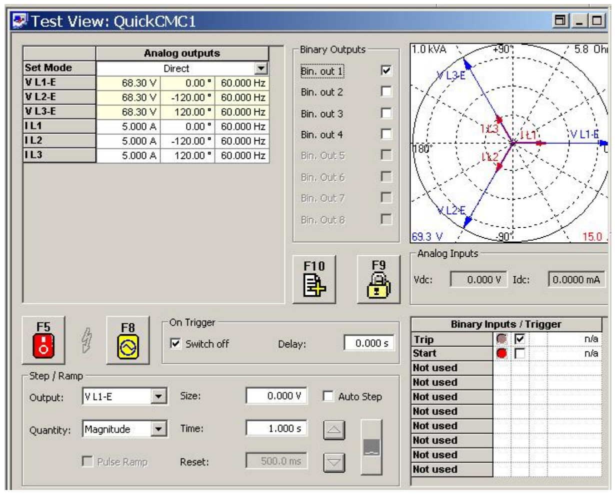

Fig. 3 Test configuration for analog signal processing and measurement functions tests

If we are interested to check the accuracy of the relay measurements at sub-nominal levels, we can configure the test software to apply 10% or 1% of the nominal values and follow a similar procedure to the one described above.

B. Testing of the fault location functions

If we (based on the measurement functions tests) assume that the relay measures accurately the applied current and voltage signals, the testing of the fault locator elements should not provide any surprises from the measuring accuracy point of view, but will rather give us an indication of what is the expected performance of the fault location function under different fault and system conditions.

The test system should be configured to apply currents and voltages with magnitudes and phase angles calculated based on the fault location, fault parameters and testing method selected.

Instead of having to simulate a fault in a steady-state fault analysis program and then manually enter the magnitudes and angles for the currents and voltages in a sequence simulation type of testing module, it is much better from the efficiency point of view if we can use a tool that allows the user to define a system model that represents all system parameters which impact on the accuracy of the fault location algorithm:

The system model to be used for the fault locator function testing should allow the user to select and configure the parameters of transmission lines with different configurations, for example:

- Single circuit transmission line with sources at both ends
- Three terminal transmission line with sources at all ends
- Double circuit transmission line with sources at both ends

By changing the parameters of the sources at the ends of the line we can test the impact of strong or weak sources, homogenous or non-homogenous systems in different combinations on the accuracy of the fault location.

Changing the sources voltage angles allows the user to control the pre-fault power flow and test its impact on the performance of the fault location function.

The user should be able to configure the type of fault as:

- single-phase-to-ground
- phase-to-phase

- three-phase

The testing of the impact of the fault location should be defined by the purpose of the test:

- If we are performing type or acceptance testing it may be appropriate to run tests at every 5 % of the line.
- If we are doing commissioning – testing at the beginning, middle and end of the line may be sufficient.
- If we are analyzing an operation of the IED during an actual fault condition – simulation of this condition should be used

The user then should also be able to define different values of the fault impedance – from faults without fault impedance to high impedance faults.

The requirements for testing of fault location functions clearly point towards dynamic testing. We still need to be careful with regard to the understanding of this term. In some cases a state change from pre-fault to fault condition may be sufficient. However, if this is represented as a step change in the fault injection to the IED under test, it still may still have an impact on the accuracy of the fault location algorithm due to the fact that the current waveform is not realistic. That is why electromagnetic transient simulation is the best way to generate the signals for the testing of the distance element.

In many cases the testing is limited to the basic use cases – a simple fault at a specific fault location. However in real life things are not always simple. That is why it is recommended that the accuracy of the fault location is tested for more complex fault conditions such as:

- Evolving faults
- Simultaneous faults at different locations on the line
- Cross-country faults on double circuit lines

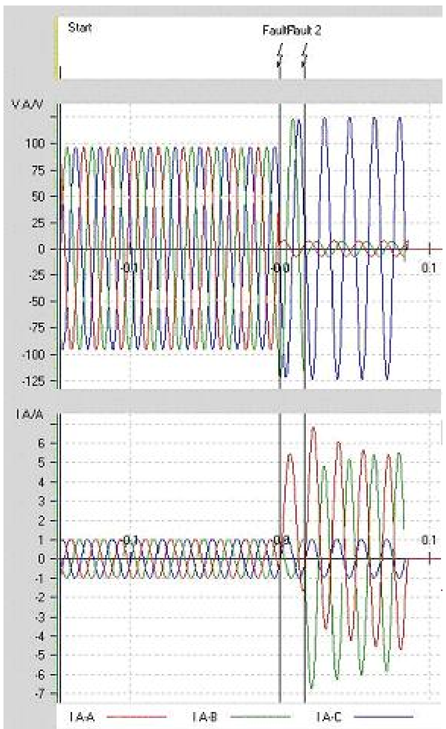

Fig. 5 Evolving fault transient simulation.

For single two or three terminal lines the simulation should include:

- Pre-fault load flow defined by the magnitude or phase angle difference of the voltages of the sources used in the system model
- Fault definition based on location, inception angle, fault type and fault impedance
- Evolving fault
- Switching of breakers at the ends of the protected transmission line

The testing of distance relays applied to double circuit lines requires the addition of several components of the model:

- Parallel line, mutually coupled with the protected transmission line
- Cross-country faults definition
- Switching of the breakers on the faulted line

The testing tools should allow easy configuration and execution of such transient simulations as part of the testing process, as well as proper evaluation and reporting of the operation of the tested device. Testing of more complex fault conditions is also a very important requirement.

If the application requires, the test cases should also include synchronous or asynchronous out of step conditions simulation to test the accuracy of the fault location functions when a fault occurs during a wide-area disturbance. (Figure 6).

Adequate simulation of power swing conditions is another key element in the fault location testing process. Most existing tools do not support such functionality, which forces the users to go through multiple steps in order to perform dynamic stability study and then convert phasor data into sampled values that can be replayed by a test system.

A better approach is to use electromagnetic transient simulation programs such as EMTP or ATP. The problem with this approach is that using these tools requires very good understanding of the modeling of all system elements, something that is not easily achieved.

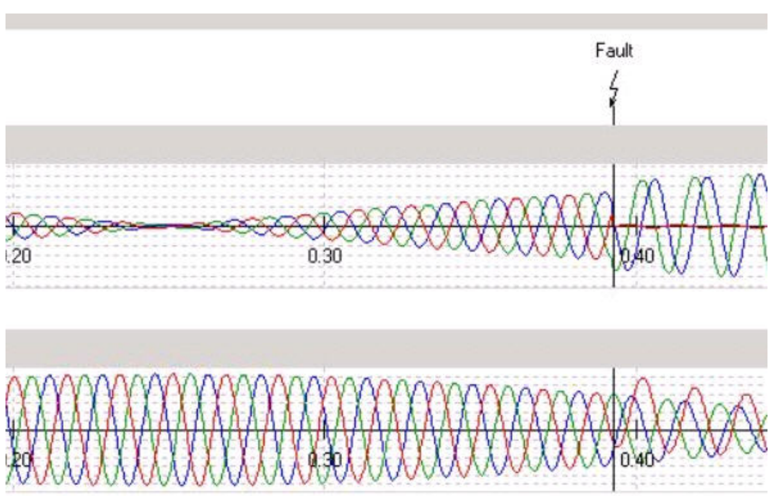

Fig. 6 Power swing and fault transient simulation

The availability of transient simulation tools that are easy to configure and use makes a big difference and results in acceptance of these methods and improvement in the use of advanced functions in distance protection relays.

Proper simulation of the load flow on the protected transmission line based on the voltage magnitude or phase angle difference between the busses at the ends of the line can be also used to check the performance of the load encroachment function at different stages of the simulation.

The simulation of synchronous or asynchronous power swings is not sufficient, since it is possible for a fault to occur during the power swing (Figure 6). That is why it is necessary to be also able to simulate such condition to test the distance protection with power swing blocking enabled.

The testing of the fault location function during dynamically changing system topology as a result of protection operation also should be evaluated. When communication aided schemes are used in complex system configurations, including double circuit transmission line or transmission line loops with or without mutual coupling, sequential tripping of faults on adjacent lines may result in incorrect operation of the fault location algorithm. For example if the fault location function is tested in parallel with a Permissive Overreaching Scheme and a fault on an adjacent line with sequential breaker opening is simulated, the test will have to include the following steps:

- pre-fault with breaker in a closed position, nominal voltage and normal load current conditions
- initial fault condition with current flowing in reverse direction
- receive of Permissive Trip signal
- current reversal fault condition (simulating the opening of the breaker by the Zone 1 trip of the relay on the adjacent line)
- post-fault condition with breaker closed, nominal voltage and normal load current conditions

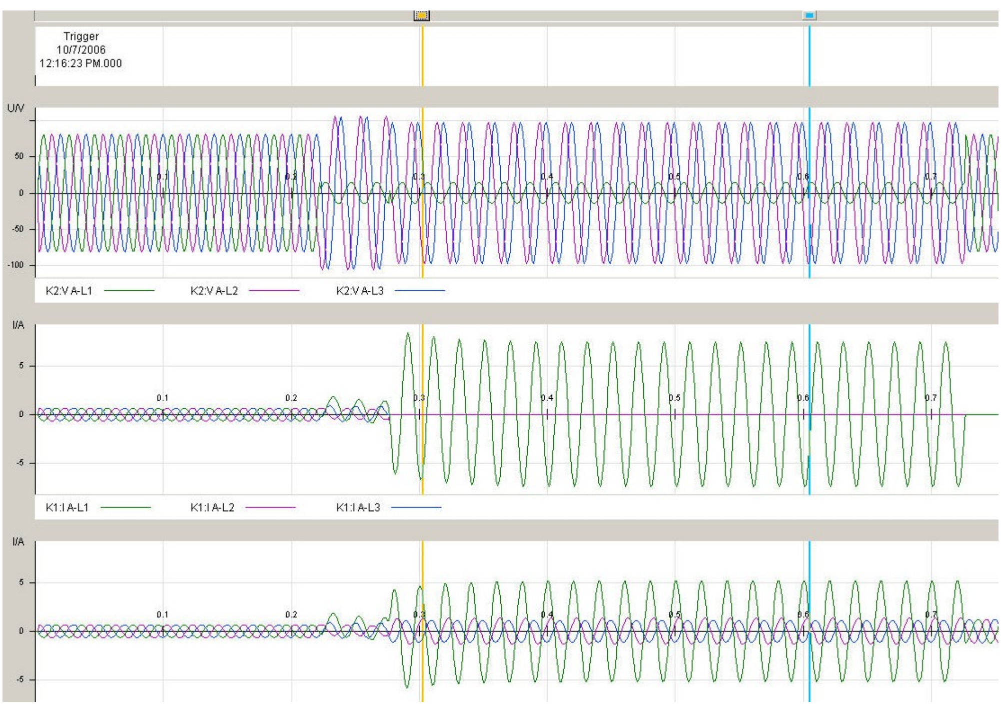

Fig. 7 Single-phase fault with current reversal simulation

The test system is used to simulate both the analog and the digital control signals received by the relay in the field. At the same time its inputs are used to monitor the operation of different relay elements as required by the scheme under test.

V. TESTING OF DOUBLE ENDED FAULT LOCATION SYSTEM

The testing of double ended fault location functions implemented in communications based protection systems can be based on all of the above described testing procedures. The main differences between the testing of single and multi-ended fault location functions are in the case of single ended fault locator we are interested only in the currents and voltages at one end of the line – where the IED under test is located. There is no requirement for communications interface to the remote end of the line and the fault location accuracy is not dependent on time synchronization.

When testing a double ended fault location system we need the currents and voltages at all ends of the line. The IEDs, depending on the fault location algorithm used, may also need to be accurately time synchronized.

When we are doing system acceptance testing of such system based on the well-established principles of end-to-end testing, the test device at the ends of the transmission line will also need to be GPS time synchronized in order to ensure that the simulation correctly represents the power system conditions for the specific use case.

However, since one of the concerns with the implementation of time synchronized systems is the effect of the loss of synchronization on the performance of the double ended fault location system, this effect needs to be tested as well. The time synchronization interface of the IED at one end of the line should be disconnected for a period of time before the fault simulation is performed. The time synchronization of the test devices at both ends of the line however should be maintained, since they represent the fault condition that is simultaneously applied to any location in the electric power system.

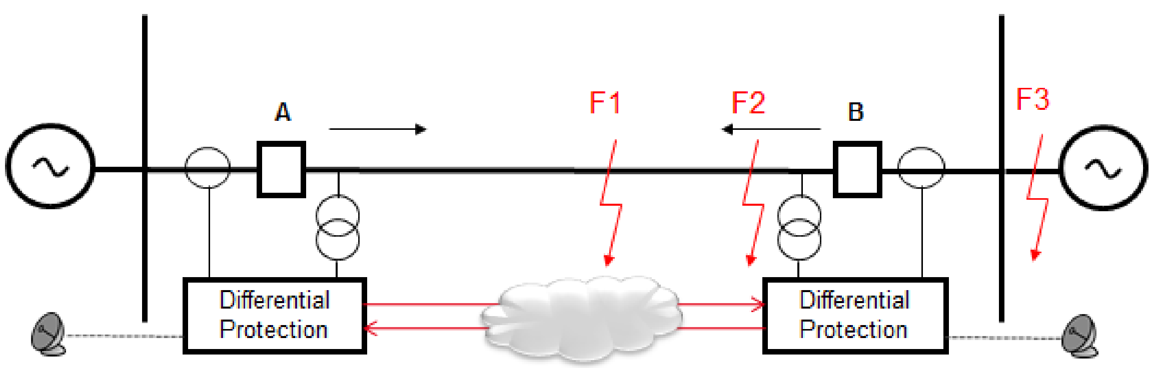

Fig. 8 Time synchronized line differential protection with double ended fault location system

VI. CONCLUSIONS

Testing of fault location functions requires good understanding of their functionality, algorithms and operating principles of the individual elements of the system.

Software and hardware tools to appropriately simulate the test conditions and determine the effect of different fault parameters on the accuracy of the fault location calculation are essential for successful performance evaluation.

The testing should follow the functional hierarchy of the multifunctional IED where the fault location function is implemented. It should start with testing of the analog signal processing and measurements, followed by the testing of the fault location function.

Testing of double ended fault location systems should be performed using the well-established principles of end-to-end testing.