Evaluation of Distance Protection Performance According to the Proposed Standard IEC 60255-121

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Introduction

The performance of distance protection devices plays a key role in the protection systems of the transmission (and some) distribution networks around the globe. The current efforts of the working group IEC TC 95 MT4 target on standardizing the type testing and verification of this performance. The feasibility and relevance of the test procedures described in the corresponding proposed standard IEC 60255-121 (chapter 6.3.2 and chapter 6.3.4) [1] was investigated in a research project. This article reports the results of this project.

Standardization of type tests of protection equipment for high and medium voltage power systems has been established by the introduction of the IEC 60255 series of standards in 1982. Currently these standards are being revised by the IEC TC 95 MT4 committee. The target of this maintenance work is to define a minimum level of type testing that shall be established by the protection equipment manufacturers. Furthermore, by standardizing type tests, end users like utilities shall be enabled to compare the specifications and type test reports of protection equipment based on the published results of standardized type tests. This article describes the results of an investigation trying to implement type tests described in IEC 60255-121 CD chapter 6.3.2 and 6.3.4 "Dynamic performance: typical operate time and transient overreach (SIR diagram)" These chapters describe a small but important subgroup of tests required in this standard proposal. To determine the feasibility of the tests proposed, automatic test routines following the requirements given in the proposed standard have been created using standard test equipment. These test plans have been applied to state of the art distance protection devices from three different vendors. The article describes the test system that was created to meet the standard requirements. Furthermore, an impression of how test results are required to be documented is given. Finally, the behavior of currently available protection equipment under such test conditions is analyzed to evaluate the significance of the test results.

Test Set-up

The required tests according to IEC 60255-121 CD Chapter 6.3.2 and chapter 6.3.4 are being realized with standard protection test equipment and network simulation software. Figure 1 shows the network that needs to be simulated. [1]

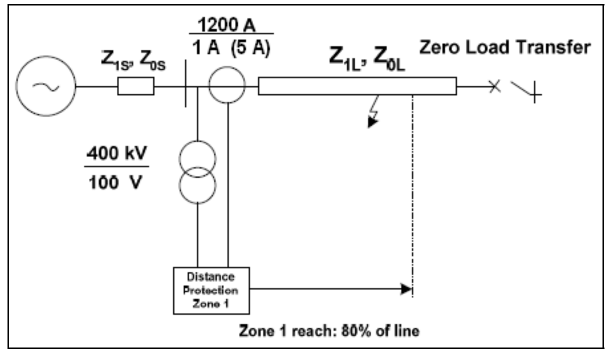

Figure 1: simulated network

The simulated network is a radial feeder network, with a local circuit breaker closed and a remote circuit breaker opened (zero load transfer). (Figure 1) A transient network simulator (*NetSim* by OMICRON) is used to simulate the required fault cases. Voltage and current transformers are considered as ideal.

The following transient fault simulation parameters for this network have to be varied to get the required test results:

- Line Length (Long Line 100km, or Short Line 20 km)
- Fault Type: L1N, L1L2, L1L2L3, L2L3N
- SIR: 0,5;5;... 30; 50
- Fault Position: 0%, 50%, ...110% of Zone Reach
- Fault Inception Angle: 0°, 30°, etc

Figure 2 and figure 3 describe the required variation of the type test parameters for one rated current (1A or 5A) and one rated frequency (50Hz or 60 Hz).

The system has to be tested with 50Hz and 60Hz. The impedances of the source and the line have to be set as described in the proposed standard [1].

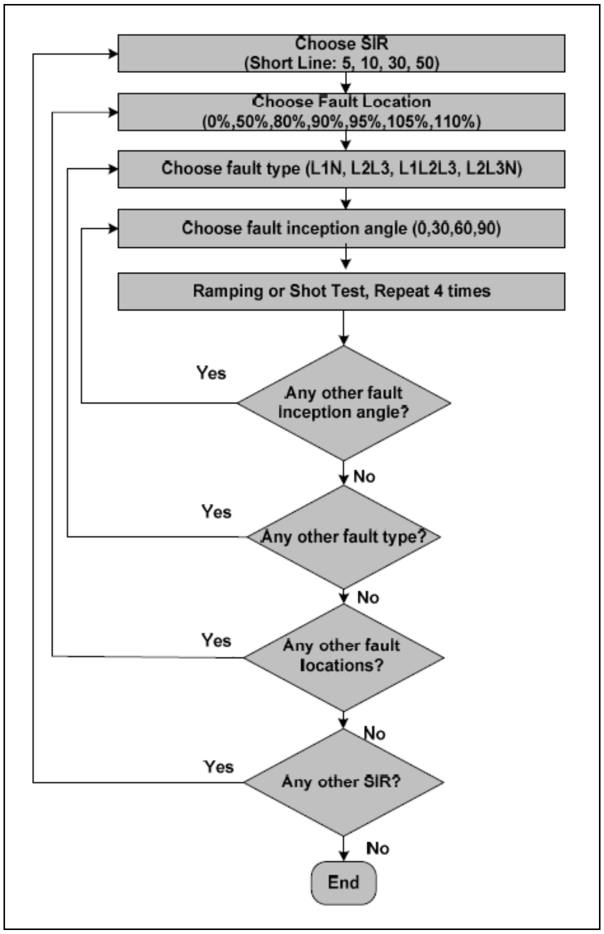

Figure 2: Test sequencefor the "short line

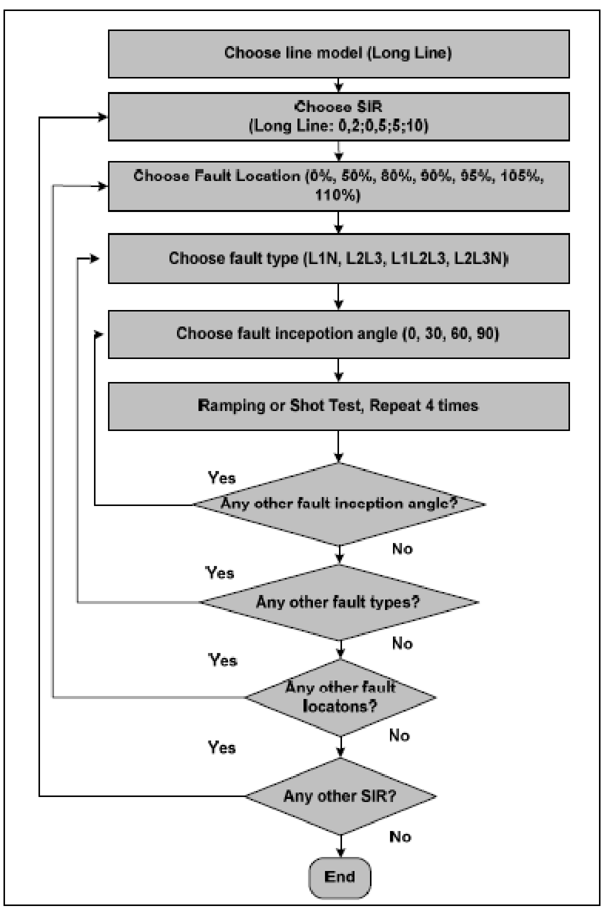

Figure 3: Test sequencefor the "long line"

All together a total of 1792 "test shots" for short line and 1792 shots for long line have to be carried out in order to publish the SIR diagrams at a rated current and a rated frequency.

Figure 4 shows the hardware test set-up. Using this configuration, a maximum voltage output of $300V_{sec}$ per phase and a maximum current output of $100A_{sec}$ per phase is possible (RMS values). This configuration of 300V/100A is sufficient for the majority of the test points. However, for 5A relays (that cannot be configured as 1A relays, too) for some test points test currents >100A are required. Additional amplifiers can be cascaded if more than $100A_{sec}$ are needed. It should be noted that protection equipment that can handle 1A and 5A CTs is tested with less test points in the 5A range than protection devices that can handle only 5A.

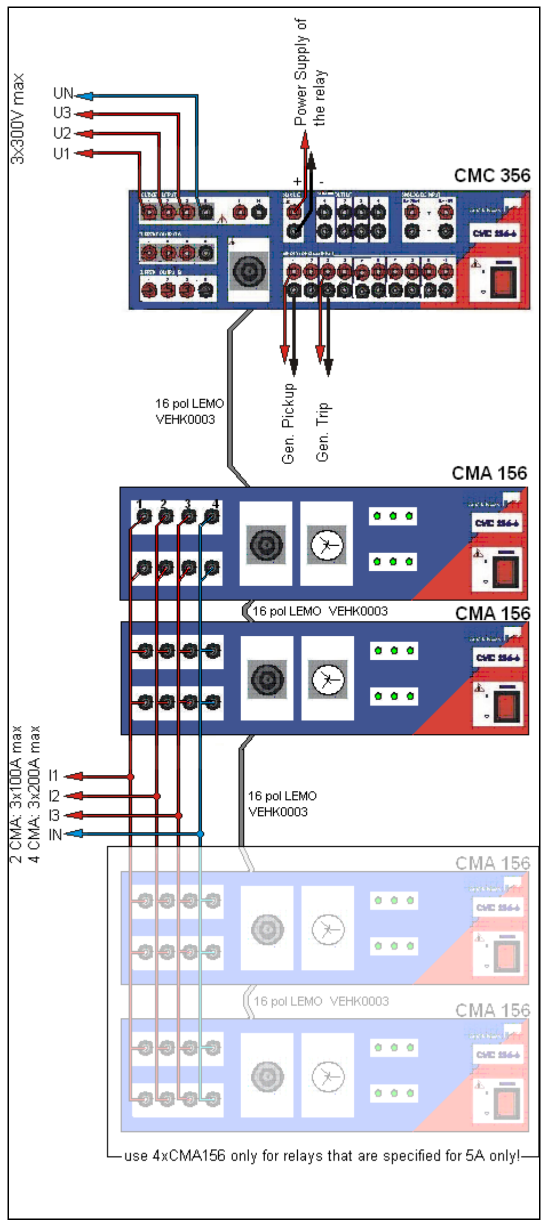

Figure 4: hardware set-up

According to IEC 60255-121 CD [1] the manufacturer shall declare with which output the operate time has been measured (example trip binary output contact, or solid state output, or IEC 61850 GOOSE). All tests described in this article have been performed by using a "classic" binary trip output contact. However, the test setup also allows using IEC 61850 GOOSE messages.

Source Impedance Ratio (SIR)

The proposed standard IEC 60255-121 CD [1] describes the source impedance ratio (SIR) of the system as the ratio between the source impedance and the impedance reach setting of the distance protection function. This is important to note because SIR in other publications and network simulation tools often is described as the ratio between the source impedance and the line impedance, which is not the case here.

Test performance

In order to test the relay according to the proposed standard, the OMICRON *Control Center* (OCC) and the Test Module OMICRON *NetSim* are used (Figures 5,6, and 7). The test plan automatically creates all test points according to the sequence described by the flowcharts in figure 2 and 3. The OMICRON Control Center test document contains the "typical operate time" statistic calculations and histogram, as well as all required SIR-diagrams.

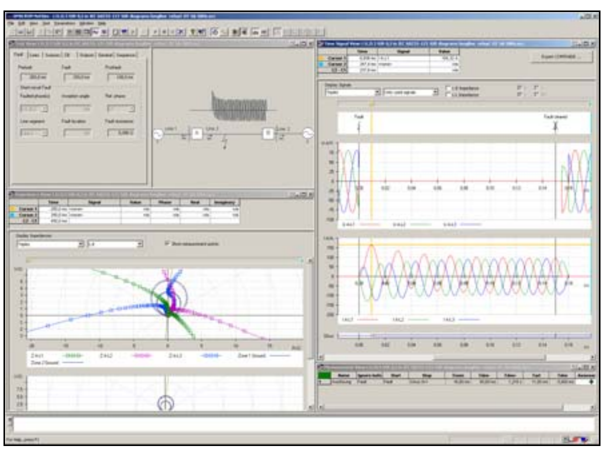

Figure 5: Transient Network Model – Test Software OMICRON NetSim

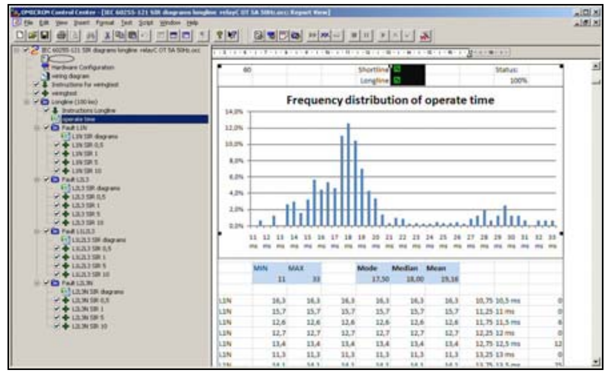

Figure 6: OMICRON Control Center test plan "long line" for a 5A relay at 50Hz – Operate time histogram

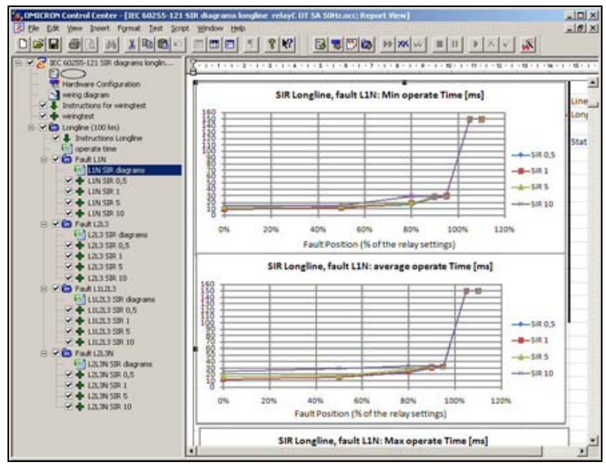

Figure 7: OMICRON Control Center test plan for a "long line" test for a 5A relay at 50Hz - "SIR Diagrams"

The statistic calculations and diagrams are updated automatically based on the results derived from the test routines as they move forward. The user does not need to handle any values. The automatically created diagrams can directly be used for further documentation and analysis right after the tests are finished. The outcome of this is a large number of shots. A total of 1792 shots for short line and 1792 shots for long line are carried out in order to publish the SIR diagrams at a rated current and a rated frequency. The test duration is about three hours per line type. All together the fully automatic test takes approximately six hours. This includes the time for the automatic generation of all SIR diagrams and "typical operate time diagrams".

SIR-Diagrams

According to IEC 60255-121 CD [1], SIR diagrams shall be reported for one rated frequency, for one rated current, and for each fault type. In total 12 short line and 12 long line SIR diagrams per frequency (min, max, and average for 4 fault types) shall be published. Minimum, maximum and average operate times are required to be documented. The average operate time is the average of the reported operate times for each fault position on 16 shots (4 fault inception angles repeated 4 times).

The maximum fault time is set to 150ms. By using a time delay of 300ms for zone 2, shots outside zone 1 should never issue a trip signal. All shots that do not record a trip signal after 150ms are exposed with a "trip time of 150ms" in the test report. Thus, transient overreach can be identified if test points with a fault location of > 100% of the zone reach are represented with trip times below 150ms. The behavior of the transient overreach, often caused by the DC component of the short circuit current, was critical for analog relays. Nowadays digital relays have a filter and adaptive measurement procedures to avoid this faulty activation [2]. However, in the results section of this article, one can see also that modern protection devices may overreach in certain cases.

Typical Operate Time - Histogram

A subset of the test results obtained from the SIR tests is also used to calculate the "typical operate time" using statistic calculations (mode, median, and mean value) and a special visualization in a histogram. Only data at fault positions 0%; 50% and 80% of the distance protection setting reach and SIR=5 are considered. The number of operate times belonging to each class (N), with 0.5ms resolution, is counted to show the histogram distribution of the operate times. The percentage of N for each class is also calculated, as well as the mode (most frequent measured value), the median (central value of the sorted measurement array) and the mean (average value of the measured trip times) of the collected values.

The operate time calculation is embedded in the OMICRON Control Center test document. A total of 384 operate times are automatically collected from short- and long line tests. The mode, median, and mean value is calculated. The data for the required histogram are calculated and the histogram "Frequency distribution of operate time" is plotted.

Results – SIR Diagrams

Three relays from different manufactures were tested.

- Relay A: 50/60Hz 1A (fig. 8.1x)
- Relay B: 50/60Hz 1A/5A (fig. 8.2x)
- Relay C: 50/60Hz 5A (fig. 8.3x)

As mentioned before, the proposed standard requires the documentation of 24 SIR diagrams for one rated current and for one rated frequency. However, only SIR diagrams are published that show a somehow "interesting" or "unexpected" behavior. The bracketed figure numbers in the list above refer to the diagram number of the corresponding relay.

Relay A:

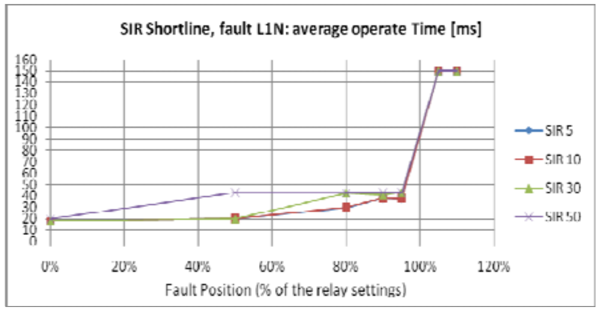

Figure 8.1a: SIR diagram relay A 50Hz 1A

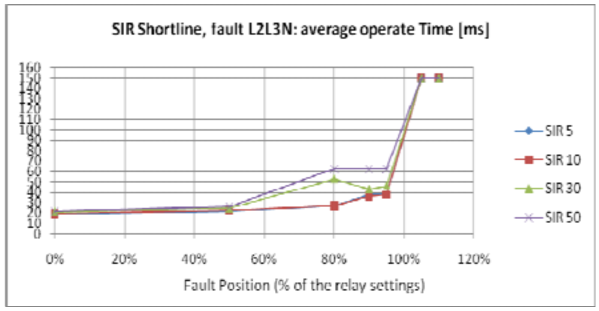

Figure 8.1b: SIR diagram relay A 50Hz 1A

Relay B:

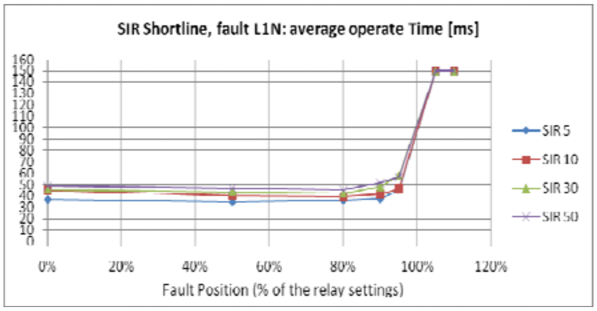

Figure 8.2a: SIR diagram relay B 50Hz 1A

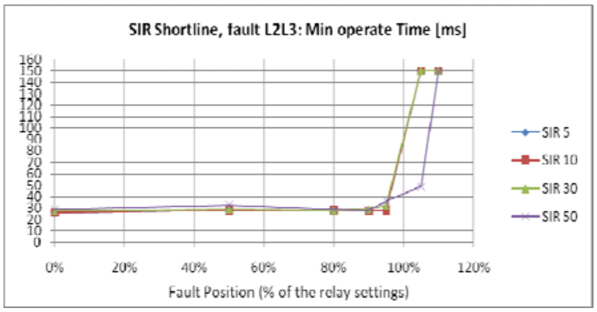

Figure 8.2b: SIR diagram relay B 50Hz 1A

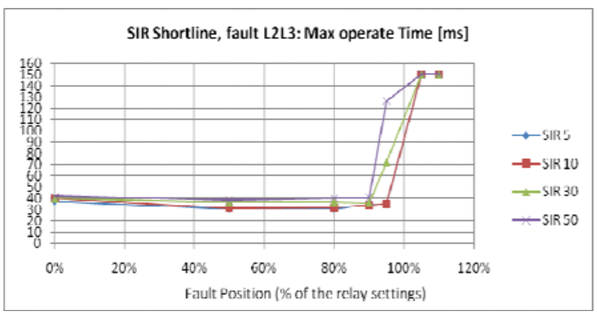

Figure 8.2c: SIR diagram relay B 50Hz 1A

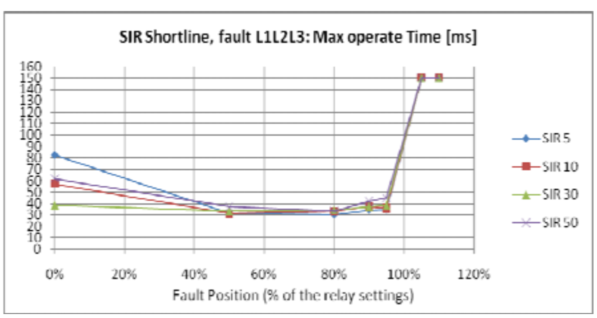

Figure 8.2d: SIR diagram relay B 50Hz 1A

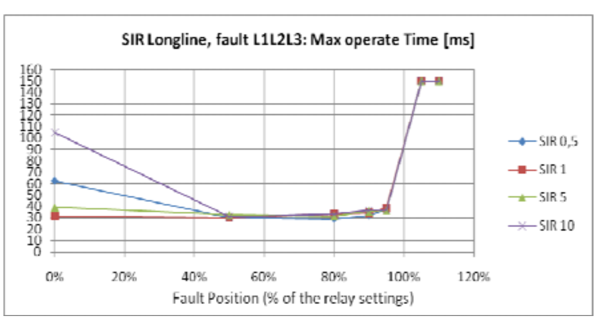

Figure 8.2e: SIR diagram relay B 50Hz 1A

Relay C:

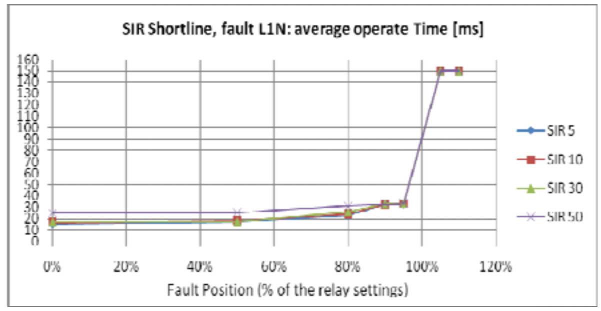

Figure 8.3a: SIR diagram relay C 50Hz 5A

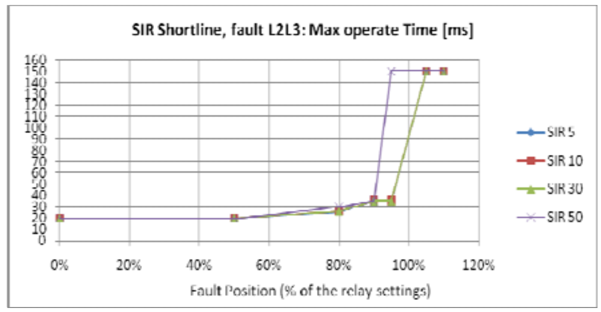

Figure 8.3b: SIR diagram relay C 50Hz 5A

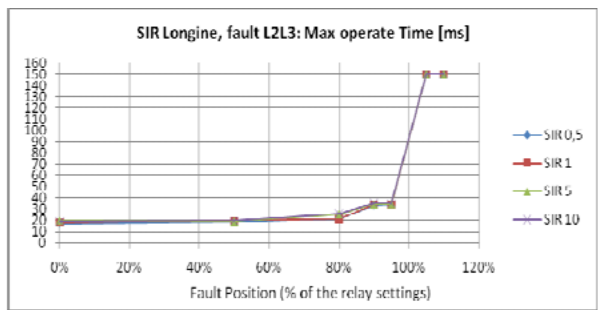

Figure 8.3c: SIR diagram relay C 50Hz 5A

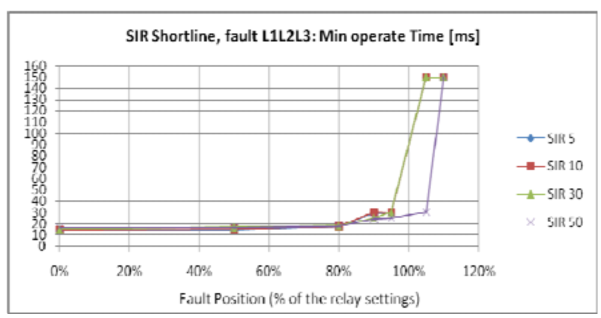

Figure 8.3d: SIR diagram relay C 50Hz 5A

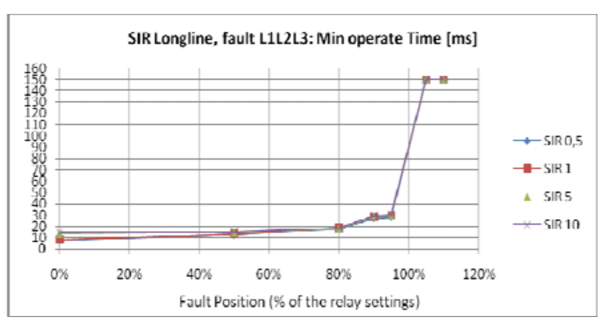

Figure 8.3e: SIR diagram relay C 50Hz 5A

Although a lot of operate times are within the scope of tolerance, there are some outliers. The following section focuses on "interesting" or "unexpected" cases.

Longer operate times for higher SIR values and at fault locations closer to zone reach:
In figure 8.1a, figure 8.2a and figure 8.3a operate times increase with increasing SIR. Another interesting fact is the increase of the operate time at a fault position of 80% of the relay setting (64% of the line length). At this point, the trip signal is about 5-10ms slower than at the beginning of the line.

Cases of transient overreach:
Figure 8.2b and figure 8.3d show minimum operate time diagrams. While the fault is located in zone 2 (105%), the relay seems to extend zone 1 wrongly (transient overreach) and trips. Nowadays digital relays try to avoid this faulty activation [2]. However, the relay B and relay C only behave "wrong" at about 5 of 3600 shots. Relay A has no transient overreach.

Slow operate times for faults at the relay location:
The diagrams figure 8.2d (short line) and figure 8.2e (long line) display the maximum values of the operate time on relay B for the same fault. In both cases the maximum trip times at the beginning of the line (0%) are utterly higher than the times in the middle of the line. Because both fault positions belong to zone 1, the operate time should be approximately the same. This fact displays that this relay has difficulties reacting fast enough, when the fault is located very close to the location of the CTs and VTs. Looking at the corresponding average diagrams of figure 8.2d and figure 8.2e in the test document, these outliers only amount to one in every sixteen shots of each SIR at 0%. However, even one higher value at the nearest fault position can be critical.

Slow operate times for zone 1 faults close to zone reach:
Other interesting outliers are shown in figure 8.2c and figure 8.3b. At the change-over from zone1 to zone 2 (fault location at 95% of the relay setting) the relay is underreaching, respectively operating "too slow".

Summing up the analyses of the SIR-diagrams it can be said that relay C has the fastest trip time, but has some outliers. Relay A is only a bit slower (about 2ms), but has no outliers at any fault position. Relay B is slow compared to the two relays mentioned before. It also has a lot of outliers.

<u>Results – Typical Operate Time</u>

A) Frequency distribution of operate time - histogram
Relating the typical operate time reports that are described in IEC 60255-121 CD [1] (chapter 6.3.4), the following diagrams (figure 9.1, 9.2 and 9.3) were automatically plotted by the OMICRON Control Center test plan.

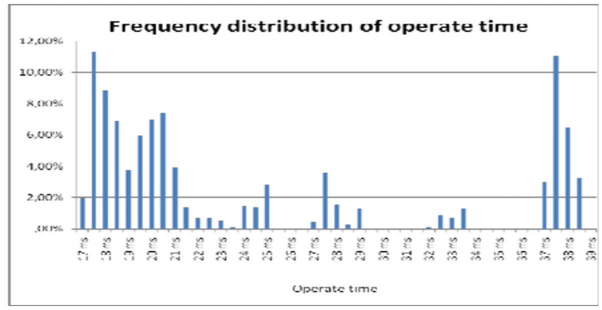

Figure 9.1:
Relay A: frequency distribution of the operate time

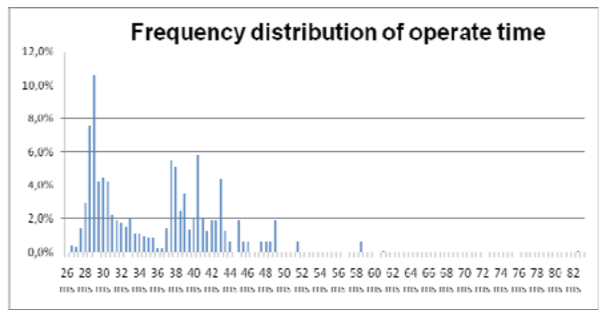

Figure 9.2:
Relay B: frequency distribution of the operate time

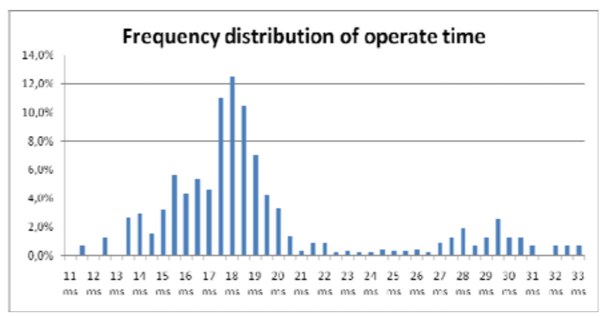

Figure 9.3:
Relay C: frequency distribution of the operate time

Analyzing the histograms of the three different distance protection relay types one can see that relay C (figure 9.3) can be very fast but the majority of faults are cleared in the same time range as is the case for relay A (figure 9.1). However, relay A shows a substantial amount of faults that require almost 2 cycles (at 50Hz) to be cleared. Relay B (figure 9.2) seems to be a completely different class of product much slower than relays A and C. In addition, relay B has the widest dispersion of operate times.

B) Statistic calculation of "typical operate time"

IEC 60255-121 CD [1] (chapter 6.3.4) describes how the "typical operate time" has to be calculated by applying statistic calculations to the total of 384 reported operate times derived from the "SIR tests". 192 operate time test results are taken from the short line tests and 192 operate times from the long line tests. The corresponding statistic values (mode, median and mean) are listed in table 1.

Relay A	Relay B	Relay C
Mode: 17,70	Mode: 37,60	Mode: 17,50
Median: 20,60	Median: 35,30	Median: 18,00
Mean: 24,88	Mean: 35,71	Mean: 19,16
All operate times are **stated** in [ms].		

Table 1: typical operate time of tested relays

Comparing the mode, median and mean values of the different relays, the conclusions of the SIR-diagrams are confirmed. It is obvious that relay C is the fastest, but relay A is nearly as fast as relay C. Relay B is more than 10ms (half cycle) slower.

Conclusions

The performance of distance protection devices plays a key role in the protection systems of the transmission and (some) distribution networks around the globe. The current efforts of the working group IEC TC 95 MT4 target on standardizing the type testing and verification of this performance. The feasibility and relevance of the test procedures described in the corresponding proposed standard IEC 60255-121 (chapter 6.3.2 and chapter 6.3.4) was investigated in a research project. This article reports the results of this research project. It shows that the standardized test procedures proposed by IEC 60255-121 CD (chapter 6.3.2 and chapter 6.3.4) can be implemented with standard test equipment and standard test software. The investigations show that automated test procedures allow a comparably fast and efficient in depth test and analysis of the performance of distance protection devices. Testing one relay type in this manner (3584 test shots) takes approximately 6 hours. This includes the time for automatic creation of the SIR diagrams, statistic calculations and a histogram that visualizes the variation of operate times. The investigated subset of test procedures described in the proposed standard are feasible and the derived test results allow a very good fingerprint-like assessment of the performance of a distance protection relay. Such standardized procedures can be very helpful for comparing the performance of different types of protection equipment. The low effort and minimal investment required to conduct such tests will help protection equipment manufacturers in their type testing procedures to easily meet this standard in the future. Utilities and research centers will benefit from this standard in their acceptance testing efforts because it becomes feasible and affordable for them to conduct their own fingerprint-tests.

The SIR-diagrams in combination with the distribution of the operate time histogram and the "typical operate time" derived from statistic calculations based on several thousand test points allows distance protection devices a very good performance-fingerprint. This fingerprint allows the comparison and classification of different distance protection relays and IEDs regarding their performance for typical zone 1 faults.

References

[1] IEC 60255-121 CD published 2010-01-08. Revision of current input section of IEC 60255-16 (1982), Measuring Relays and Protection Equipment - Part 121: Functional standard for distance protection

[2] G. Ziegler: 'digital distance protection, basics and applications', Publics Corporate Publishing, Erlangen, 2. Edition, 2008

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