Investigation into a double-circuit line fault using the mutual coupling impedance

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Abstract

This paper investigates a double-circuit line fault with non-selective tripping caused by the parameterization of the relay based on inaccurate/insufficient knowledge of the line impedances. Analysis of the fault is based on the measured line impedances and the simulation/system-based testing using RelaySimTest. An appropriate procedure was adopted and documented to measure the line impedances of double-circuit lines in a minimally invasive manner.

Keywords

double-circuit lines, mutual coupling, distance protection, line impedance measurement, selectivity, RelaySimTest, system-based testing

1 Introduction

Parameterization of a distance relay requires precise knowledge of the positive-sequence impedance Z1 and zero-sequence impedance Z0 of the line being protected. If, in addition to this, the circuits are parallel (or partially parallel) to one another, the coupling impedance of the zero sequence Z0M must also be considered.

The distance protection relay, which in this paper tripped a ground fault non-selectively, was parameterized solely based on estimated Z1 and Z0 values. However, as the mutual coupling impedance Z0M of this double-circuit line is significant, it must also be considered. Chapter 2 describes the details of the fault.

Chapter 3 deals with the measurement of the line impedances Z1, Z0, and Z0M using the conventional method.

Chapter 4 compares the simulation carried out in RelaySimTest with the fault recording.

Chapter 5 examines procedures for the system-based investigation into the protection scheme using RelaySimTest.

Chapter 6 describes the minimally invasive measurement of Z1, Z0, and Z0M as an alternative to the measurement method discussed in chapter 3.

2 Fault description

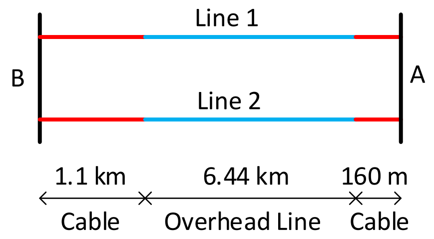


Figure 1: Topology of the double-circuit line

The double-circuit line discussed in this paper consists of two identical electric circuits “Line 1” and “Line 2” (Figure 1) and connects the two busbars A and B. It is part of a solidly grounded urban distribution network with a nominal voltage of 110 kV.

Busbar A is a gas-insulated switchgear with a cable run of 160 m to the overhead line gantry. Busbar B opposite is a cable section 1.1 km in length. The overhead lines are located on the same poles, which explains why a significant zero-sequence coupling impedance Z0M exists.

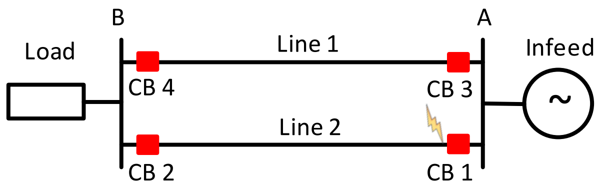


Figure 2: Switching state 1: Δt1 = 53ms

The fault shown in Figure 2 occurred on the cable of the overhead line gantry on phase L1 of line 2. It was caused by sawing of the cable following unauthorized access to the overhead line gantry. The sole infeed of the fault was busbar A via three 220kV/110kV transformers. One of these three transformers was destroyed by the fault, since it was not designed to withstand the fault current.

Most of the fault current initially flowed directly via the feeder of line 2. Only a small portion flowed via line 1 and busbar B. The distance and differential protection of CB1 and CB2 tripped CB1 and CB2 correctly. CB1 was the first to open, 53ms after fault inception.

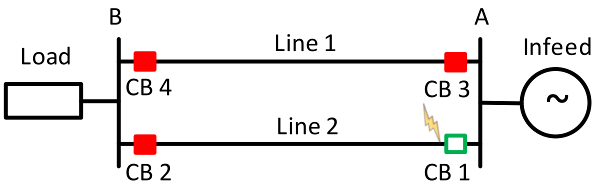


Figure 3: Switching state 2: Δt2 = 20ms

The fault is now fed from line 1 and busbar B. CB2 has not yet opened, as its trip time is a little longer than that of CB1. This switching state lasted just 20ms, or one cycle at 50 Hz.

Switching state 2 resulted in the distance relay of CB3, a Siemens 7SA513, detecting the fault in zone 1 and tripping immediately. The cause of this overreach is explained in detail in section 4.

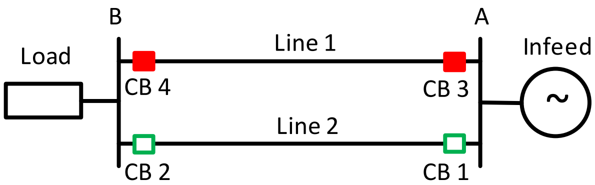


Figure 4: Switching state 3: Δt3 = 50ms

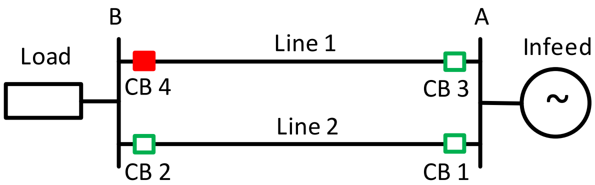


Figure 5: Switching state 4:

Once CB2 is open, as shown in Figure 4, CB3 opens shortly afterwards (Figure 5) as a reaction to the incorrect trip command in switching state 2. As a result, the load at busbar B was no longer supplied.

Although outside of the scope of this paper, it is worth mentioning that when attempting to reconnect the load on busbar B using one of the two lines, the faulty line 2 was connected. Before this connection was made, the load flow was optimized and adapted to the new grid conditions. As a consequence of the new infeed configuration, an additional outgoing line from busbar A (to another busbar, C) was disconnected, as the distance protection on busbar C of this line had detected the fault through the incorrect setting of the impedance-related parameters in zone 1 and tripped instantaneously. At that moment three lines were therefore disconnected instead of one.

3 Measuring the line impedance

When measuring Z1, Z0, and Z0M, both circuits of the double-circuit line were de-energized at the same time so that the official test template for the measuring device CP CU1 could be used; the results are shown in Table 1. [1] and [2] suggest an alternative, minimally invasive procedure that enables Z1, Z0, and Z0M to be determined with just one circuit taken out of service. This procedure was also adopted during the investigation of this fault. Chapter 6 provides details about this measurement.

The measurement took place at the overhead line gantry of busbar A – the line on busbar B was grounded. The overhead line and the cable on busbar B were thus considered for the measurement – the short cable section from the overhead line gantry to the switchgear of busbar A was ignored.

Table 1: Results of the line impedance measurement

	Z_1 (R/X)	Z_0 (R/X)	Z_{0M} (R/X)
Measured in Ω	0.849 2.776	2.131 9.132	1.144 5.779
Estimated in Ω	0.94 2.78	3.07 17.2	not present
Error in %	10.85 0.13	44.71 88.29	not present

As the positive-sequence impedance can be estimated to a high degree of accuracy, its deviation from the measured value is insignificant. The error in the estimated Z0, on the other hand, is significant. Moreover, the fault is positive, which tends to result in overreaching protection. There was no estimate of the coupling impedance to compare with the measured value.

4 Simulation of the fault in RelaySimTest

4.1 Simulation of the fault

The simulation of the voltages, currents, and impedances that occurred during the fault, and that are required for analysis purposes, was carried out using the RelaySimTest software. First, the double-circuit line with single-sided infeed was entered in the software, see Figure 6:

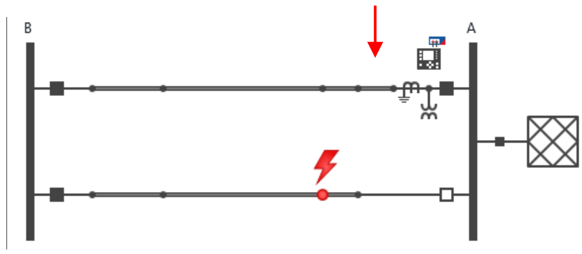


Figure 6: Entering the line in RelaySimTest

The double-circuit line depicted in Figure 6 contains the 3 sections of each of the two circuits, which were parameterized as follows:

- Busbar A cable

- Z1‘ and Z0‘ are identical to the values of the busbar B cable
- Overhead line
  - Z1 and Z0 represent 96% of the measured values
  - Z0M corresponds to the measured value
- Busbar B cable
  - Z1 and Z0 represent 4% of the measured values

The 96%:4% split of the measured impedances assumes that Z1 and Z0 of an overhead line are 4 times greater than the impedances of a cable. The fact that cable impedances have a smaller angle is ignored in this instance.

A further constraint is that the fault is fed exclusively from busbar A.

Figure 9 shows the simulation of the fault (A-G) at the actual fault location (overhead line gantry = 200%). State 2 (from 53ms to 73ms) is studied in more detail below, because the relay misoperated as a consequence of this state. As this state only lasts 20ms, the time domain depiction for voltage and current was used for comparing the simulation and fault recording, as a steady-state impedance does not occur owing to the short duration of state 2.

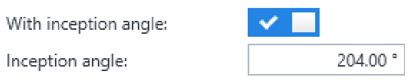


Figure 7: Entering the fault inception angle

The inception angle of the fault has a major impact on the transient response of the fault current. It must therefore be read from the fault recording as accurately as possible. Figure 7 shows the input of the fault inception angle in RelaySimTest; in this case the angle is 204°.

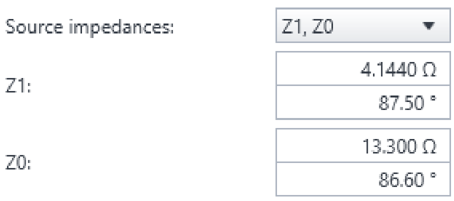


Figure 8: Entering the source impedances

The internal impedances Z1s and Z0s of the source determine the amplitude of the voltage and current. To plot the simulated current as accurately as possible against the actual fault current, the parameters shown in Figure 8 were determined through trial and error. As can be seen from Figure 9, the actual fault current can be simulated very precisely. Similarly, the simulated voltage closely matches the voltage from the fault recording. The close match between the simulated values and those from the fault recording indicates that the measured line impedances (see Table 1) are extremely accurate.

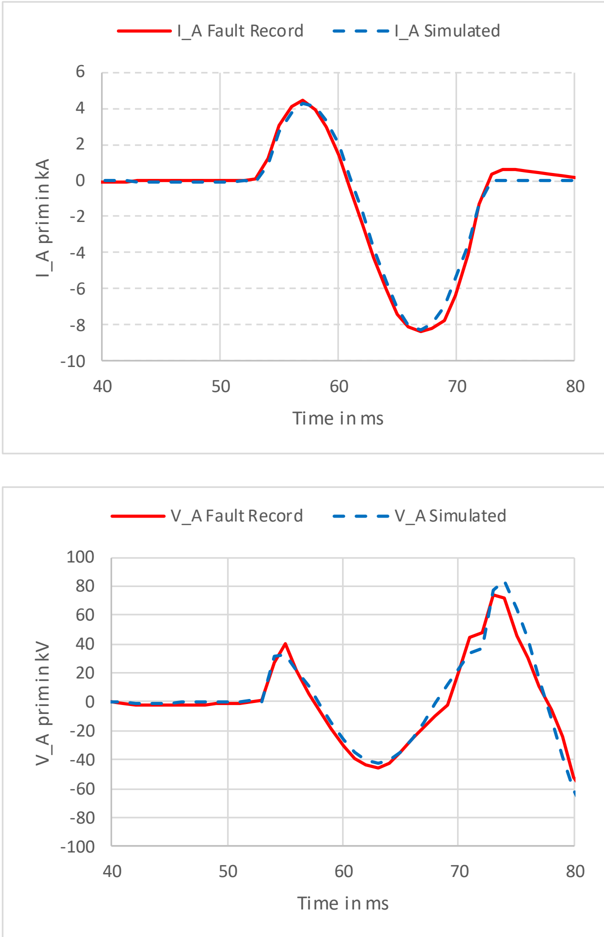


Figure 9: Simulation of the fault (adapted to the fault recording)

4.2 Approach for variable fault distance

Among the variables that influence the impedances determined by the distance protection relay and consequently its response are:

a) The line impedances Z1, Z0, and the coupling impedance Z0M
b) The various switching states during fault clearing (see Figure 2 and 3)
c) The fault location
d) The fault type
e) The infeed conditions (single-sided or double-sided infeed) and the internal impedances Z1s and Z0s of these sources
f) The zero-sequence compensation factor kE required for computing the phase-to-ground loops.

The variables a), b), and c) were varied for Figure 11. This plot shows the reactance versus the fault location in the event of a phase-to-ground fault. The results were determined in RelaySimTest using equation

$$X_{A-G} = imag\{\underline{Z}_{A-G}\} = imag\left\{\frac{\underline{U}_{A-G}}{\underline{I}_A - \underline{k}_E * \underline{I}_E}\right\} \qquad \text{Eq. 1}$$

(see Figure 10) and correspond to the steady-state results that a relay would determine[1].

V A-N prim.:	29.351 kV	∠	-2.72 °
V B-N prim.:	73.084 kV	∠	-124.39 °
V C-N prim.:	70.814 kV	∠	135.91 °
I A prim.:	4.8151 kA	∠	-75.39 °
I B prim.:	0.0000 A	∠	NaN
I C prim.:	0.0000 A	∠	NaN
Z A-N prim.:	2.2742 Ω	∠	65.94 °
Z B-N prim.:	+∞	∠	NaN
Z C-N prim.:	+∞	∠	NaN

Figure 10: Steady-state currents, voltages, and impedances in RelaySimTest according to Figure 6, fault location 200%

A fault location of 200% corresponds to a fault at the start of the parallel line of the double-circuit line.

The following assumptions were made in this case:

a) There is a fault A-G. This applies to the example in question.
b) The fault current is only fed from one side. This applies to the example in question.
c) The set X value for zone 1 corresponds to the value set in the relay at the time of the fault.
d) The set kE factor corresponds to the value set in the relay at the time of the fault.

Figure 11, : The reactance versus the fault location for state 2 is shown; the measured values for Z1, Z0, and Z0M are considered. It can be seen that the impedance at a fault location of 200% is a little smaller than the values set for zone 1. In this example, this led to the overreach, which would have been easy to predict using RelaySimTest and the measured impedance values.

Figure 11, : The reactance versus the fault location for state 1 is shown; the measured values for Z1, Z0, and Z0M are considered. The comparison with shows the effect of the switching state.

Figure 11, : The reactance versus the fault location is shown; the measured values for Z1 and Z0 are considered, but the coupling impedance Z0M is not. The fact that coupling is not considered shows that the impedance is independent of the switching state.

The differences compared with the plots and are plain to see.

Figure 11, : The reactance versus the fault location is shown; the estimated values for Z1 and Z0 are considered, but the coupling impedance Z0M is not. The overreach cannot be predicted with this plot, as the impedance values are markedly different and the coupling is not considered. A comparison with reveals the considerable difference between the measured impedance values and the estimated ones.

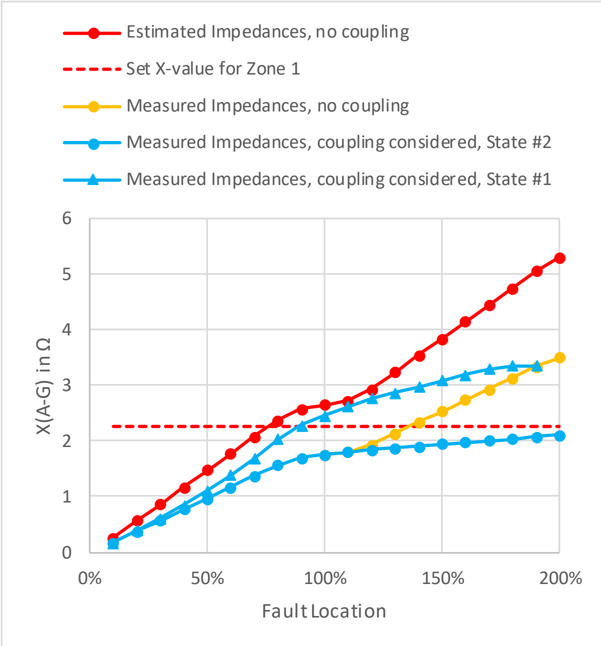


Figure 11: Reactance versus the fault location

This leads us to the following interim conclusions:

- The line impedances should be measured, as values from tables or computations can be inaccurate (compare with)
- The coupling impedance in the zero sequence must be considered in the case of phase-to-ground faults (compare with and with)
- Any possible switching states that occur during the fault clearing sequence must be considered (compare with)

5 Testing the protection concept

This section looks at a double-circuit line protected by a distance protection relay to demonstrate how complex protection schemes can be tested.

1 The k-factor of the first line section in the forward direction of a relay determines the computation of the Phase-to-Ground impedances in RelaySimTest. For this reason, the 4th (auxiliary) section was added in Figure 6 (red arrow). To keep the additive effect of the auxiliary section as low as possible, the minimum impedance value, 5mΩ, was entered.

5.1 Determining the relevant test cases

The previous sections have illustrated that the various switching states during fault clearing are among the factors that must be considered when developing and testing a protection scheme.

The sequence in which these states occur depends on the order in which the relays issue trip commands and the trip times of the corresponding circuit breakers. As these depend on other variables, such as the fault location, the fault type, and the infeed configuration, different scenarios using worst-case assumptions can be examined. For example, the following scenarios can be investigated[2]:

- Scenario 1: The fault occurred at t=0ms; CB1 opened after t=60ms and CB2 opened at t=120ms.
- Scenario 2: The fault occurred at t=0ms; CB2 opened after t=60ms and CB1 opened at t=120ms.

In this instance, rather than using all possible infeed configurations, different scenarios with worst-case assumptions and various fault types and fault locations can again be examined.

RelaySimTest is a tool that quickly and easily computes all the cases under consideration. The program computes both the time domain currents i(t) and voltages u(t) and the associated steady-state phasors of $\underline{I}$ and $\underline{U}$ for each switching state. The impedances of all six loops are also computed. Equation 1 is used, resulting in the same impedances that a distance protection device would have determined using a steady-state method.

Described below are two potential applications, which, when taken together, provide a meaningful examination of the protection concept.

5.2 Assessing with steady-state values (step 1: with no relay)

The testing of the protection scheme for a double-circuit line with steady-state values can be carried out as follows:

- The loop impedances of all relays and all relevant test cases are computed according to section 5.1, see Figure 10. Figure 11 provides a potentially helpful depiction.
- In each test case, the impedances are compared with the planned parameter values and an assessment is performed to determine the zone in which the relays would trip.

This test would be able to detect any possible overreach that actually occurred, as the fault is seen in zone 1 in switching state 2.

This approach means that the protection scheme can be tested as early as the design stage using the results of the steady-state computation. As no relay and no OMICRON testing device are needed, the computations using RelaySimTest do not require a license.

5.3 Testing with time domain signals (step 2: with relay)

If the relays are present, a further test with the computed time domain current and voltage values can be carried out.

The procedure in this case is as follows:

- The relay is parameterized as designed.
- It is then connected to RelaySimTest using an OMICRON test device to enable the currents and voltages to be output and the binary signals from the relay system (for example, trip command) to be measured.
- The test is carried out. If all the relevant test cases are successful, the test has been passed. The target values and tolerances for evaluating the measured binary signals are entered beforehand into RelaySimTest.

Testing with the relay is more reliable than testing with steady-state values, as the response of the relay is emulated directly. This test would have also detected any overreach that occurred.

The test can be carried out for every single distance protection relay or simultaneously for several relays. Figure 12 illustrates the testing principle with predefined switching state sequences according to the examples “Scenario 1” and “Scenario 2” cited in section 5.1. The simultaneous testing of several relays enables some other relevant functions, such as directional comparison, to be tested as well. RelaySimTest supports the control of test sets via the internet (distributed testing) so that relays at various locations can be tested simultaneously.

2 Alternatively, the actual sequence of switching states can be determined using the “Iterative Closed-Loop” method. See Figure 13

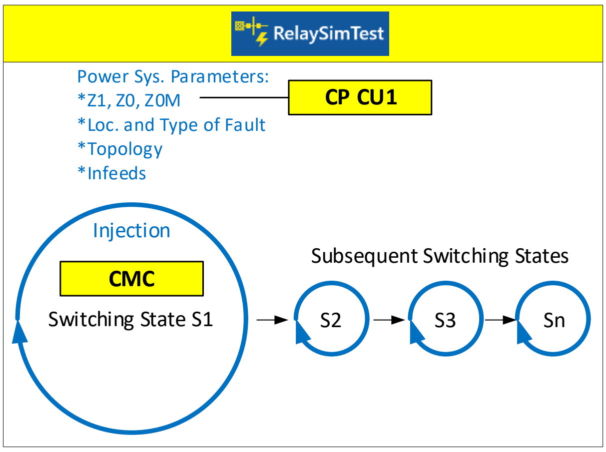


Figure 12: Testing with a predefined sequence of switching states

The "Iterative Closed-Loop" method implemented in RelaySimTest enables the simultaneous testing of several relay systems to be fully automated, see Figure 13. There is consequently no need to define the switching state sequence using worst-case assumptions. The trip commands of all relays are acquired iteratively and, taking the trip times of the CBs into account, the actual state durations are determined and the test signals are applied according to an actual fault.

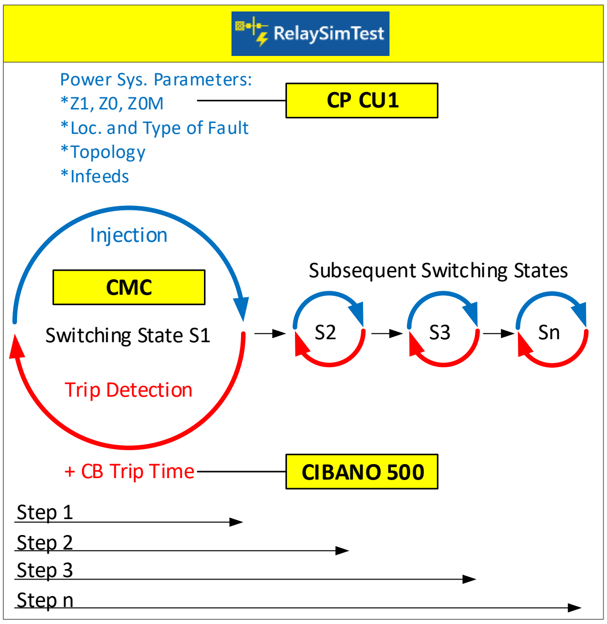


Figure 13: Testing using the "Iterative Closed-Loop" method

6 Minimally invasive measurement of the line impedance

A procedure proposed at the 2017 OMICRON user meeting in Friedrichshafen allows the zero-sequence impedance Z0 and the coupling impedance Z0M of a double-circuit line with only one line taken out of service to be determined by measurement; see [1]. The simultaneous disconnection of two coupled electric circuits is difficult to arrange once the line has been commissioned. However, the conventional method of measuring a double-circuit line requires simultaneous de-energization, which is why the alternative, minimally invasive procedure for the retrospective measurement of double-circuit lines is of such interest. The verification of this method by actual measurement could not be carried out until after the 2017 user meeting and is described in [2]. The relevant paper was presented at the 2018 user meeting in Berlin. Familiarity with [1] and [2] is recommended, as it will help with the understanding of this section.

Table 2: Results of the minimally invasive line impedance measurement

	Z_1 (R/X)	Z_0 (R/X)	Z_{0M} (R/X)
Normal (in Ω)	0.849 2.776	2.131 9.132	1.144 5.779
Minimally invasive (in Ω)	0.863 2.776	2.200 8.690	1.25 5.01
Error in %	1.65 0	3.24 -4.84	9.27 -13.3

Table 2 presents the results of both measurements. As expected, the deviation in respect of Z1 is negligible. The deviation of less than 5% in the case of Z0 is still within acceptable limits, whereas the deviation of more than 13% for Z0M requires further analysis.

As described in [1] and [2], the accuracy of the procedure depends on two variables:

- Current Ip in the in-service circuit and the derived current factor fsp
- Auxiliary impedance

Figure 14: Primary measurement of Ip with 4 Rogowski coils

The measurement of Ip was carried out in two different ways:

- Secondary, as discussed in [1] and [2]
- Primary, on the cable of the overhead line gantry, see Figure 14. This option has not been possible to date.

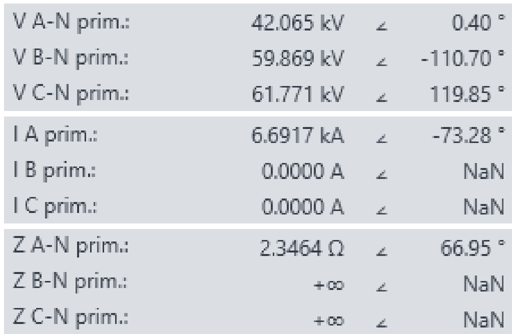
Table 3: Current factor fsp from the primary and secondary measurement of Ip

	Magnitude	Phase angle
Primary	0.5818	7.28°
Secondary	0.5888	6.39°

When measuring the secondary current using the Chauvin Arnoux K2 measuring probe, a current transformer transformation ratio of 800A:1A and an angular error of the current probe of -5° at 50 Hz were considered. A comparison of the two measurements showed that in addition to the successful comparison in [2], the secondary measurement was extremely accurate.

This demonstrates that the errors in Table 2 are all to do with the inaccuracy of the auxiliary impedance. When determining the auxiliary impedance, in this instance the geometry of the six conductors of the two circuits was available. No further examination into the accuracy of this data was carried out.

What is crucial is the effect of the inaccuracy of the impedances Z0 and Z0M on the simulated impedance of the fault in RelaySimTest in Figure 6.



V A-N prim.:	42.065 kV	∠	0.40 °
V B-N prim.:	59.869 kV	∠	-110.70 °
V C-N prim.:	61.771 kV	∠	119.85 °
I A prim.:	6.6917 kA	∠	-73.28 °
I B prim.:	0.0000 A	∠	NaN
I C prim.:	0.0000 A	∠	NaN
Z A-N prim.:	2.3464 Ω	∠	66.95 °
Z B-N prim.:	+∞	∠	NaN
Z C-N prim.:	+∞	∠	NaN

Figure 15: Currents, voltages, and impedances according to Figure 6 of the minimally invasive measurement

The X value of the loop impedance shown here is 2.16Ω. The error in this value compared with the value of 2.10Ω derived from the correct line impedances (Figure 10) is 3%.

The inaccuracy of the impedance arises from the inaccuracy of Z1, Z0, and Z0M. However, it must be borne in mind that Z0M may only be of any significance under certain conditions, depending on the coupling of a particular fault scenario. In the case of the fault under discussion here, the coupling has the maximum possible effect, as the coupling impedance has an impact along the entire length of the line.

It can also be seen from [1] that the accuracy of Z0 is less dependent on the auxiliary impedance than Z0M. Despite all the above, an attempt should be made to estimate the auxiliary impedance as accurately as possible. Refer to the three options in [2], Chapter 5 for more information.

7 Summary

This paper demonstrates that by measuring Z1, Z0, and Z0M and carrying out a simulation in RelaySim-Test, the currents and voltages associated with a fault can be simulated extremely accurately. The currents and voltages of a real fault are applied to the relay, which then responds in a correspondingly realistic manner.

OMICRON provides the comprehensive solution:

- Minimally invasive measurement of Z1, Z0, and Z0M with CP CU1. Minimally invasive means that only one circuit must be de-energized. This paper once again demonstrates the accurate results produced using this method.
- Simulation of the test values using the network model in RelaySimTest, taking mutual coupling into account.
- Consideration of the various switching states during fault clearing.

The user therefore has access to a comprehensive range of test sets and software to facilitate the simple, practical, and system-based testing of the distance protection relays of double-circuit lines.

References

[1] Pikisch, M.: The significance of mutual coupling in the line model. OMICRON User Meeting 2017; Friedrichshafen

[2] Konzelmann, S.; Pikisch, M.: Measuring the impedance on double-circuit lines with the parallel system in operation. OMICRON User Meeting 2018; Berlin

About the authors

Moritz Pikisch studied electrical engineering at the Karlsruhe Institute of Technology. After working in training at OMICRON from 2010 to 2013, he switched to a product management role in 2014. In this capacity, he was responsible for the CPC 100 and CP CU1, with an emphasis on line impedance measurement and grounding system testing. Since March 2018 he has been working as an application engineer for OMICRON USA. In this role, he continues to be the main contact within the company for line impedance and ground measurements.

Rainer Luxenburger studied electrical engineering at the University of Saarland. From 2000 to 2006 he worked as a research assistant at the Technical University of Dresden. He has been working as an application engineer for OMICRON in Germany since October 2006. His work in this role covers the areas of training and technical consultancy.

OMICRON is an international company serving the electrical power industry with innovative testing and diagnostic solutions. The application of OMICRON products allows users to assess the condition of the primary and secondary equipment on their systems with complete confidence. Services offered in the area of consulting, commissioning, testing, diagnosis and training make the product range complete.

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