Assessment of a misoperation on a distance protection relay by means of line impedance measurement and system-based testing

Moritz Pikisch, Rainer Luxenburger

OMICRON electronics

***Abstract*—This paper investigates a double-circuit line fault with non-selective tripping caused by the parameterization of the relay based on inaccurate/lack of knowledge of the line impedances. Analysis of the fault is based on the measured line impedances and using network simulation software. 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, system-based testing**

I. 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 mutual coupling impedance 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 **Error! Reference source not found.** describes the details of the fault, chapter III deals with the measurement of the line impedances Z1, Z0, and Z0M using the conventional method.

Chapter IV compares the network simulation with the fault recording.

Chapter V examines procedures for the system-based investigation into the protection scheme.

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

II. Fault Description

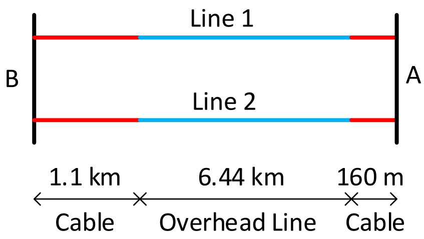

Fig. 1. Topology of the double-circuit line

The double-circuit line discussed in this paper consists of two identical electric circuits “Line 1” and “Line 2” (Fig. 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.

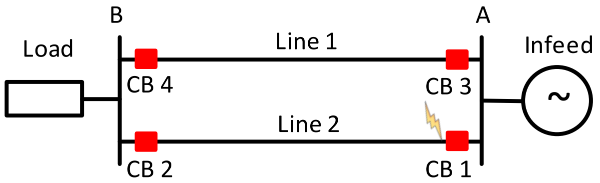

Fig. 2. Switching state 1: Δt1 = 53ms

The fault shown in Fig. 2 occurred on the cable of the overhead line gantry on phase A 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 cor-rectly. CB1 was the first to open, 53ms after fault inception.

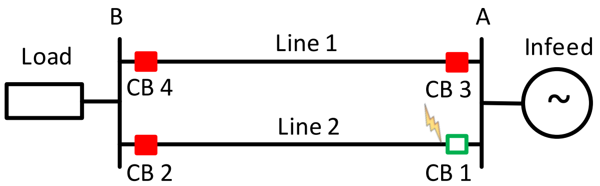

Fig. 3. Switching state 2: Δt2 = 20ms

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.

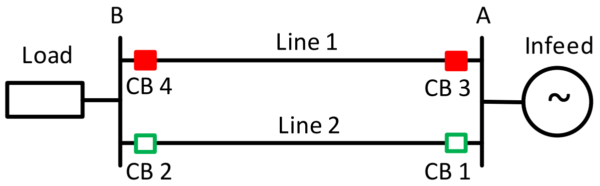

Fig. 4. Switching state 3: Δt3 = 50ms

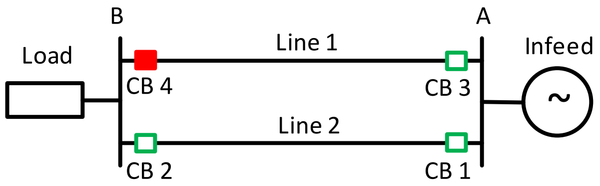

Fig. 5. Switching state 4

Once CB2 is open, as shown in Fig. 4, CB3 opens shortly afterwards (Fig. 5) as a reaction to the incorrect trip command in switching state 2. As a result, the load at busbar B was not supplied anymore.

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.

III. Measuring the Line Impedance

When measuring Z1, Z0, and Z0M, both circuits of the double-circuit line were de-energized at the same time; 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 VI 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 I. Results of the Line Impedance Measurement

	Z1 (R/X)	Z0 (R/X)	Z0M (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.

IV. Network Simulations

A. *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 network simulation software. First, the double-circuit line with single-sided infeed was entered in the software, see Fig. 6:

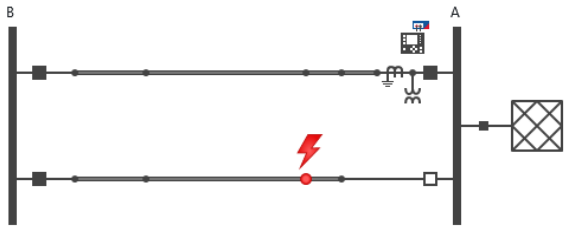

Fig. 6. Entering the line topology

The double-circuit line depicted in Fig. 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.

Fig. 7 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, as 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.

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. In this case the inception angle is 204°.

The internal impedances Z1s and Z0s of the infeed determine the amplitude of the voltage and current. To plot the simulated current as accurately as possible against the actual fault current, Z1s and Z0s need to be determined through trial and error. As can be seen from Fig. 7, 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.

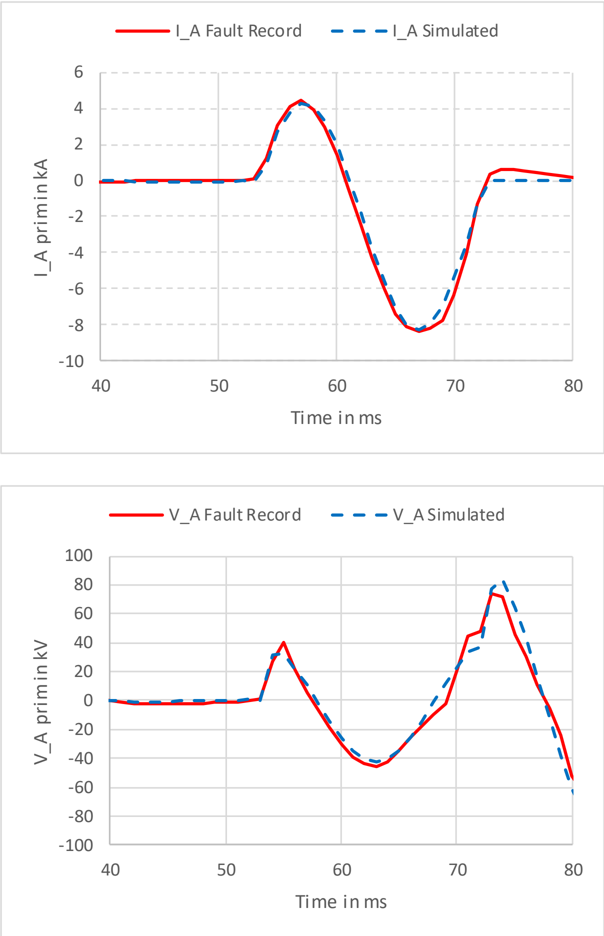

Fig. 7. Simulation of the fault (adapted to the fault recording)

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 Fig. 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 Fig. 9. This plot shows the reactance versus the fault location in the event of a phase-to-ground fault. The results were determined in the power system simulation software using equation

$$X_{A-G} = imag\{\underline{Z}_{A-G}\} = imag\left\{\frac{\underline{V}_{A-G}}{\underline{I}_A - \underline{k}_E * \underline{I}_E}\right\} \quad (1)$$

(see Fig. 8) and correspond to the steady-state results that a relay would determine.

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

Fig. 8. Steady-state currents, voltages, and impedances according to Fig. 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:

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

Fig. 9, : 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 employing network simulation by means of the measured impedance values.

Fig. 9, : 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.

Fig. 9, : 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.

Fig. 9, : 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.

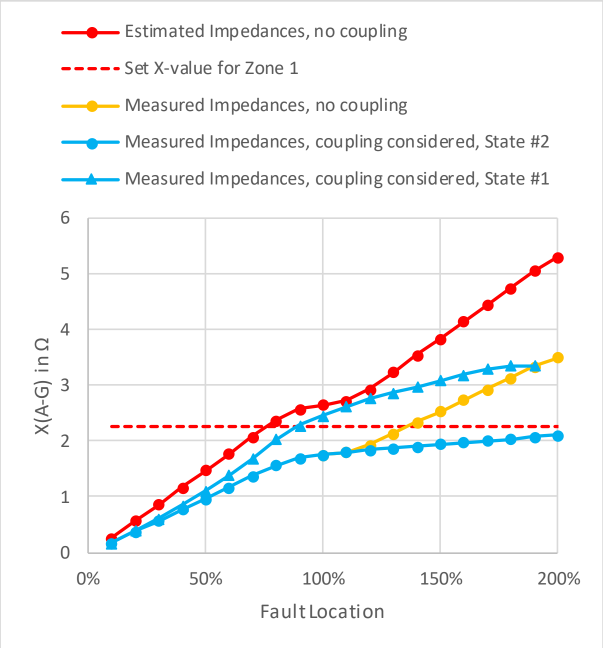

Fig. 9. Reactance versus the fault location

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)

V. Testing the Protection Scheme

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

A. 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[1]:

- 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.

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

B. 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 A, see Fig. 8. Fig. 9 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.

C. 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 a protection test set to enable the currents and voltages to be output and the binary signals from the relay (e.g., trip command) to be measured.
- The test is carried out. If all the relevant test cases are successful, the test has been passed.

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. Fig. 10 illustrates the testing principle with predefined switching state sequences according to the examples “Scenario 1” and “Scenario 2” cited in section A. The simultaneous testing of several relays enables some other relevant functions, such as directional comparison, to be tested as well.

1 Alternatively, the actual sequence of switching states can be determined using the “Iterative Closed-Loop” method. See Fig. 11

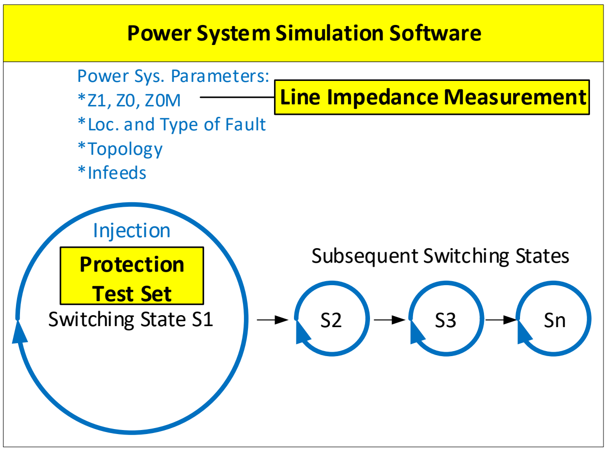

Fig. 10. Testing with a predefined sequence of switching states

Fully automated testing could be accomplished by means of determining the trip times of all involved, distributed and consecutively tripping relays, to be referred to as "Iterative Closed-Loop" testing, see Fig. 11. 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.

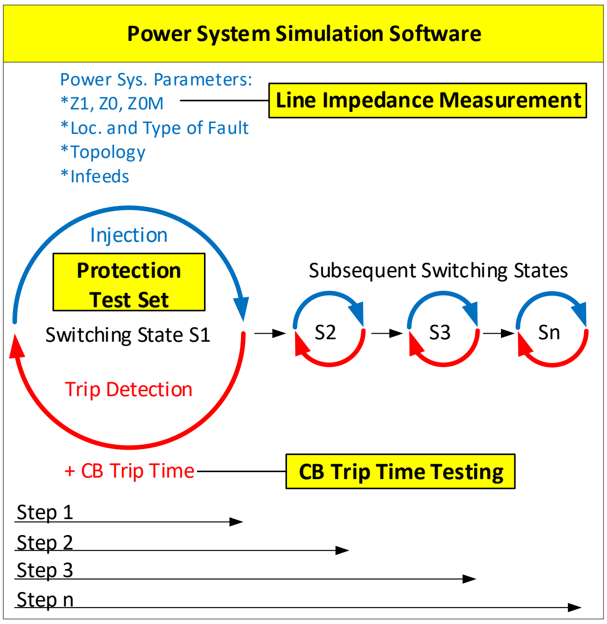

Fig. 11. Testing using the "Iterative Closed-Loop" method

VI. Minimally Invasive Measurement of the Line Impedance

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. Familiarity with [1] and [2] is recommended, as it will help with the understanding of this section.

TABLE II. Results of the Minimally Invasive Line Impedance Measurement

	Z1 (R/X)	Z0 (R/X)	Z0M (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

Fig. 12. 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 Fig. 12. This option has not been possible to date.

TABLE III. 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 network simulation software in Fig. 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

Fig. 13. Currents, voltages, and impedances according to Fig. 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 (Fig. 8) 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.

VII. Summary

This paper demonstrates that by measuring Z1, Z0, and Z0M and using network simulation software, 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.

A solution in three steps is suggested:

- Minimally invasive measurement of Z1, Z0, and Z0M. 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 impedances by means of network simulation software, taking mutual coupling into account.
- Consideration of the various switching states during fault clearing.

References

[1] M. Pikisch, “The significance of mutual coupling in the line model,” OMICRON German User Meeting 2017

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