Measuring the impedance on double-circuit lines with the parallel circuit in operation

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Abstract

Measuring the impedance of double-circuit lines has, in the past, always necessitated switching off both circuits. This state is seldom possible on operational grounds, for which reason at the last user meeting a procedure was proposed which theoretically allows a measurement to be made while only switching off one system. The measurement procedure has since been verified by a field measurement. This article deals with the results of this measurement.

Keywords

Double-circuit line, mutual coupling, distance protection, line impedance measurement, line model

1 Introduction

A procedure had already been proposed at the 2017 OMICRON user meeting in Friedrichshafen that allows the zero-sequence impedance $\underline{Z}_0$ and the coupling impedance in the zero-sequence domain $\underline{Z}_{0M}$ of a double-circuit line with only one line taken out of service to be determined by measurement, see [1]. The verification of this method by actual measurement could not be carried out until the 2017 user meeting, and is now described in this article. Knowledge of [1] is recommended when reading this article and to aid understanding, as the theoretical principles of the new method are not repeated in detail here.

Verification of the method requires a double-circuit line measurement based on the method which has been used until now, in which both systems are taken out of operation at the same time. This is generally only possible before commissioning of a double-circuit line. Such a possibility arose before commissioning a 380 kV double-circuit line between Altenfeld (Thuringia) and Redwitz (Bavaria). It was possible here to take the measurement first with both circuits switched off at the same time in order to have a comparison basis for the measurement used in the procedure proposed in [1] (Chapter 2). After that, one of the two circuits was energized in order to obtain the typical influence of a parallel line in operation (as Chapter 3).

Data of the double-circuit line:

- Voltage level: 380 kV
- Length:
  - 56.7 km in total
  - 25.7 km in the 50 Hz TSO zone
  - 31.0 km in the TenneT TSO zone
- Between the Altenfeld substation (50 Hz TSO) and the Redwitz substation (TenneT TSO)
- Designations of the two circuits: Line 459 and line 460

2 Measurement with both systems de-energized at the same time

The following measurements were taken with both systems out of operation at the same time:

- Line 459 total
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- Line 459 in the 50 Hz TSO zone. Both circuits systems were grounded at the last pole in the 50 Hz TSO zone.

The corresponding values for the section of line 459 in the TenneT zone were calculated using subtraction. The table below summarizes the results of these measurements.

Table 1:Impedances based on the conventional measuring method

Line	Z_1 (R/X)	Z_0 (R/X)	Z_{0M} (R/X)
459 total	0.858 14.1	4.98 38.8	3.94 15.4
460 total	0.866 14.2	5.00 39.1	3.98 15.6
459 50 Hz zone	0.494 6.54	2.64 16.8	1.98 5.55
459 in TenneT zone (calculated)	0.364 7.56	2.34 22.0	2.00 9.76

3 Verification of the alternative method

The method verified in this article calls for the following measurements to determine $\underline{Z}_0$ and $\underline{Z}_{0M}$:

- Measurement of the impedance $Z_{ABC-G,Operation}$ of the loop ABC-G with the parallel circuit in operation.
- Determination of the factor between the current fed into the loop ABC-G and the resulting current in the parallel circuit. This factor is named $\underline{k}$ in [1], Equation 5 but for practical reasons is designated $\underline{fcp}$ (factor of the current in the parallel system) from here onwards.

The CPC 100 with CP CU1 test equipment was connected to line 460 for this. At the time of the measurement, line 459 was in operation and under load with an operating current between 1000 A and 1100 A. Due to the high load and the length of the line, an induced voltage with values in excess of 500 V would have arisen at the open end of the line, which exceeded the permissible voltage of the CP CU1 coupling unit. Special voltage limiters were used to lower the voltage to below 500 V and enable the measurement despite these circumstances.

In addition, the auxiliary impedance $\underline{Z}_{ABC[I-II]}$ had to be estimated.

The following chapters explain how the factor $\underline{fsp}$ was measured and $\underline{Z}_{ABC[I-II]}$ was estimated, taking the field measurement as a basis, and comparing it with the results from Chapter 2.

4 Determining the current factor

A current $\underline{I}_m$ was applied to the ABC-G loop of the 460 circuit to determine the factor $\underline{fsp}$. System 459 was in operation at the time. The current $\underline{I}_p$ in system 459 was measured at the same time. The measurement was taken at the N conductor of the CT's metering core in order to determine the total of the currents in the three phase conductors generated by the coupling with the parallel circuit. The current in the N conductor was measured with a Chauvin Arnoux model K2 current clamp, see [1].

The factor has the index *dir* here, as it is a *directly-determined* factor from a current measurement.

$$\underline{fcp}_{dir} = \frac{\underline{I}_p}{\underline{I}_m} \qquad \text{Eq. 1}$$

In order to have a value based on the impedance measurement from Chapter 2 for comparison, the indirect factor $\underline{fcp}_{ind}$ is calculated using the following equation (see [1], equations 8 and 9):

$$\underline{fcp}_{ind} = \frac{\underline{Z}_0 - 3 * \underline{Z}_{ABC-G,Operation}}{\underline{Z}_{0M}} \qquad \text{Eq. 2}$$

The two factors $\underline{fcp}_{dir}$ and $\underline{fcp}_{ind}$ were then determined three times, with the results shown in Table 2:

Table 2: Results of the current factor measurements

	$\underline{fcp}_{dir}$	$\underline{fcp}_{ind}$	$\varepsilon = \frac{\underline{fcp}_{dir}}{\underline{fcp}_{ind}}$
Measurement 1	0.243 (-7.10°)	0.214 (-10.93°)	+13% (3.38°)
Measurement 2	0.235 (-8.01°)	0.240 (-10.37°)	-2% (2.36°)
Measurement 3	0.237 (-9.22°)	0.24 (-9.82°)	-1% (0.6°)

Explanation of the three measurements:

- **Measurement 1:** $\underline{Z}_{ABC-G,Operation}$ (the basis for $\underline{fcp}_{ind}$) was measured about half an hour before $\underline{fcp}_{dir}$ was measured. The terminating impedances $\underline{Z}_{T1}$ and $\underline{Z}_{T2}$ of the line 459 in operation clearly cannot be assumed as being constant over time. This is shown by the differences between the respective values of $\underline{fcp}_{dir}$ and $\underline{fcp}_{ind}$, see [1], Figure 2.
- **Measurement 2:** This was an attempt to take the two measurements as quickly as possible in succession, which results in a considerably smaller discrepancy.
- **Measurement 3:** CPC 100 currently doesn't feature the simultaneous determination of $\underline{Z}_{ABC-G,Operation}$ and $\underline{fcp}_{dir}$. This would require the capability to take measurements using the three channels IAC, V1AC, and V2AC simultaneously. The DANEO 400 was, therefore, used here with which $\underline{I}_m$, $\underline{V}_m$, and $\underline{I}_p$ could be recorded simultaneously. With a discrepancy in magnitude of only 1% and a phase displacement of 0.6°, this is a high degree of measurement accuracy. It must be noted in this respect that both the current transformer from line 459 and the current clamp contain an error which, however, clearly turns out to be negligible.

5 Estimating the auxiliary impedance

As well as the impedance $Z_{ABC-G,Operation}$ and current factor $\underline{fcp}$, the auxiliary impedance $\underline{Z}_{ABC[I-II]}$ must also be determined (see [1]). This impedance cannot be measured at all, as it would entail taking both circuits of the double-circuit line out of operation at the same time. Since this impedance refers to the 6 phase conductors of the two electric circuits and is independent of the ground path, it can, however, be determined very accurately from the geometry of the conductors.

There are a total of three possibilities for calculating the auxiliary impedance:

- **Option 1:** Calculating the loop impedance of all 15 conductor pairs and then solving the matrix accordingly. The solution of the matrix is not described in any more detail here for reasons of complexity. OMICRON has already prepared an unofficial template for this, however.
- **Option 2:** Measuring the three respective loop impedances in circuit I and II. The measurement of L-L loops is not affected by parallel circuits still in operation. Based on the six measured loop impedances, the nine other impedances can be calculated. This method is recommended especially if significant discrepancies exist between the measured and calculated positive-sequence impedance $\underline{Z}_1$.
- **Option 3:** Use of $\underline{Z}_0$ and $\underline{Z}_{0M}$ from power system analysis software. The auxiliary impedance can then be calculated from $\underline{Z}_0$ and $\underline{Z}_{0M}$ as follows. The accuracy of the auxiliary impedance is comparable with that of the positive-sequence impedance, since only the geometry of the phase conductor is relevant here.

$$\underline{Z}_{L1L2L3[I-II]} = \frac{2}{3} * \underline{Z}_0 - \underline{Z}_{0M} \quad \text{Eq. 3}$$

The section of the line in the TenneT zone was used for evaluating the auxiliary impedance. This section of the line has the following characteristics:

- Length: 31 km
- Conductor diameter: 3.285 cm
- Distance between conductors in the bundle: 40 cm
- Number of conductors in the bundle: 4

On the basis of this data and the conductor arrangement of the double-circuit line, the following values result:

$$X_1 = 7{,}8\Omega \quad \text{Eq. 4}$$

$$X_{ABC[I-II]} = 8{,}1\Omega \quad \text{Eq. 5}$$

The measurement of the L-L loops gives the following positive-sequence impedance:

$$\underline{Z}_1 = 0{,}364 + j7{,}563 \quad \text{Eq. 6}$$

The corrected value of the auxiliary reactance can now be calculated from the measured and calculated value of the positive-sequence reactance:

$$X_{ABC[I-II],corr} = 7{,}85\Omega \quad \text{Eq. 7}$$

The R value of the auxiliary impedance is calculated by multiplying the R value of the positive-sequence impedance by ⅔. This simple calculation is possible because the R value is not dependent on the distance between the phase conductors.

$$R_{ABC[I-II]} = 0{,}243\Omega \quad \text{Eq. 8}$$

The comparative value for the auxiliary impedance can now be calculated using equation 3, based on the measurement from Chapter 2. This works out at:

$$R_{ABC[I-II]} = 0{,}226\Omega \quad \text{Eq. 9}$$

$$X_{ABC[I-II]} = 8{,}16\Omega \quad \text{Eq. 10}$$

The R values of the auxiliary impedance from equations 8 and 9 only differ very slightly from each other. The X value from equation 7 only differs by 4% from the reference value in equation 10. This shows that the auxiliary impedance can be determined very accurately on the basis of the geometry and the measurement of the positive-sequence impedance, and $\underline{Z}_0$ and $\underline{Z}_{0M}$ can, therefore, also be determined very accurately.

6 Comments on the practical application of the method

6.1 Measuring the impedance

The template for a single-circuit line has been used here. The loop measurements for A-G, B-G and C-G can be omitted, however. The four measurements A-B, B-C, A-C and ABC-G will suffice, and loop impedances at power frequency can be calculated. The positive-sequence impedance calculated in the template is correct, since parallel systems do not have any significant effect on the positive-sequence impedance. The value for the zero-sequence impedance is (probably) too small, depending on the influence of the parallel live line.

6.2 Estimating the influence of the parallel live line

While a current was being applied to the ABC-G loop, the current was measured with a Chauvin Arnoux, model K2 current clamp at the N conductor of the current transformer of the parallel line that was in operation. This can be done with a twisted pair cable to detect the phase angle. However, for an initial estimate, the magnitude of the current can be measured without a twisted pair cable using the HGT1 handheld ground tester and the current clamp. Experience has shown that twisted pair cables are usually not available. In addition, depending on the location of the measurement of the current, the requirements on the length of the test lead may exceed the length of any available lead.

The magnitude of the current factor $\left|\underline{fcp}\right|$ is then determined as follows:

$$\left|\underline{fcp}\right| = CTRatio * \frac{\left|\underline{I}_{p,sec}\right|}{\left|\underline{I}_{m}\right|} \quad \text{Eq. 11}$$

- CTRatio: ratio of the current transformer
- $I_{p,sec}$: current measured with the current clamp
- I_m: applied current

In addition, the auxiliary impedance must be estimated. Nonetheless, this can be simplified for an initial rough estimate by assuming ⅔ of the positive-sequence impedance for the auxiliary impedance.

The necessary calculations can be carried out based on EXCEL, for example. The figure below shows the unofficial template prepared by OMICRON:

	Re	Im	Abs	φ in °
Z_ABC-G,Operation in Ω	1.128	11.776	11.83	84.53
Current Factor fcp	0.235	0.000	0.235	0.00
Auxiliary Impedance in Ω	0.57733	9.4	9.42	86.49
Z_0,apparent in Ω	3.38	35.33	35.49	84.53
Z_0,corrected in Ω	4.16	41.85	42.06	84.33
Error Z_0,apparent	-18.61%	-15.58%	-15.61%	0.20
Z_0M in Ω:	3.29	27.75	27.94	83.24

Figure 1: Example of a calculation tool based on EXCEL

Notes to Figure 1:

- Input fields are blue
- The apparent zero-sequence impedance is 3 times the impedance $Z_{ABC-G,Operation}$, comparable with a single-circuit line measurement
- The corrected zero-sequence impedance is calculated according to [1], equation 8
- The error for the apparent zero-sequence impedance refers to the corrected zero-sequence impedance
- The coupling impedance is calculated according to [1], equation 9

Figure 1 shows an initial rough estimate for measurement 2 from Table 2. $Z_{ABC-G,Operation}$ was taken directly from the EXCEL template for measurements on single-circuit lines. An angle of 0° was entered for the current factor, as the angle is generally between -20° and +20°. Trying different angles in this range revealed that the error did not change significantly. The auxiliary impedance was assumed as ⅔ of the positive-sequence impedance from line 460.

Errors in the lower double-digit range were estimated for R and X of the zero-sequence impedance. The actual error will be somewhat smaller, as the auxiliary impedance was estimated in a simplified way (specifically: smaller), so the error was a conservative estimate. It is reasonable in the case of such a high expected error to undertake a correction of the zero-sequence impedance by means of accurate determination of the current factor and auxiliary impedance.

	Re	Im	Abs	φ in °
Z_ABC-G,Operation in Ω	1.128	11.776	11.83	84.53
Current Factor fcp	0.233	-0.033	0.235	-8.01
Auxiliary Impedance in Ω	0.57733	15.6	15.61	87.88
Z_0,apparent in Ω	3.38	35.33	35.49	84.53
Z_0,corrected in Ω	4.80	38.78	39.07	82.94
Error Z_0,apparent	-29.56%	-8.90%	-9.17%	1.59
Z_0M in Ω:	3.94	15.38	15.87	75.64

Figure 2: Determining the final impedances with the calculation tool

Notes to Figure 2: Determining the current factor by measurement gives an angle of -8.01°. The R value of the auxiliary impedance corresponds to ⅔ of the positive-sequence impedance. The X value of the auxiliary impedance must be estimated from the geometry of the line. The X value of the auxiliary impedance is determined here from $\underline{Z}_0$ and $\underline{Z}_{0M}$ from the measurement in Chapter 2. The results for $\underline{Z}_0$ and $\underline{Z}_{0M}$ from Figure 2 agree very well with the results from Chapter 2. This again underlines the capability of this method to eliminate the influence of parallel lines in operation.

	Re	Im	Abs	φ in °
Z_ABC-G,Operation in Ω	0.3	2.64	2.66	83.52
Current Factor fcp	0.007	0.000	0.007	0.00
Auxiliary Impedance in Ω	0.139	2.304	2.31	86.55
Z_0,apparent in Ω	0.90	7.92	7.97	83.52
Z_0,corrected in Ω	0.90	7.95	8.00	83.51
Error Z_0,apparent	-0.54%	-0.40%	-0.40%	0.01
Z_0M in Ω:	0.70	4.50	4.55	81.19

Figure 3: Example of negligible influence of a parallel line

Figure 3 shows an example of a measurement with negligible influence of a parallel line. The estimate here is again based on the magnitude of the current factor and the assumption that the auxiliary impedance is ⅔ of the positive-sequence impedance. The zero-sequence impedance error here is estimated as less than 0.5%. This means that an accurate determination of the current factor is not necessary. However, the auxiliary impedance must be estimated as accurately as possible in order to obtain the most precise determination possible of the coupling impedance. The value of $\underline{Z}_{0M}$ in Figure 3 is, therefore, not correct.

7 Summary

The measurement described in this article has provided proof of the value of the method described in [1]. It was done by comparing a conventional measurement of a double-circuit line, in which both electric circuits had to be taken out of operation at the same time, and the measurement as proposed in [1]. As a result, double-circuit lines can now be correctly measured after commissioning, when switching off both circuits is significantly more difficult than before.

References

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

About the authors

Dr. Simon Konzelmann studied electrical engineering at the Ruhr-University Bochum from 1999 to 2004. From 2005 to 2009 he was a scientific staff member at the Institute of High Voltage Technology and EMC at TU Dortmund. From 2009 to 2011 he was with EnBW Regional AG (now Netze BW) as an electrical equipment engineer responsible for power transformers and standard design 110 kV equipment. In 2011 he moved to TenneT TSO GmbH at Bayreuth, where he held various posts before becoming team manager of TenneT maintenance and service groups in 2017, responsible for the operation of the TenneT substations in Bavaria and Hesse.

Moritz Pikisch studied electrical engineering at the Karlsruhe Institute of Technology. After working in training at OMICRON between 2010 and 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.

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