MEASUREMENT AND ANALYSIS OF ZERO-SEQUENCE CURRENT LEVELS DURING NORMAL OPERATION

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ABSTRACT

In the Netherlands, power grids and railway systems are located in close proximity over considerable lengths. Zero-sequence currents in the transmission grid may have an influence on neighbouring systems through inductive coupling. Not much is known about these currents during normal operation: Literature on the topic is scarce and modelling is complicated for various reasons.

Several measurements were analysed to obtain insight in 150 kV and 380 kV branches. Both PMU measurements and measurements using the secondary wiring of current transformers were used. The results are presented in this paper. The paper also presents a measurement uncertainty analysis. on the reconstruction of zero-sequence currents for both measurement types, indicating the influence of the measurement principles.

The considered measurements show several types of correlation between positive-sequence and zero-sequence currents.

- *The 150 kV measurements show constant zero-sequence currents that do not vary with increasing positive-sequence currents.*
- *Three of the 380 kV branches show an increase of zero-sequence currents as positive-sequence currents increase.*

All measured zero-sequence currents that have been observed are below the values used in the interference studies.

INTRODUCTION

In the Netherlands, power grids and railway systems are located in close proximity over considerable lengths due to spatial requirements and obligations. Although this has obvious spatial advantages, Electromagnetic Compatibility (EMC) has to be considered during the design phase and in case of major changes in any of these systems, for example when the transmission capacity of electrical power systems is increased. Standard interference studies are based on a set of assumptions that might be too conservative. This may lead to costly measures to mitigate calculated risks. There is a need to find a balance between ensuring good EMC and the prevention of over-dimensioned mitigating measures.

One of the considered parameters in the studies is the zero-sequence current in power systems[1]. High zero-sequence currents may have a significant impact on inductive coupling between systems. The resulting magnetic field decays less as a function of distance compared to the magnetic field of a symmetric three-phase current.

Studies of interference by high voltage connections on railway systems currently assume that the zero-sequence current is 10% of the maximum positive sequence current in normal operation. This percentage was based on one single measurement and assumed a linear relationship between the positive sequence and the zero sequence currents. This assumption often leads to significant exceedances of limits, resulting in costly measures in the railway infrastructure. The aim of this study is to obtain a better understanding and a realistic estimation.

Up to now, detailed argumentation and insight is lacking.

To model zero-sequence currents in transmission systems under all normal operating conditions is complicated due to:

- Unknown system parameters (not only network data, but also data from connected parties);
- Fluctuating load and generation and outages of components;
- The size of the area to be studied in combination with the meshed (transmission) grid;
- Metal conductors of third parties that influence the return path.

Balanced models typically used by network operators are not suitable for these type of calculations. International literature rarely considers zero-sequence currents under normal operation.

Measurements can provide more insight on:

1. The relation between zero-sequence and positive-sequence current;
2. To what extend branch loading is in accordance with the assumptions used in interference studies.

Several measurements were analysed to understand the levels and behaviour of zero-sequence currents that occur in practice under normal operating conditions:

A. 150 kV: Zero-sequence current measurements were analysed for a set of two 150 kV branches in the Netherlands. These current measurements were performed by measuring the currents on the secondary side of the current transformers that are connected to the 150 kV side[2].

B. 380 kV: Some 380 kV branches in the Netherlands are continuously monitored using a phasor measurement unit (PMU) system. The advantage of PMU measurements is that both phase angle and amplitudes are recorded. This enables a full reconstruction in symmetric components of a circuit. The analysed locations were chosen on the basis of existing cases with possible interference.

Note that these measurements are a snapshot at a selected number of locations. Although they provide much insight it is not possible to draw conclusions for other locations and / or other operational conditions in the grid.

MEASUREMENT PRINCIPLES

A: 150 kV measurements using the secondary wiring of existing current transformers

Existing current transformers are installed for protection and control. Current clamps were installed to measure the three phase currents and the zero-sequence current directly (see Figure 1). The current clamps were connected to a four-channel digital oscilloscope to record the currents.

The substation that was chosen for the measurements is connected by two 150 kV branches, which consist of a combination of overhead lines and underground cables. On the substation, there are three 150/10 kV power transformers and two 150/25 kV single-phase transformers[1] present. Measurements were performed during 250 hours on both branches.

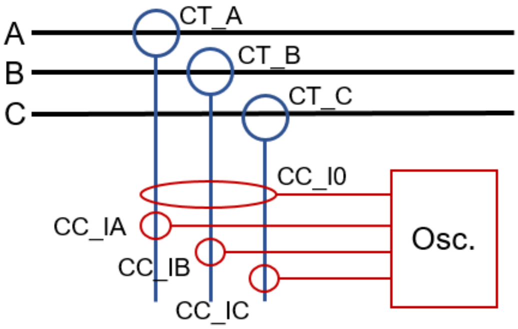

Figure 1: Schematic overview of the 150 kV measurement. Four current clamps are connected to the oscilloscope, three for each phase current and one to directly measure the zero-sequence current.

B: 380 kV measurements using PMU-systems

A PMU system records phase currents in a similar way to the way the measurements were performed in the 150 kV-case. Here, current transducers are connected to the secondary leads of the current transformers, but there is no direct measurement of the zero-sequence current. The zero-sequence current is determined by summing the three phase currents.

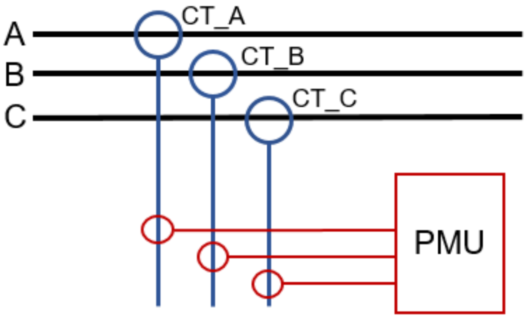

Figure 2: Schematic overview of the 380 kV PMU measurements.

In total, three PMU systems were available to extract the measurements from. Each PMU system is connected to two 380 kV branches.

USING PMU-MEASUREMENTS TO RECONSTRUCT SYMMETRIC COMPONENTS

Several authors report the use of PMU measurements to assess the imbalance in power systems [3], [4]. These contributions mainly look at the theoretical aspects of imbalance (albeit inverse or zero-sequence unbalance) on the performance of the PMU system.

Since PMU systems provide measurements of both the magnitude and phase angle of all phases, it allows for the full decomposition into symmetrical components[1]:

$$\begin{bmatrix} I_+ \\ I_- \\ I_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_A e^{j\varphi_{I_A}} \\ I_B e^{j\varphi_{I_B}} \\ I_C e^{j\varphi_{I_C}} \end{bmatrix}$$

WhereI_+, I_- and I_0 are the positive-sequence, negative-sequence and zero-sequence current components, respectively, $\alpha = e^{j\frac{2\pi}{3}}$ is a mathematical rotation over $\frac{2\pi}{3}$ radians and $I_A \ldots I_C$ are the magnitudes and respective phase angles.

By choosing one of the phase angles as the canonical angle (for instance, phase A), a symmetric component reconstruction can be made, where the other angles are defined by the difference in phase angle with respect to phase A.

When no phase angle information is available, but the three phase magnitudes are available, one can choose to assume a phase angle difference of 120° between phases.

1 These single-phase transformers are connected between two 150 kV phases to feed a railway system. Because of the way these are connected, these transformers do not give a contribution to the zero-sequence current.

MEASUREMENT UNCERTAINTY ANALYSIS

Using the known measurement accuracies of the different components in the measurement chain, a measurement uncertainty analysis was carried out, using Monte Carlo simulations. This type of simulations uses randomly generated values (e.g. errors) to determine the statistical distribution of possible outcomes by performing many iterations of a simulated physical process. In this case, a predetermined zero-sequence current is injected into the system and the statistical distribution of the outcomes is plotted for different load currents. The following inaccuracies of the measurement system are taken into account in the uncertainty analysis:

[For both the 150 kV and 380 kV measurements]:

- The ratio error of the primary current transformers;
- The phase angle error of the primary current transformers;

[A: For the 150 kV measurements]:

- The measurement uncertainty of the current clamps;
- The input error of the oscilloscope;

[B: For the 380 kV measurements]:

- The Total Vector Error (TVE) of the PMU system.

Measurement errors were modelled as a uniform distribution. The current values were chosen to represent typical current values that were observed during measurements.

A: 150 kV measurements (direct measurement of zero sequence currents)

The current transformers installed are class 0.2[5]. The accuracy of the current clamps is 1%, the accuracy of the oscilloscope is 0.2%, determined by measurements.

B: 380 kV measurements (PMU measurements)

The current transformers installed are class 0.2s[5], the PMU system has a maximum Total Vector Error (TVE) percentage of 1%.

The simulations show that the measurement median lies around the input value, except for a input zero-sequence current of 0 A. The width of the distribution (the difference between the highest measured value and lowest measured value) is greater for higher zero-sequence currents and higher load current. Comparing both measurement strategies, the direct measurement of I_0 (i.e. the 150 kV measurements) yield the smallest measurement uncertainty. This is especially the case at relatively low values of I_0.

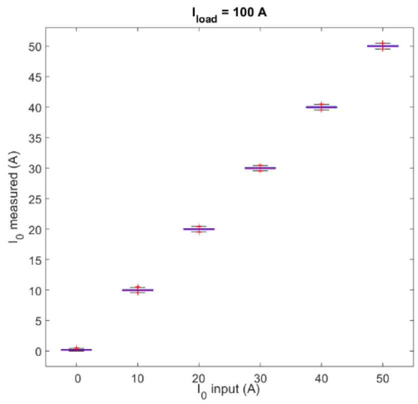

Figure 3: A: Distribution of outcomes for direct zero-sequence current measurements at a positive-sequence current of 100 A.

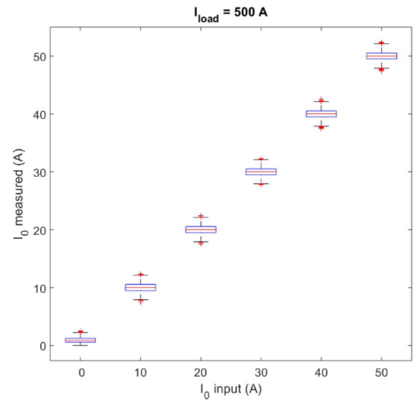

Figure 4: Distribution of outcomes for direct zero-sequence current measurements at a positive-sequence current of 500 A.

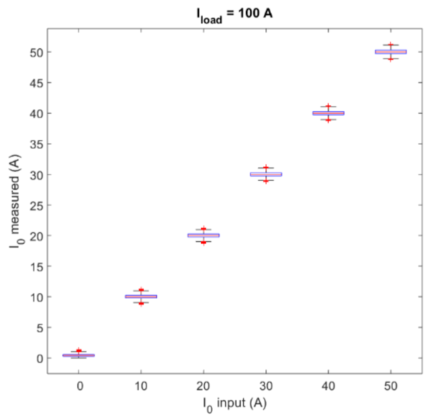

Figure 5: Distribution of outcomes for indirect zero-sequence current measurements at a positive-sequence current of 100 A.

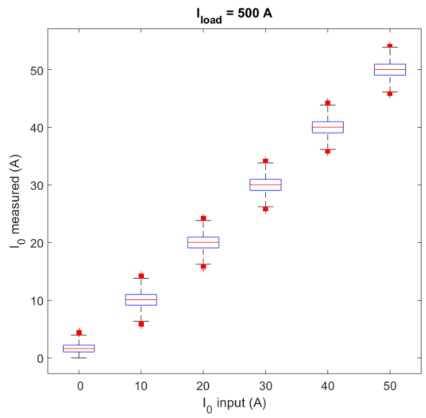

Figure 6: Distribution of outcomes for indirect zero-sequence current measurements at a positive-sequence current of 500 A.

MEASUREMENT RESULTS

The figures in this chapter present the outcomes of the analysed measurements. For clarity, the number of analysed samples were limited to 100 per plot, so that one point corresponds to 1% of the measurement time during the considered period. As shown in Figure 8, the sampled data accurately represent the complete data set.

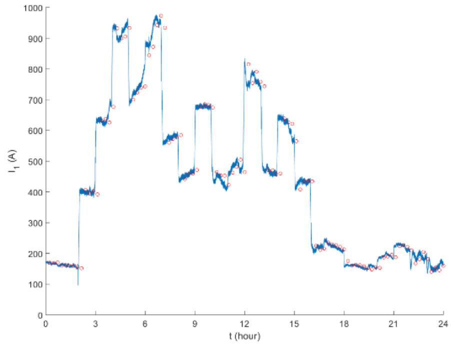

Figure 7: Graphical illustration of the data sampling for one day of data. The plot shows the complete data set in blue and the sampled data used in the analysis in red.

A: Measurement outcomes 150 kV (2 branches)

A plot of each branch shows the measured positive-sequence currents and its corresponding zero-sequence value at that time plotted in blue points

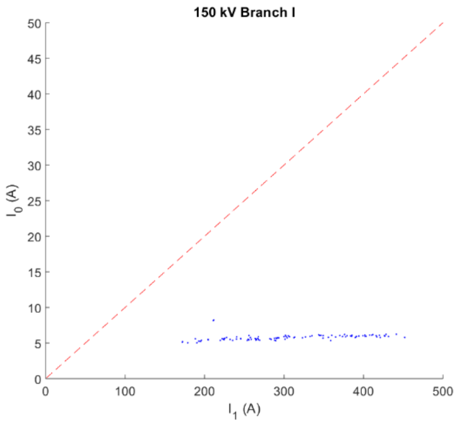

Figure 8: Measurement outcomes for 150 kV branch I during the measurement time of 250 hours.

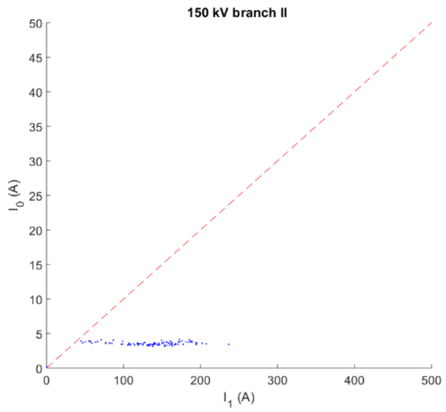

Figure 9: Measurement outcomes for 150 kV branch II during the measurement period of 250 hours.

The plots also show the corresponding line of 10% zero-sequence unbalance using a dashed red line.

The measurements show a flat correlation of the zero-sequence currents as a function of positive-sequence current, indicating a constant zero-sequence current.

B: Measurement outcomes 380 kV (4 branches)

For the 380 kV measurements data of approx. 1 month was analysed. The figures presented here show the results of the day with the highest I0 during that period.

The measurements show a positive correlation between zero-sequence currents and positive-sequence currents. An increase in positive-sequence current is correlated with an increased zero-sequence current

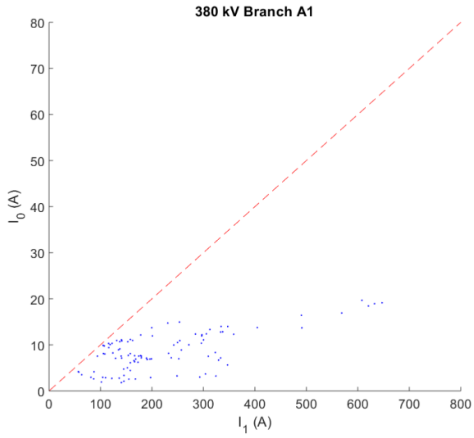

Figure 10:Measurement outcomes for 380 kV branch A1.

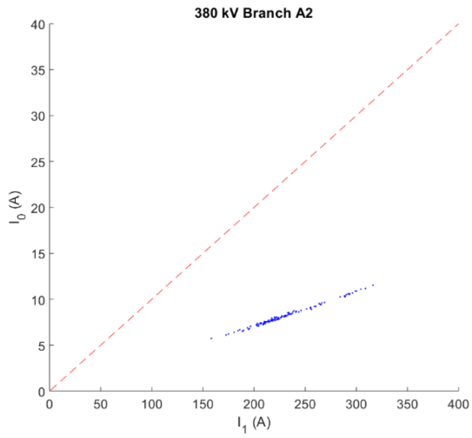

Figure 11: Measurement outcomes for 380 kV branch A2.

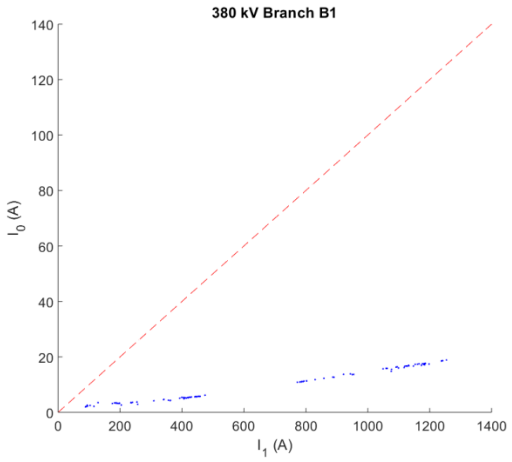

Figure 12: Measurement outcomes for 380 kV branch B1.

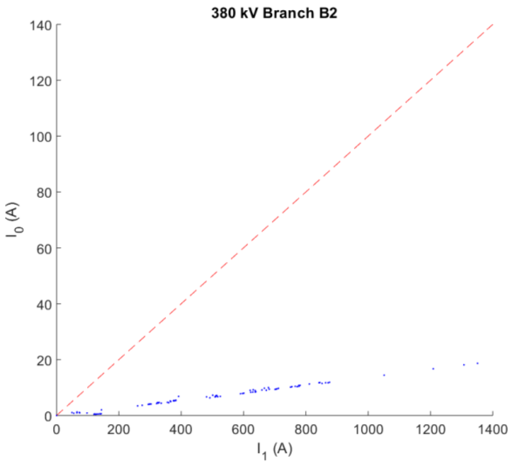

Figure 13: Measurement outcomes for 380 kV branch B2.

CONCLUSIONS AND FUTURE ACTIVITIES

Using existing measurement systems and purpose installed systems, measurements were used to increase understanding of zero-sequence currents that occur in practice during normal operation. Based on this, the following conclusions can be drawn:

1. The considered measurements show several types of correlation between positive-sequence and zero-sequence currents.
    a. The 150 kV measurements show constant zero-sequence currents that do not vary with increasing positive-sequence currents.
    b. Three of the 380 kV branches show an increase of zero-sequence currents as positive-sequence currents increase. The highest measured slope is around 4%.
2. For high positive-sequence currents, the determination of the (relatively low) zero-sequence current is complicated due to measurement uncertainty.
3. In no cases zero-sequence currents have been observed in the order of the assumed maximum zero-sequence currents used at this moment in interference studies.

The above mentioned aspects will be used to achieve realistic basic assumptions for future interference studies.

FUTURE ACTIVITIES

In this research, only the currents flowing in the phase conductors have been studied. In reality, the phases of zero-sequence currents can be different and there will be induced currents in lightning wires and through the earth. These effects need to be taken into account in interference studies. This will be included in the continuation of this research.

Using the uncertainty analysis, the biggest influencing factors on measurement uncertainty will be identified.

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