# CIRED
## 20th International Conference on Electricity Distribution
## Prague, Czech Republic
8-11 June 2009


Paper Title:

**Measurement of line impedance and mutal coupling of parallel lines to improve the protection system**


Authors:

Lutz Hulka

Ulrich Klapper

Markus Pütter

Wolfgang Wurzer

# MEASUREMENT OF LINE IMPEDANCE AND MUTUAL COUPLING OF PARALLEL LINES TO IMPROVE THE PROTECTION SYSTEM

Lutz HULKA Ulrich KLAPPER Markus PÜTTER Wolfgang WURZER
Lutz.Hulka@omicron.at Ulrich.Klapper@omicron.at Markus.Puetter@omicron.at Wolfgang.Wurzer@omicron.at

all with OMICRON electronics GmbH – Austria

## *ABSTRACT*

*Reliability of transmission widely depends on the reliability of the applied protection system. It is obvious that the main requirements for the protection system are that it is safe, selective and fast. In the case of distance relays, these requirements can only be fulfilled when the mechanisms called "Earth Impedance Compensation" and "Mutual Coupling Compensation" work sufficiently.*
*The life cycle management of transmission line protection requires proper setting and testing of the selected relays under conditions that as closely as possible match the real system parameters. Calculations of line impedances and mutual coupling are not sufficient to meet these requirements. Changes in the system configuration due to addition of new transmission lines that are on the same right-of-way require updates in the system model, re-calculation of the relay settings, checking of the relay's coordination with these new settings, as well as their re-testing*

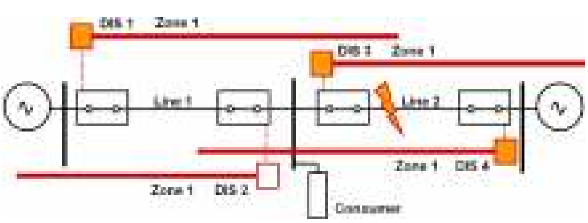


*Figure 1 –Relays with zone 1 over-reach, consumer is cut off from power because of wrong setting of the Earth Impedance Compensation factor*

*A substantial error in the k-factor will cause zone over- or under-reaches, so the high effort that was invested in the protection system does not pay off. This means that the fault is not cleared as fast as it could be because of one single relay setting. The way overhead lines are constructed regarding symmetry has a significant impact on the quality of the protection system.*
*Various measurements that have been performed by the authors on more than 50 real overhead lines or power cable installations show two things:*

- *The error of the set k-factor is in average 63% related to the real value; therefore the lines are not properly protected. Wrong anticipations on the power lines or problems when calculating the k-factors are the main reasons for this.*
- *Generally lines are much more asymmetric than anticipated by the protection engineers. Transposing of power lines is not done often, especially for short overhead lines. The k-factors for the different phases of the systems differ considerably in many cases so that proper settings are almost impossible. Individual k-factor settings per phase in upcoming relays might be a solution to this problem.*

*The problem of asymmetries is even bigger between systems which result in a more error prone calculation of k-factors for mutual coupling settings. The theory that every phase of one system couples identically into every phase of the other system is simply not the case on most lines.*
*The paper discusses the effects found by measurements on several overhead lines and power cables in various countries in four continents and also points out how important transposing is not only for system symmetry regarding power flow but also for proper system protection. Ideas of introducing individual k-factors per phase for distance protection are another contribution for discussion.*

## INTRODUCTION OR WHAT IS THE K-FACTOR?

To protect an overhead line or a power cable protective relays are needed. When a fault occurs on the line, such as an arc between phases or against ground, it has to be cleared safe, selective and fast. Selectivity means that the line is only switched off, if the fault is really on this specific line [1].
There are two basic methods to obtain selectivity on power lines, differential protection or distance protection. The better principle is the first one, but there is by far more effort involved, because the relays on both ends of the line need to communicate with each other. This paper does not further discuss this method. For cost reasons on most power lines distance protection relays are used.
One of the most important settings of a distance protection relay is the Positive Sequence Impedance, which is half of the complex impedance of the phase to phase loops.
When a fault occurs the distance relays on both ends measure the impedance. If the impedance is (typically)

below 80% or 90% of the line impedance they switch off as fast as possible (zone 1), because it is for sure that the fault is on this specific line. If the impedance is higher the relay switches off delayed (≥ zone 2), to give another relay that might be closer to the fault the chance to clear it before.

On faults of one or more phases against ground, the impedance of the fault loop is different. Because the impedance of the ground path, or to be more precise, of this line to ground loop, is different, a factor within the relay gives the relation between the line to line and the line to ground impedances. This factor has many names, it's called ground impedance matching factor, residual compensation factor, earthing factor or simply k-factor, as it is often referred to.

If the impedances or k-factors of a relay are not set properly, zone over- or under-reaches will occur [2]. Besides the damage of customers having no power, the risk of loosing system stability becomes also higher by such false trips.

## K-FACTOR DEFINITION

Unfortunately the standard k-factor does not exist. There are various formats available; the three principal types are discussed here. All formats of k-factors can be considered to be constants for a particular line and are generally independent of its length. They express the relationship between the impedance of a phase to phase loop and that of a phase to ground loop. Half of a phase to phase loop (i.e. the impedance of one line) for fully transposed (symmetrized) lines is referred to as the Positive Sequence Impedance $Z_1$. Three times the impedance of the ground loop consisting of the three phase conductors - which have to be in parallel - and the earth return path is referred to as Zero Sequence Impedance $Z_0$. Three times to reflect the single phase model. In order to circumvent the principally necessary, but complex calculation with symmetrical components it is convenient and approved practice to split the loop impedance into two parts: The “line impedance” $Z_L$ and an “earth return path” $Z_E$ (Figure 2).

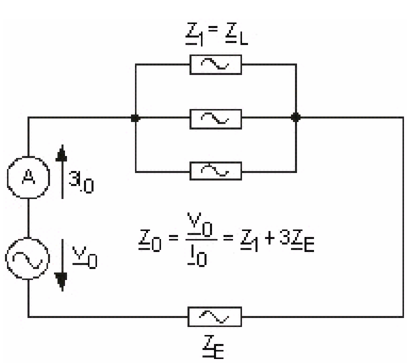


Figure 2 – Equivalent Diagram

As can be shown, the “line impedance” $Z_L$ can be assigned to the positive symmetrical impedance $Z_1$.

$$\underline{Z}_L = \underline{Z}_1 \tag{1}$$

One can interpret the line to ground loop impedance as a series connection of the a.m. “line impedance” $Z_L$ and a ground (or “earth return path impedance” $Z_E$).

One definition of the Ground Impedance Matching Factor $k_E$, $k_L$, $k_{E0}$ or sometimes called only $k_0$-factor is given below:

$$\underline{k}_E = \underline{k}_L = \underline{k}_{E0} = \frac{\underline{Z}_E}{\underline{Z}_L} = \frac{1}{3}\left(\frac{\underline{Z}_0}{\underline{Z}_1} - 1\right) \tag{2}$$

From Figure 2 it can be seen that:

$$\underline{Z}_E = \frac{\underline{Z}_0 - \underline{Z}_1}{3} \tag{3}$$

Defining the ground impedance this way, can obviously lead to stunning, strange looking results of $Z_E$, if the line to ground loop inductance is smaller than the phase to phase inductance. This is the case on some power cables when the shield is grounded on both ends and is close to the conductors if they are relatively far apart (and the shields are not cross bonded). This fact does not concern the theme of the paper but is important to note.

Another format is the complex ratio of the Zero Sequence Impedance to the Positive Sequence Impedance. Sometimes this factor like $k_{E0}$ is also called $k_0$ only, which may become confusing. To avoid misunderstandings we call it $k_{Z0}$ here.

$$\underline{k}_{Z0} = \frac{\underline{Z}_0}{\underline{Z}_1} \tag{4}$$

Splitting the complex impedances $Z_E$ and $Z_L$ into their real and imaginary parts 'R' and 'X' allows defining ratios. This is the third commonly used definition.

$$\frac{R_E}{R_L} \text{ and } \frac{X_E}{X_L} \tag{5, 6}$$

It is certainly possible to convert the different formats [3] however one has to be careful how a k-factor is defined before using it.

Distance protection relays use algorithms that make use of these different k-factors to convert all phase to ground faults, so they can be assessed as if they were phase to phase faults. This allows the same zone polygons to be used independently of the line geometry. Because different relays use different algorithms, identically measured voltages and currents can lead to different impedances depending on the algorithm used.

Details of these algorithms [4] are not discussed any further in this paper; it is suffice just to mention that the entry format of the k-factor does not allow deducting which algorithm is used by the relay.

## CALCUALTION VERSUS MEASUREMENT OF LINE IMPEDANCES AND K-FACTORS

Up to now the effort to measure line impedances and k-factors was so high, that it has hardly been done. To obtain the data needed they had been calculated manually, or by using appropriate software tools [5].
A lot of parameters needed to calculate the line impedance have to be taken into account.
The geometrical configuration is needed (Figure 3):

- height above ground and horizontal distance for each phase conductor and each ground wire
- average sag of the line and ground wires at mid-span

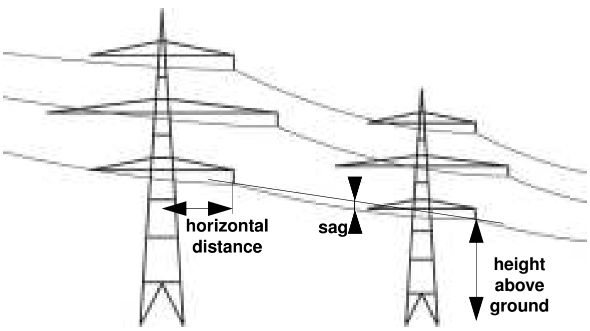


Figure 3 – Overhead line geometrics

Several electrical parameters have to be known:

- ground/soil resistivity ρ
- DC resistance of all conductors
- spiralling construction of the conductors
- geometrical mean radius of the conductors
- overall diameter of the conductors

Similar parameters are needed for calculating line impedances of power cables, on a first glance they might seem even simpler, but when this is the case for new cables it might be the opposite for old installations where often a mixture of different cable types is used – not documented too well quite often.
In general, the calculation of the Positive Sequence Impedance works quite well and sufficient. For the Zero Sequence Impedance calculations are also sufficient as long as the ground wire is a good one. When the ground wire or shield is not a very good conductor and a large component of the fault current is flowing back through the soil, things tend to become complicated. The influence of the ground/soil resistivity ρ and the accurate distance of the wires above ground, are growing and both are very difficult to determine along the whole length of the line (especially in complicated landscape geometry).
Another cause for concern is that a huge number of parameters are involved in the calculation of line parameters. If one parameter is wrong this might cause a substantial error. In the Positive Sequence Impedance there are several, but even more prone to error is the Zero Sequence Impedance or k-factor, because they need parameters for their calculation.
Compared to the calculation the measurement of line parameters including the k-factors is nowadays relatively simple. Using lightweight variable frequency sources suppression of noise is easy by measuring with frequency selective filters.
In the period from June 2004 to April 2007 we have compared the calculated versus the real line impedances and k-factors on 30 overhead lines and underground cable installations on voltage levels from 20 to 200 kV. Lines with lengths between a few hundred meters up to 270 km have been measured on four continents.
For the common k-factor formats the deviation between calculation and measurement has been compared (Figure 4). Just exemplary the reactive component of one format $X_E/X_L$ that is especially important for distance calculation had an error bigger than 20% on 70% of the lines! Certainly this does not mean an error of more than 20% when calculating the faults distance but still the error will be significant.

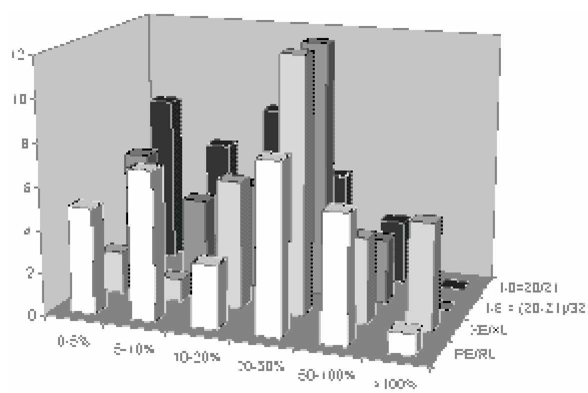


Figure 4 - Deviation of k-factors between calculation and measurement on 30 lines measured

Up to now we did not carry out in depth investigations how well set mutual coupling impedances do reflect the real situation. However we assume it will not be much better than the results discussed above. Maybe we can report about such comparisons in the coming years.

## LINE SYMMETRY

Another assumption that was made in all the considerations up to this point is that the power lines are fully transposed and therefore perfectly symmetrical.
As can be seen in Figure 5 on non transposed lines the phase to phase loops will enclose different areas between the conductors and as this influences the inductance of the loop considerably, the different loops have different impedances. The system becomes asymmetrical.

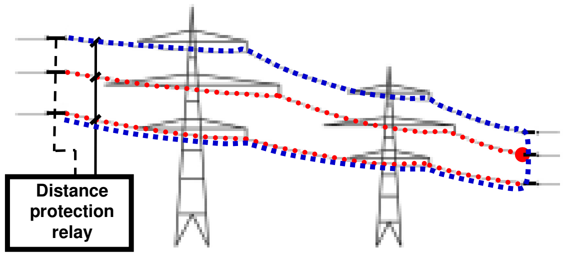


Figure 5 - Different Positive Sequence Impedance loops

In the period from November 2003 to August 2007 we have made investigations on 54 overhead lines and underground cables on voltage levels from 10 to 400 kV regarding symmetry.

As can be seen in Figure 6 almost 30% of all lines measured have an asymmetry on the reactance X of the three line to line (L-L) loops of more than 10%. The biggest deviation of the three values found was 35%! Protecting these 30% of lines with protective relays that make use of a single positive sequence impedance setting is problematic. The line to earth (L-E) fault loops are slightly better symmetrical, but still more than 25% of the lines differ more than 5% between the phases.

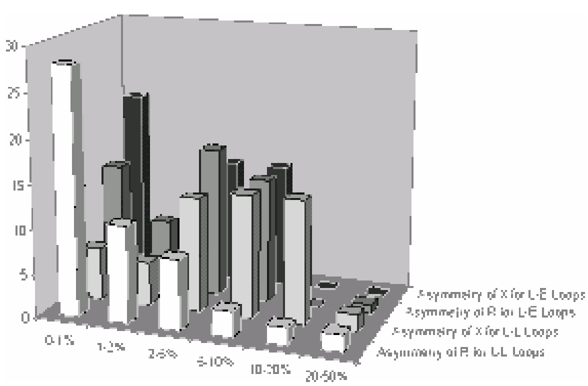


Figure 6 - Asymmetries found on 54 lines measured

The above asymmetries need to be taken into consideration when setting the distance relays in order to avoid mal-operation. Protection relays with settings based on the 3x3 impedances matrix may need to be considered.

## CONCLUSION

Measurements on more than 50 power lines around the globe show that power lines are far from being symmetrical. The logical consequence of this research seems to be that upcoming generations of protective relays will have individual impedance setting for all possible fault loops.

Verifications of line impedances and k-factors on 30 randomly chosen power lines on various voltage levels in different companies show that the calculated values reflect the real values only very poorly.

The poor quality of the relay settings that seem to be reality today can easily be overcome when the line parameters are measured to verify or replace the calculations.

With the state of the art measurement techniques for line impedance the effort to perform the measurements is only a share of what it used to be. By using frequency shift technology and frequency selective filtered measurement inputs the noise reduction can easily be achieved with portable equipment.

More complex relay settings should be implemented in future relays to take line asymmetries into account. This should become reality with modern line impedance measurement devices making it easy to obtain the proper relay parameters. Measurements instead of calculation should reduce some problems for the protection engineer of the future.

## BIBLIOGRAPHY


[1] W. Doemeland, *Handbuch Schutztechnik*, Huss-Medien GmbH, Berlin, Germany, 48-49

[2] U. Klapper, 2005, "Reliability of Transmission by Means of Line Impedance and k-Factor Measurement", *CIRED 2005, 18th International Conference and Exhibition on Electricity Distribution,* 6-9 June 2005, Turin - Italy

[3] W. Wurzer, 2007, "Measurement of Line Impedances and Mutual Coupling of Parallel Lines", *CIGRE Conference on Relay Protection and Substation Automation in Modern Power Systems,* September 2007, Cheboksary - Russia

[4] S. Kaiser, 2004, "Different Representation of the Earth Impedance Matching in Distance Protection Relays" *Proceedings OMICRON User Conference* in Germany 2004, OMICRON electronics GmbH, 11.1-11.5

[5] A. Dierks, 2004, "Accurate Calculation and Physical Measurement of Transmission Line Parameters to Improve Impedance Relay Performance" *Proceedings Southern African Power System Protection Conference*, Eskom Enterprises, 143-149

[6] J. Neufert, 1996, *Induktive Kopplung bei Doppelleitungen* Technische Universität Berlin, Fachbereich Elektrotechnik, 83-84

**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.

Customers in more than 130 countries rely on the company's ability to supply leading edge technology of excellent quality. Broad application knowledge and extraordinary customer support provided by offices in North America, Europe, South and East Asia, Australia, and the Middle East, together with a worldwide network of distributors and representatives, make the company a market leader in its sector.


**Americas**
OMICRON electronics Corp. USA
12 Greenway Plaza, Suite 1510
Houston, TX 77046, USA
Phone: +1 713 830-4660
+1 800-OMICRON
Fax: +1 713 830-4661
info@omicronusa.com

**Asia-Pacific**
OMICRON electronics Asia Limited
Suite 2006, 20/F, Tower 2
The Gateway, Harbour City
Kowloon, Hong Kong S.A.R.
Phone: +852 2634 0377
Fax: +852 2634 0390
info@asia.omicron.at

**Europe, Middle East, Africa**
OMICRON electronics GmbH
Oberes Ried 1
6833 Klaus, Austria
Phone: +43 5523 507-0
Fax: +43 5523 507-999
info@omicron.at