RELIABILITY OF TRANSMISSION BY MEANS OF LINE IMPEDANCE AND K-FACTOR MEASUREMENT

Ulrich KLAPPER, Michael KRÜGER, Steffen KAISER
OMICRON electronics GmbH - Austria
ulrich.klapper@omicron.at

INTRODUCTION

Distance relays are important elements for the reliability of electrical power transmission. The Positive Sequence Impedance and the Ground Impedance Matching Factor, or k-Factor, as it is often referred to, are some of the most important settings of such a relay. Should one of these settings be done improperly, the whole investment in protection from instrument transformers over the relay up to the circuit breaker is not used as efficient as it could be.

This paper explains the difficulty of k-Factor settings and points out cost effective solutions for preventing incorrect behaviour of distance protection schemes.

IMPORTANCE OF K-FACTORS

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 very 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 (FIGURE 1).

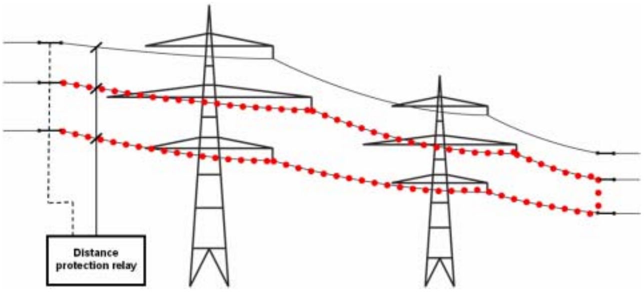

FIGURE 1 – Impedance loop between two phases

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 very 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 (FIGURE 2). Because the impedance of the ground path, or to be more precise, of this ground loop, is different, a factor within the relay gives the relation between the line and the ground impedance. This factor is called ground impedance matching factor or simply k-factor, as it is often referred to.

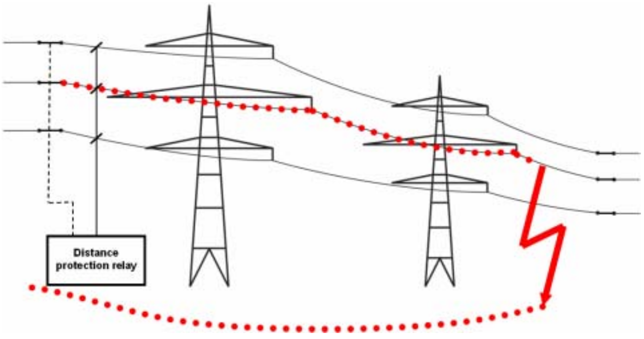

FIGURE 2 – Impedance loop on a single phase ground fault

If the relay settings are done properly a customer that is supplied from two ends (FIGURE 3) continues to receive energy from one line if the other trips.

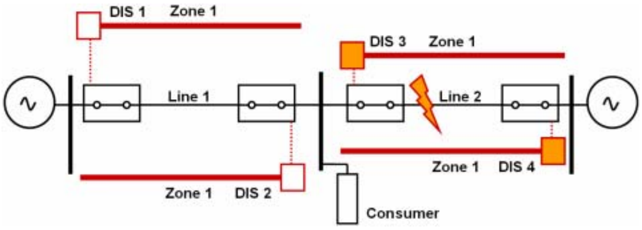

FIGURE 3 – Relays with optimum zone 1 reach

If the impedances or k-factors of a relay are not set properly, zone over- or under-reaches will occur (FIGURE 4).

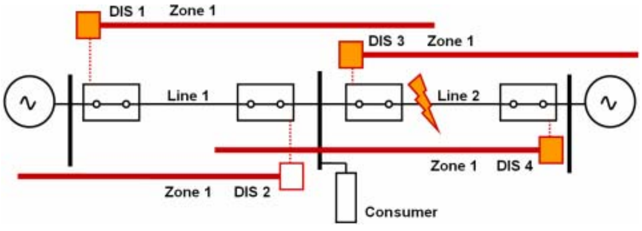

FIGURE 4 – Relays with zone 1 over-reach

In the example above three relays instead of two see the fault in zone 1 and trip, a second power line is dead. The customer is cut off power for no reason. Besides the damage of customers having no power, the risk of loosing system stability becomes also higher by such false trips.

DIFFERNET K-FACTOR FORMATS

Unfortunately *the* k-factor does not exist. There are various formats out there; the three major types are discussed here. For all types it is to say that they are constants of the line, in general independent from the length. They express the relationship of the impedance of a phase to phase loop and a three phase to ground loop. The half of a phase to phase loop (i.e. the impedance of one line) is referred to as Positive Sequence Impedance $\underline{Z}_1$; three times the impedance of a three phase to ground loop is referred to as Zero Sequence Impedance $\underline{Z}_0$.

One common format is the complex ratio of the Zero Sequence Impedance and the Positive Sequence Impedance.

$$\underline{k}_0 = \frac{\underline{Z}_0}{\underline{Z}_1} \tag{1}$$

Because $\underline{Z}_1$ is the impedance of one line it is also named $\underline{Z}_L$ quite often.

$$\underline{Z}_L = \underline{Z}_1 \tag{2}$$

The ground (or British "earth") impedance $\underline{Z}_E$ can be calculated from the Zero Sequence Impedance as follows:

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

Defining the ground impedance this way, obviously leads to strange results with a negative inductive component in $\underline{Z}_E$, as soon as the three-phase to ground inductance is much smaller than the inductance between two phases. This is the case on some power cables when the shield is close to the conductors but the conductors are relatively far from each other. This fact is of no further concern; it is just good to know that it can happen.

Another possibility to express the relationship is the ratio of ground to line impedance.

$$\underline{k}_L = \frac{\underline{Z}_E}{\underline{Z}_L} \tag{4}$$

$\underline{k}_E$ or unfortunately even also $\underline{k}_0$ are other common names for this definition. One has to be careful how a k-factor is defined before using it.

Splitting the complex impedances $\underline{Z}_E$ and $\underline{Z}_L$ into their real and imaginary parts R and X lead and defining real ratios, leads to the third commonly used definition.

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

Conversions between the different k-factor formats are possible.

$$\underline{k}_0 = 1 + 3\underline{k}_L \tag{7}$$

For converting from the format (5) and (6) to the other formats the other line constants (or at least the line angle) have to be known.

$$\underline{k}_L = \frac{R_E / R_L}{1 + jX_L / R_L} + \frac{X_E / X_L}{1 - jR_L / X_L} \tag{8}$$

The line angle can be used to obtain the ratio X_L / R_L that is needed for the conversion in (8).

$$\tan(\varphi_L) = X_L / R_L \tag{9}$$

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

Details of these algorithms [2] are not further discussed in this paper; it is only to mention that the entry format of the k-factor does not allow deducting which algorithm is used by the relay.

CALCUALTION OF 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 [3] like PowerFactory from DIgSILENT, PSS from Shaw PTI or CAPE from Electrocon.

The parameters needed to calculate the line impedance are many.

The geometrical configuration is needed (FIGURE 5):

- 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

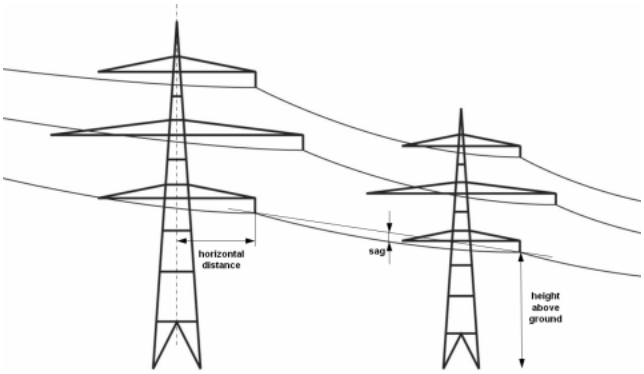

FIGURE 5 – Overhead line geometrics

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 it can be said that the calculation of the Positive Sequence Impedance works quite well and sufficient for the Zero Sequence Impedance as long as the ground wire is a very 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.

On several occasions when our team found wrong relay settings it was the Zero Sequence Impedance or the k-factor that was set wrong. But we also had the situation that two similar lines were just mixed up.

MEASUREMENT OF K-FACTORS

Compared to the calculation the measurement of line parameters including the k-factors is nowadays relatively simple.

FIGURE 6 – Test equipment for line impedance measurement

The test set CPC 100 and CP CU1 from OMICRON comprising a frequency variable amplifier (29 kg), a coupling unit (28 kg) and a protection device (6 kg) is all that is needed for the measurement (FIGURE 6).

The CPC 100 is a multi functional, frequency variable test set for various tests on primary equipment. It is capable of generating currents up to 800 A or voltages up to 2000 V, with special software modules it can be used for various automated tests on CTs, VTs, power transformers or other primary equipment. With other accessories it can also be used i.e. for tangent delta testing on power transformer bushings or windings with test voltages up to 12 kV. In the application of line impedance measurement it is used as frequency variable power generator, measurement tool and analyzer. Due to the variable frequency generation it is possible to generate signals first under then over mains frequency. Using digital filter algorithms allows measuring frequency selective at the frequency that is currently generated, this means all other frequencies but the generated one are filtered out. Disturbances at mains frequency are thus no longer influencing the result.

The coupling unit CP CU1 is used for galvanic decoupling of the generated signals in output direction and analyzed signals in input direction. The decoupling is needed mainly for safety reasons. For optimum performance there is also a range selector switch and for a quick check of induced voltages or burden a built in voltmeter.

The protection device CP GB1 is a tool for easy connection to the overhead line or power cable, existing grounding sets of the substation may be used. In case of unexpected high voltage on the power line due to faults on a parallel system, lightning discharges or transients due to switching operations, the GB1 is capable of discharging short transients or permanently shorting fault currents of up to 30 kA for at least 100 ms. These features allow the user safe operation even in critical situations.

The measurement is performed with currents between 1 and 100 A depending on the line length. Using frequency selective measurement allows using currents in the size of a fraction of the nominal currents. Anyway higher currents mean higher accuracy therefore the biggest current possible is chosen. Measurements on lines up to 270 km have been performed so far.

Overall seven measurements per system are made, three for each combination of phase to phase loops, three for each phase against ground and one for all three phases against ground. There is some redundancy in these measurements, allowing reliability crosschecks and calculation of individual k-factors for each phase. The latter seems strange at a first glance, but especially for short lines often not too much care is taken having a symmetrical line, leading to quite different values for the phases. Knowing about the problem allows tending rather to smaller k-factors to avoid zone overreaches in all cases.

The results can be loaded into Microsoft Excel allowing easy post processing; the results are displayed in a format fit for direct usage for relay settings (FIGURE 7).

Impedance results:	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
Positive sequence impedance Z_1	2,500	10,000	10,308	-0,15°
Zero sequence impedance Z_0	5,500	25,000	25,598	77,59°
Overall Ground Resitance Matching Factor:			**[1]**	
$k_L = Z_E / Z_L$			0,495	2,73°
R_E / R_L and X_E / X_L			0,400	0,500
$k_0 = Z_0 / Z_1$			2,483	77,75°

FIGURE 7 – Major measurement results

CASE STUDY

A measurement on a 400 kV overhead line with a total length of 22 km has been performed in June 2004 at a large utility that sells over 180 000 GWh of electrical energy per year to its customers. The name of the utility is withheld because of data protection.

The reason for the test was a false trip that was subject to closer investigation.

FIGURE 8 – First tower of the 22 km - 400 kV line

The whole measurement had to be done within one hour, because the line was not available for a longer period. The measurement could be performed without problems; the chosen test current was 10 A.

Looking at the frequency response it was obvious, that the results taken at 50 Hz, which was the local mains frequency, were useless.

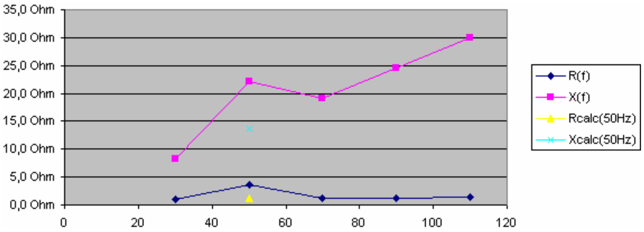

FIGURE 9 – Measured impedance versus frequency in Hz

Most interesting was the comparison of the measured results versus the settings in the distance relay.

Settings of the relay	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
Positive sequence impedance Z_1	0,542	7,019	7,040	85,58°
Zero sequence impedance Z_0	6,692	23,822	24,744	74,31°
Measured results	**R [Ω]**	**X [Ω]**	**Z [Ω]**	**Phi (°)**
Positive sequence impedance Z_1	0,587	7,128	7,152	85,29°
Zero sequence impedance Z_0	4,623	16,067	16,718	73,95°

FIGURE 10 –Relay settings versus measurement results

The Positive Sequence Impedances matched perfectly, but the Zero Sequence Impedance showed a deviation of 48%. Another re-evaluation of calculation showed, that the type of the ground wires used, was not entered correctly into the system, once corrected the calculation matched the measurement for the zero sequence as well.

The correctness of the calculation was not questioned before a false trip occurred, even then the error was not found. Once the measurement showed that only the Zero Sequence Impedance was involved the range to search for the error was narrowed and so it was finally found. The company where the test has been performed plans to purchase several of these test sets this year to perform measurements, at least on their most important lines.

CONCLUSION

Nowadays the costs and effort for k-Factor measurements are a fraction of what they used to be. Measurements showed that for several reasons calculations often gave wrong results. Therefore, most likely measurement and calculation will be done in future. Save, selective and fast failure clearance is only possible, if all relay parameters are set properly. Line impedance and k-Factor are of highest importance for a fully operational distance protection relay.

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