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K-FACTOR MEASUREMENT OF CABLES FOR OPTIMUM RELIABILITY OF DISTANCE PROTECTION AND FAULT LOCATORS

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ABSTRACT

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 incorrect, the whole protection system, including the instrument transformers, the relay and the circuit breaker, is not used as effectively as it could be.

This paper explains the difficulty of making the k-Factor settings and illustrates cost effective solutions for preventing incorrect behavior of distance protection schemes.

IMPORTANCE OF K-FACTORS

Protective relays are needed to protect a power cable or an overhead line. When a fault occurs on the line, such as an insulation breakdown, it has to be cleared safely, selectively and quickly. Selectivity means that only the line on which the fault is located is switched off, thus minimizing the outage.

There are two principal methods to obtain selective tripping on power lines, these are differential protection and distance protection. Differential protection is often considered to be a better solution but is dependent on the availability of a secure communication channel because the relays at each end of the line need to communicate with each other. Furthermore, differential protection does not provide back-up protection. This paper does not discuss this method further. For cost reasons and because of the lack of back-up protection, 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 strictly applicable only for fully transposed (symmetrized) lines and is half of the complex impedance of the phase to phase loops (Figure 1).

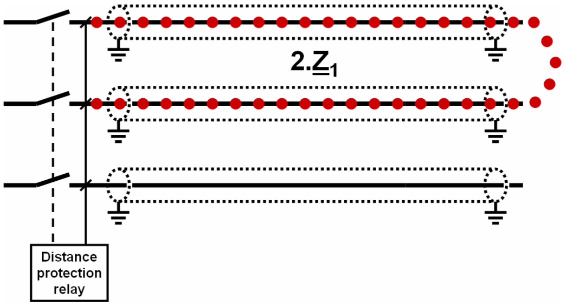

Figure 1: Impedance loop between two phases

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 trip as fast as possible (zone 1), because it is clear that the fault is on this particular section of line. If the impedance is higher, the relay will trip after a delay (≥ zone 2), to give another relay, that might be closer to the fault, a chance to clear it.

For faults of one or more phases to 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 to that of the phase to phase loop, a factor within the relay gives the relationship between the line return and the ground return impedance. This factor is called the ground impedance matching factor, the residual compensation factor or simply the k-factor.

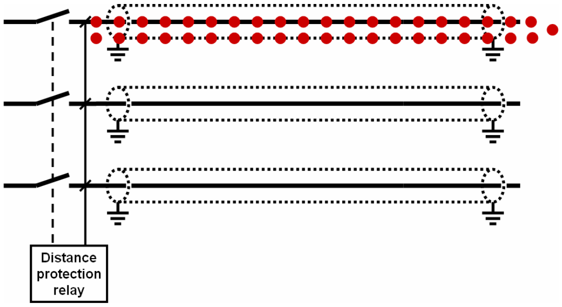

Figure 2: Impedance loop on a single phase to ground fault

If the relays are set properly, a consumer that is supplied from two sources (Figure 3) continues to receive energy from the healthy line if the other one trips.

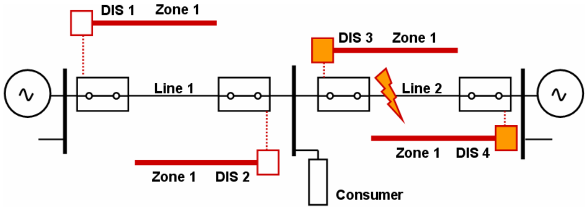

Figure 3: Relays with optimum zone 1 reach

If the impedances or k-factors of a relay are not set properly, zone over- or under-reach may occur (Figure 4).

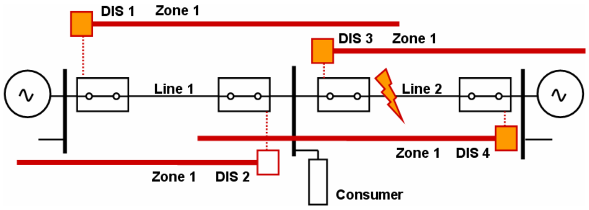

Figure 4: Relays with zone 1 over-reach

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In the example above, three relays instead of two see the fault in zone 1 and trip. This causes a second power line to be isolated and the consumer has his power cut off unnecessarily. Besides the problem of customers having no power, the risk of losing system stability becomes much higher as a result of such false trips.

DIFFERENT K-FACTOR FORMATS

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 $\underline{Z}_1$. Three times the impedance of the ground loop consisting of the three phase conductors - which have to be paralleled - and the earth return path is referred to as Zero Sequence Impedance $\underline{Z}_0$. Three times to reflect the single phase model.

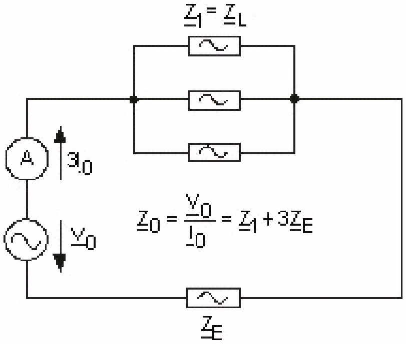

Figure 5: Equivalent Diagram

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” and an “earth return path” (Figure 5).

As can be shown, the “line impedance” 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” and a ground (or “earth return path impedance”), called $\underline{Z}_E$.

One definition of the Ground Impedance Matching Factor $\underline{k}_E$, $\underline{k}_L$, $\underline{k}_{E0}$ or sometimes called only $\underline{k}_0$-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 5 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 $\underline{Z}_E$, 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 $\underline{k}_{E0}$ is also called $\underline{k}_0$ only, which may become confusing. To avoid misunderstandings we call it $\underline{k}_{Z0}$ here.

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

Conversions between the different k-factor formats are possible using formulas (2) and (4).

$$\underline{k}_{Z0} = 1 + 3\underline{k}_{E0} \tag{5}$$

Splitting the complex impedances $\underline{Z}_E$ and $\underline{Z}_L$ into their real and imaginary parts 'R' and 'X' allows defining ratios. This is the third commonly used definition.

$$\frac{R_E}{R_L} \text{ and } \frac{X_E}{X_L} \tag{6, 7}$$

For converting from the format (6) and (7) to the other formats, the other line constants (or at least the line angle) have to be known.

$$\underline{k}_{E0} = \frac{R_E / R_L}{1 + jX_L / R_L} + \frac{X_E / X_L}{1 - jR_L / X_L} \tag{8}$$

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

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

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 [2] 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.

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CALCULATION OF K-FACTORS

Up to now the effort required to *measure* the line impedance and k-factors has been so great that it has rarely been done. The data needed had to be calculated manually, or by using appropriate software tools [3] such as PowerFactory from DIgSILENT, PSS from Shaw PTI or CAPE from Electrocon.

Many parameters are needed to calculate the line impedance. For cable installations the data given in the data sheet provided by the cable manufacturer, as well as the physical arrangement of the conductors, are the basis of calculation. The shield configuration; whether cross bonding is applied and if the shield is grounded on one or both ends, are other important parameters. When the shield is grounded on both ends or if there is a parallel ground wire involved, calculations become quite complicated. When the shield is grounded only on one end or grounded via a surge arrestor the calculation is relatively simple but then the soil resistivity or other parallel conductive paths are a major influence.

For old installations, where there is often a mixture of different cable types used – and which are quite often not well documented – it is not possible to calculate all these parameters.

For the 19 cable or cable-overhead line combinations which have been measured over the past three years, the differences between the measured values and the actual relay settings showed that there is typically a need to adapt or change something within the relay settings.

In general it can be said that the calculation of the Positive Sequence Impedance works better than that for the Zero Sequence Impedance but it is still not accurate enough.

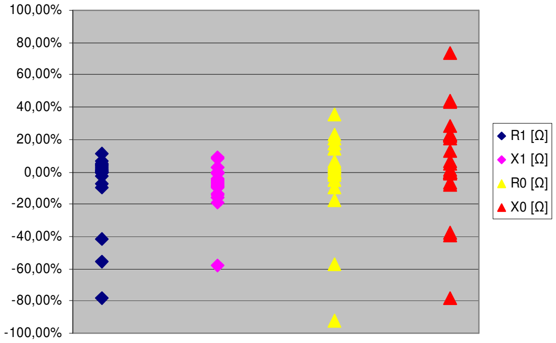

Figure 6: Comparison of measured values versus relay settings on 19 cable installations

One cause of the problems is the large number of parameters involved in the calculation of line parameters. Even if just one parameter is wrong this might cause a substantial error. In the Positive Sequence Impedance there are several of these parameters but the Zero Sequence Impedance or k-factor calculation is even more prone to error, because there are so many more parameters for the calculation.

On several occasions when incorrect relay settings were found, it was the Zero Sequence Impedance or the k-factor that was set wrong. Although there was also an example of the settings for two similar lines being mixed up!

MEASUREMENT OF K-FACTORS

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

For a long time the problem when measuring line parameters was that to overcome disturbances and interferences from other live systems, either currents close to or above the nominal current had to be used. Alternatively, big diesel generators were needed to allow the beat method to be applied.

Today, using electronic generators allows the use of signals with frequency shifted away from the mains. Applying a frequency selective measurement, that measures only that part of the incoming signal that matches the generated frequency, gives accurate results even in an environment experiencing heavy disturbances. With this method it is possible to work with currents that are a fraction of the nominal line current and so the equipment becomes comparably lightweight with components weighing less than 30kg.

Surge arrestors that are part of the measurement system can discharge currents of up to 30 kA safely to ground giving optimum safety in the case of an unexpected event on the cable during testing, such as a fault in an adjacent system.

Figure 7: OMICRON equipment for line impedance measurement

One of the big advantages provided by the measurement of line parameters is that the line does not need to be modified to perform it. The shield is left connected, or unconnected, as it is in normal operation. When cross-bonding is in place, the compensation of the induced voltages on the shield works in the same way during the measurement as it does when the cable is live. For a real symmetrical load on the line the three voltages compensate each other on the three phases. Using the single phase test set, only two phases have currents flowing but the induced voltages still compensate each other so that no current is flowing in the shield.

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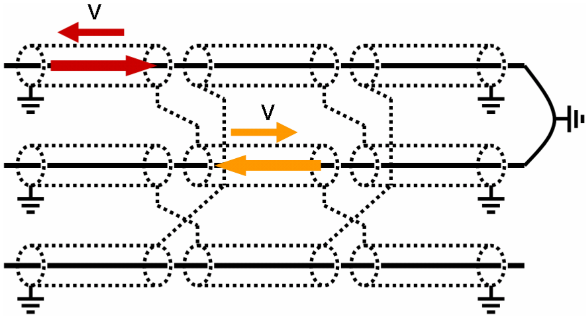

Figure 8: Induced voltages compensating each other on a cross bonded cable tested single phase

Even when transformers are connected along the line there is no need to disconnect them, because the protective relays would measure the same impedance as the test set.

For example, should, the shield of an installed cable differ from what is shown in the documentation it will not necessarily be found by the measurement, but the parameters measured and set as relay parameters would match the real situation and the relay would operate correctly.

CASE STUDY

In June 2004 an experiment was performed by a German utility to compare the results of a line impedance measurement and the readings of a distance protection relay after the simulation of a real fault [3]. The utility owns a municipal 20kV network that has low ohmic star point grounding to limit the short circuit current of ground faults to 2 kA.

On June 8th 2004 two short circuit experiments were performed. In one a symmetrical three phase to ground fault was simulated by short circuiting all three phases to ground on one end of a cable. Then, via several other cables to reduce the fault current and a separate transformer not connected to the rest of the 20kV network, the cable was switched on. The fault current was about 9 kA and the distance protection relay on the line tripped in zone 1 as expected.

Figure 9: Measurement of the cable impedance

Subsequently, a single phase to ground fault was simulated connecting only one phase to ground. Again the relay tripped immediately.

On the same day a line impedance measurement using the variable frequency equipment was carried out. The injected current was about 0.2% of the three phase fault current.

There where concerns because a part of the cable had steel shields and it seemed possible that non-linear effects would be seen if magnetic saturation had taken place. However the analysis showed that the results of the simulated fault and the line impedance measurement matched within two percent.

The utility was highly satisfied with the result and decided to perform measurements on all its cable installations. To date, about 50% of its 400 cables have been measured and the relay settings are being adapted accordingly.

CONCLUSION

Today the costs and effort required for k-Factor measurements are a fraction of what they used to be. Measurements have shown that for several reasons calculations based on unverified data often give wrong results. Therefore, in future, the use of calculations based on actual line measurements will be preferred.

Safe, selective and fast fault clearance is only possible if all relay parameters are set properly. Correct values of line impedance and k-Factor are of the highest importance for a fully operational distance protection relay.

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