PROOF OF LOAD ON CABLE SHIELD AND CABLES WITH DECENTRALIZED COMPENSATION AS WELL AS RELIABLE EARTH FAULT DETECTION

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Abstract

The increasing cabling of medium voltage grids is also increasingly influencing the operation of electrical grid, which are often, due to historical origin, operated as compensated distribution grid. That is why the decentralized compensation has become a focus again, which, however, also has been raising many questions that must be resolved from the operator's point of view. These include additional thermal loads on equipment like cable shields or transformers and the proper continued functioning of existing systems such as the selective earth fault detection. In the paper, practical approaches and methods for determining these influences and limits are shown and the results are used, to answer the open questions, considering existing framework conditions.

1. Introduction

Due to increasing cabling, the need arises that in compensated medium-voltage grid, the positioning of the compensation devices no longer takes only place in the substations and that's why these are more and more installed directly in the distribution grid nearby longer cable lines.

On the one hand, this is due to the fact that the distribution grid transformers (e.g. 110 / 20kV) are restricted in their transmission behaviour by connecting the compensation device to the transformer star point and on the other hand e.g. also the operational aspect that a double earth fault can lead to a disconnection of a not inconsiderable amount of the line-earth-capacitance, which in turn results in incorrect compensation.

At the same time, the decentralized compensation also creates new challenges for the distribution grid operator that have not been directly in focus up to now. On the one hand, there is additional thermal load in the distribution grid, which results from the losses from the superposition of the load current, the shield current and possibly from circulating currents, and on the other hand there is the question of the proper functioning of the selective earth-fault localization with a decentralized compensation, considering the installed technology.

In the following a practical approach will be used to determine the equipment load using real primary measurements and specifically addresses the following questions:

- current flow distribution between cable shield and ground
- current flow distribution between different cable shields e.g. parallel cable routes
- influence of different fault transition resistances

In addition to these operational issues, there are from a protection point of view, the following questions, which must be also addressed as system operator:

- proper functioning of installed earth fault location methods with decentralized compensation
- limits for transient and stationary location methods

2. Grid design and setup

The main compensation with a total amount of 600A is, as shown in *Figure 1,* positioned in a 110kV substation at the medium voltage star point of one 110/20kV transformer.

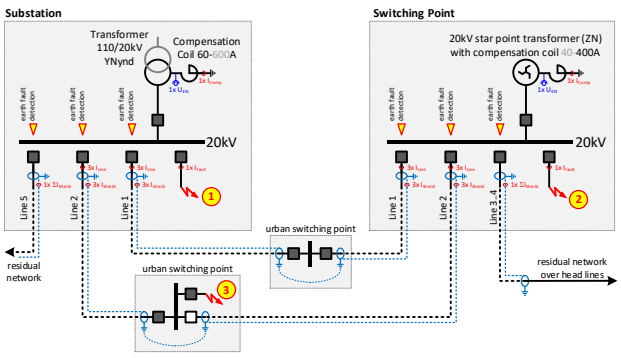

Figure 1 simplified grid design of the measurement setup

The distribution grid itself is characterized by a pure cable grid in the urban area around the substation, with quite extensive overhead lines in the peripheral areas. The decentralized compensation coil, with a total amount of 400A, is near the transition to the edge area, but still in the cable grid. The distribution network itself is operated with an overcompensation of 12 to 15A.

The setup of the distribution grid for the measurements, with a capacitive earth fault current of approximately 450A, was adapted to the installed compensation services.

3. Current flow distribution

3.1. General consideration

In this case it is important to define how the cable shield earthing is carried out. As long as the cable shield is grounded only on one side, no return current path can arise via this and the entire compensation current must flow through the earth ground. In the case of cable shield grounding on both sides, the return current path of the compensation current is given both through the cable shield and through the earth ground. Thereby the distribution is defined by the impedance ratios of the two paths.

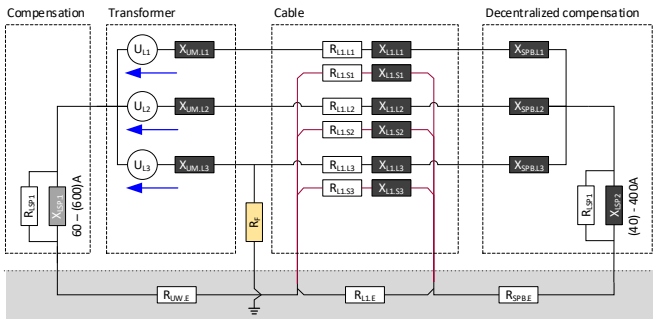

Figure 2 simplified model

On closer examination as shown in *Figure 2*, the inductance is the dominant measurand that determines this relationship. The positive sequence impedance of the cable can be determined without consideration of the cable shield treatment. The zero impedance of the cable section is mostly depending on the earthing of the cable ends the specific earth resistance and the frequency as shown in table 1.

Table 1: Zero impedance depending on ground resistance

Specific earth resistance	Cable grounded on one side				Cable grounded on both sides			
	50 Hz		250 Hz		50 Hz		250 Hz	
100 Ωm	38,6 Ohm	81,5 °	177,1 Ohm	84,5 °	15,6 Ohm	21,2 °	18,3 Ohm	27,0 °
200 Ωm	39,8 Ohm	81,8 °	183,3 Ohm	84,7 °	15,7 Ohm	20,7 °	18,3 Ohm	26,9 °
400 Ωm	41 Ohm	82,1 °	189,5 Ohm	84,9 °	15,8 Ohm	20,3 °	18,3 Ohm	26,6 °
800 Ωm	42,3 Ohm	82,3 °	195,7 Ohm	85,0 °	15,8 Ohm	19,9 °	18,3 Ohm	26,6 °
1600 Ωm	43,5 Ohm	82,5 °	201,9 Ohm	85,2 °	15,9 Ohm	19,5 °	18,2 Ohm	26,5 °

3.2. Current distribution using primary test

During the primary measurement, all relevant currents as well as all cable shields and earthing systems that contribute to the reduction of the current through the ground were measured in the substation and also at the decentralized switching point with the decentralized compensation coil.

One result with a 100% decentralized compensation of about 400A and an earth fault in the substation is shown in *Figure 3*. A striking and very significant superimposition of the compensation current of approx. 130A to a rather lower load current can be seen here in the single lines.

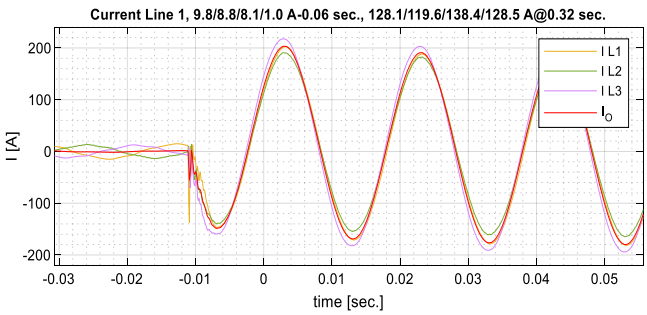

Figure 3 line current of the supply line to the decentral switching point with 400A decentralized compensation

In a practical use case, this means that this superimposition of the zero current leads to an increase in current at least in one conductor, which puts additional thermal stress on it. In the worst case, it even overloads as shown in *Figure 4*.

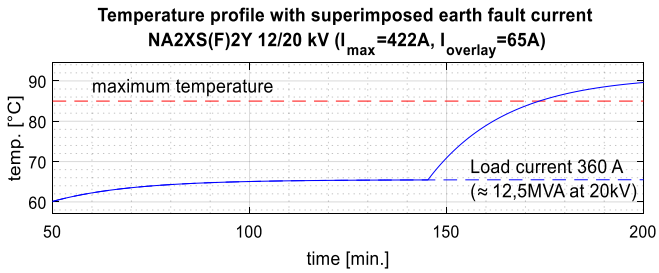

Figure 4 temperature profile with 65A overlay (I_{COMP}=200A)

Another important fact is that in addition to the additional thermal stress caused by the superimposition of the zero sequence, a further second heat source occurs due to the currents flowing in the cable shield.

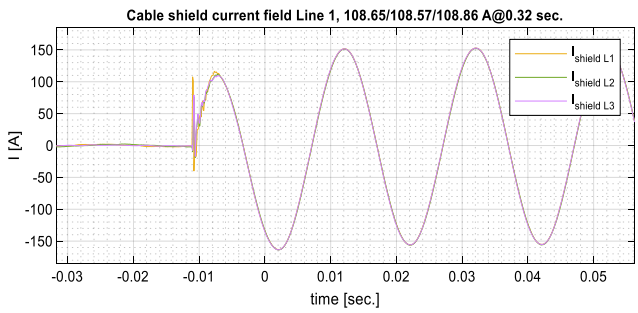

Figure 5 shield current of the supply line to the decentral switching point with 400A decentralized compensation

As shown in *Figure 5* almost 70-85% of the compensation current flows through the cable shield from the fault location back to the compensation coil, uniformly divided between the 3 shields. A holistic view of the thermal load on a cable can be seen in *Figure 6* and also in *Figure 7* as result of a calculation, based on the real grid design.

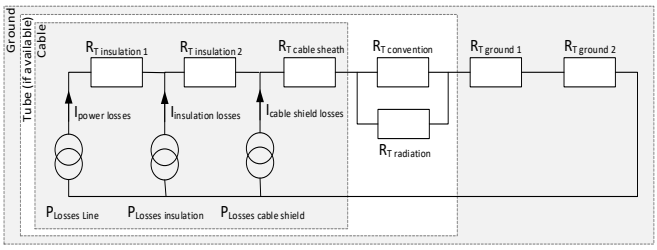

Figure 6 simplified thermal model of an underground cable

This simulation result shows a significant thermal load in one cable, in which the phase position of one operating current and the superimposed zero current are approximately same. In this case, from the operator's point of view, immediate relief measures are required to protect the equipment from premature aging. This leads to the conclusion that, with increasing cabling and the associated case, of an increasing decentralized compensation, a reduction in the permissible operating time in the event of earth faults should also be considered.

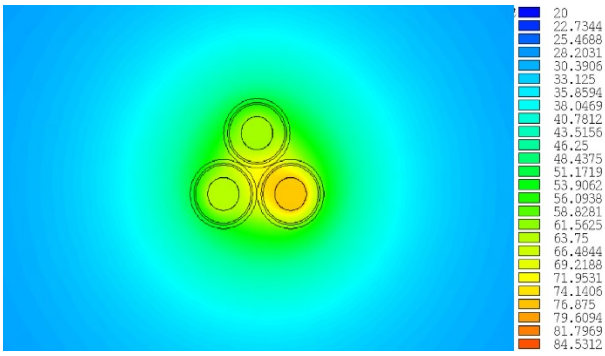

Figure 7 simulation result of a thermal load

As already mentioned, the double-sided grounding of the cable shield also results in an additional thermal load and thus a reduction in the power that can be transmitted by a cable system. In the event of an earth fault, the compensation coil's current flows directly, via the affected line, or indirectly, via the two unaffected lines and the star points in the grid, to the earth fault location and from there back through the ground, almost directly under the outgoing conductor. In the case of a cable line, the current can also use the return path over the cable shields instead of the ground. This fact has a positive effect with regard to possible touchable voltages due to the reduction of the current through the ground, and a negative effect with regard to the cable shields load.

The load ($P_{L\ shield}$) on the cable shields must therefore not be disregarded. They are mostly made of copper but in the medium voltage they only have a very small cross-sections of round about 16 - 35mm². Therefore, often a not permitted high power loss occurs at the cable shield, which is dealt with in more detail below.

$$P_{L\ shield} = I^2 * R = I^2 * \frac{l}{\kappa * A} \qquad \textit{Equ. 1}$$

P_L...power losses [W] *l.....length [m]*
I.....current [A] *A....cross section [mm²]*
R....resistance [W] *κ ...conductivity [m/(Ω*mm²)]*

3.3. Current distribution between ground and cable shields

The distribution of the currents flowing back from the fault location to the decentralized compensation via the ground and the cable shield takes place according to the impedance ratios. In doing so, not only the direct current resistance has to be considered, but above all the alternating current resistance must be focused, which is decisive here.

An example can be seen in *Table 1*. The cable shield earthed at one end corresponds to a pure earth return line and can therefore be compared to the cable shield earthed at both ends. With the focus to the value at 50 Hz, with a specific earth resistance of 200 Ωm, the zero-sequence impedance of an earth return conductor (39,8Ω∠81,8° ≈ 5,7+39,4i) has a lower ohmic resistance, but the inductive resistance is many times greater compared to the value of a both sides shield earthed cable (15,7Ω∠20,7° ≈ 14,7+5,5i) as return conductor.

$$L_A = \frac{\mu_0 * \mu_r}{2 * \pi} * \ln\left(\frac{D}{d}\right) \qquad \textit{Equ. 2}$$

L_A.....external inductance [H]
*μ_0.....magnetic field constant [V*s / A*m]*
μ_r.....magnetic permeability [-]
D.....inner shield diameter [m²]
d.....conductor diameter [m²]

The large inductive difference inevitably results from the external inductance. The calculation is shown in equation 2. This is defined by the geometry of the inductive loop and thus by the enclosed area which is determined on the one hand by the distance between the conductor and the shield and on the other hand from the conductor to the earth return conductor. This can also be seen to some extent in *Figure 2.*

Using the *equation 1* and the measured cable shield currents on line 1 (*Figure 5*), the installed cable of type NA2XS(F)2Y 12 / 20kV 3x1x240RM / 25 produces on each shield power losses from approx.

$$P_{shield} = 108{,}7^2 \frac{4625m}{57 \frac{m}{\Omega * mm^2} * 25mm^2} \approx 38{,}3\ kW$$

The return path from the fault location back to the decentralized compensation can also take place through other cable shields, which are parallel to the system own shield of the direct system.

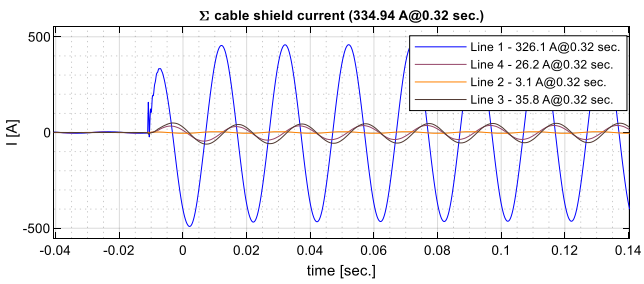

Figure 8 distribution on different cable systems

Here, too, the inductive fault loop is decisive for the current distribution. This effect from a real measurement, during an

earth fault, can be seen in *Figure 8*. In the signal curves shown, the direct system with an energy transport in the positive sequence system, can be detected easily because the largest return flow takes place there (line 1). In all the other parallel cable shields without an energy transport in the positive sequence system, the return flow is much less even though the parallel system is relocated nearby (e.g. line 3, line 4).

Due to the multiple return possibilities of the current for decentralized compensation via the cable shields, the current is reduced via the ground and therefore also via the earthing systems. The ratio of such a current distribution is also referred to as the reduction factor.

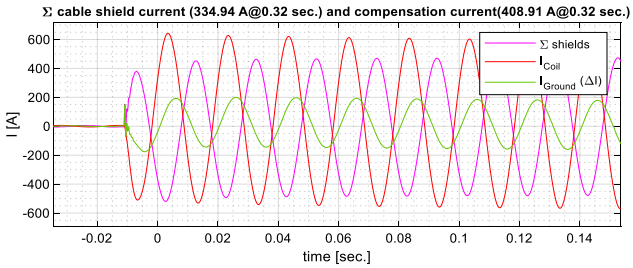

Figure 9 reduction of current through the ground

Due to the different phase positions of the currents through the cable shields, they cannot simply be subtracted from the compensation current to determine the reduction, but they have to be geometrically subtracted.

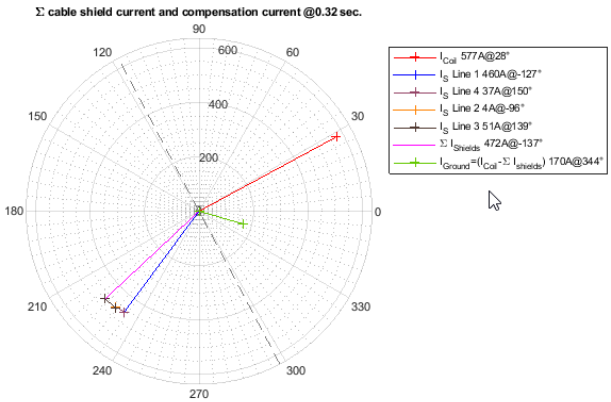

Figure 10 aggregated shield currents, as well as decentralised compensation and ground current

According to the real measured data, there is a reduction of the current via ground as shown in *Figure 9* and *Figure 10*. From the measured decentralized compensation current of approx. 409A, approx. 335A, with a phase angle of approx. 15.7° deviating from the compensation current, is returned by the cable shields of all outgoing cable systems of the switching point. This results in an effective current trough the ground of approx. 125A, which is responsible for the voltage drop through the earthing system of the station and for the touch voltage too.

From a statistical point of view, it can be said that with a series of measurements of 68 tests, with the real distribution grid, the expected value of the current over earth in the switching point is approx. 31.7% of the decentral compensation current and the relationship of the shield currents is approx. 76.0% of the decentral compensation current. Further details, such as the standard deviation, can be found in *Figure 11*.

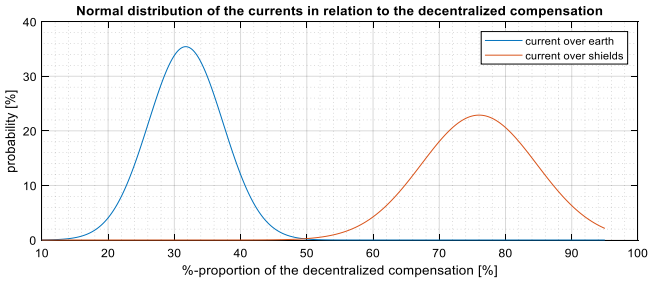

Figure 11 normal distribution of earth and shield currents

4. Selective earth fault detection

An important operational aspect is the proper functioning of the selective earth fault detection and the field-related assignment of the earth fault. In comparison to a central compensation, in which the zero sequence components can be foreseen from their flow directions and their phase positions, this cannot always be predicted with a decentralized compensation. As can be seen in *Figure 12*, in Plot 1 and Plot 2, there are no such changes in a branch without decentralized compensation, whereas in a branch with decentralized compensation, Plot 3 and Plot 4 in *Figure 12*, there is a change in the reactive power direction, which in return depends on the ratio of the decentralized compensation to the capacitive earth fault current of the affected field.

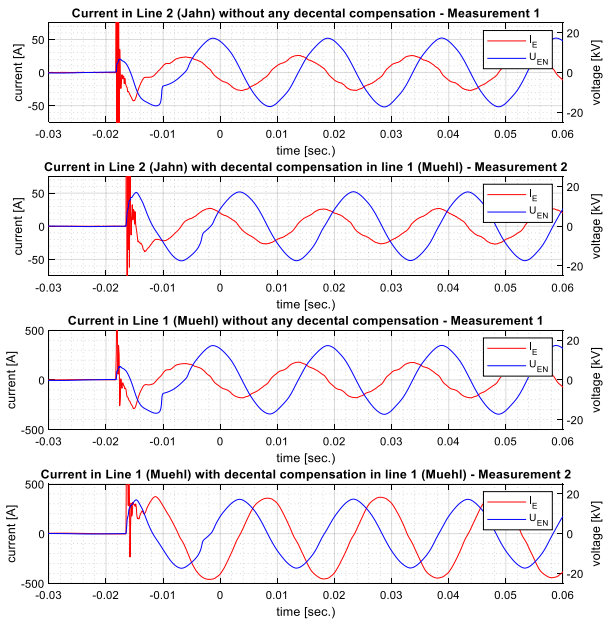

Figure 12 Signal curve from two different substation feeds.

In todays' modern protective devices there are several different earth fault location methods integrated, which evaluate the transient behaviour when the earth fault occurs (e.g. qu2 or qu4), as well as the transient behaviour during the earth fault (e.g. qui2 or qui4 method) and, last but not least,

also the stationary behaviour (e.g. watt metric or harmonic method), which is already known from earlier generations of earth fault location devices.

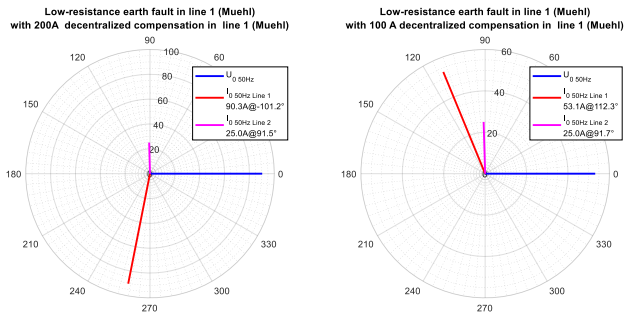

Figure 13 vector diagram of the 50Hz components

The previously described behaviour of the transition from a capacitive to an inductive behaviour of a distribution line can also be observed in Figure 13 for the 50 Hz component of the signals. It can be clearly seen, that the active component of the currents does not change direction, in relation to the voltage U_0, when the transition take place. From this it can be concluded, that for example a watt metric detection method also works under these conditions. This could also be traced and confirmed with numerous real field measurements. The same applies to all transient (qu2, qu4, qui2, qui4) and other stationary (harmonics) methods as shown e.g. in *Figure 14* for the $q_{(u)}$ method.

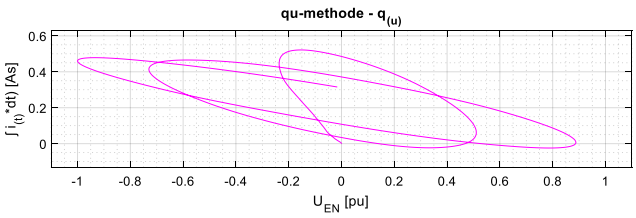

Figure 14 $q_{(u)}$-evaluation in the distribution line with the decentralized compensation in the case of inductive behaviour

One effect that could be observed in context with the field tests was, that the watt metric method tends to overreact in the case of an intermittent fault behaviour. A very simple and effective method to counteract this is to block this detection method when detecting intermittent earth faults. A further optimization can be achieved by prioritizing individual detection methods or at least by weighting the location results, since there are definitely differences in reliability between the different methods.

4 Conclusion

The decentralized compensation in medium-voltage networks is justified, especially in the case of extended medium voltage distributions with a larger conductor-earth capacity. As a result of the current developments in the energy transition, long medium-voltage connection lines to decentralized generation systems are increasingly being integrated into the distribution network. With these, a compensation is always installed at a decentralized point.

Due to this decentralized compensation, currents are superimposed on the active conductor as well as on the cable shield, which represent an additional thermal load for the cable. This reduces the transmission capacity of the cable and can end in a thermal overload, accelerated ageing and in the worst case in a destruction of the cable. It is therefore important to prevent such overloads by means of predictive grid design and planning, e.g. by limiting the size of a decentralized compensation coil to a value of e.g. 200A in a 20kV distribution network.

The same effect of such a superposition can, however, also occur with central compensation devices. These are not the subject of this study, but the result can also be applied there accordingly. There the focus should be on the connection line to centrally positioned neutral point transformers. The supply line to a network transformer is usually implemented with parallel laid cables. So, if this transformer is used for a neutral point connection the total cross-section of the shields are mostly large enough form the thermal point of view.

In conclusion, with the focus on earth fault detection, it can be stated that the measurements carried out show that all currently known selective earth fault location methods work, but, depending on the distribution network design (e.g. degree of cabling), it can make sense if individual methods (e.g. transient) are preferred.

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