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Distance protection of multiple-circuit shared tower transmission lines with different voltages and underground cable sections

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Abstract: Multiple-circuit transmission lines combining different voltage levels in one tower present extra challenges when setting a protection philosophy, as faults between voltage levels are possible. This study analyses faults in multiple-circuit transmission lines that are partly underground cable, by investigating the impact of the cable section on the fault current magnitude and operation of distance protection relays, without pilot scheme. The study shows that a cable's bonding configuration and layout have a small impact on the short-circuit magnitude, whereas the screen's grounding impedance and the presence of an earth continuity conductor impact the fault current magnitude. It was also demonstrated that distance protection relays settings used to protect the higher voltage line against single-phase-to-ground faults are capable of protecting the line against combined faults, for typical line configurations and short-circuit powers.

1 Introduction

The continuous development of the European electrical transmission system requires an increasing number of transmission lines and/or their restructuring, in order to enable a high penetration of electricity generated by renewable sources, while maintaining a high security of supply. However, public opinion opposes the construction of new overhead lines (OHL) and their commissioning is a long process that may extend up to a decade. Consequently, the use of existing corridors is becoming more relevant and the installation of lines of different voltage levels at the same tower more common, as a way of increasing the transmitted power and perform network reinforcement. The presence of lines at different voltage levels in the same tower possibilities inter-circuit combined faults between different voltage levels, with conductor galloping and ice throw-off being some of the major causes for these faults. The fault loop impedance measured by distance protection relays is different for these faults and it becomes a challenge to ensure a fast trip, as a simple relation between fault loop impedance and line parameters may no longer exist.

In order to address this problem, the authors have previously proposed a protection philosophy for this type of lines in [1, 2], based on distance relays without pilot scheme. However, the study did not take into account the possibility of the presence of long cables as a section of the line. Hybrid cable-OHL lines are sometimes used at transmission level, especially when considering areas of natural beauty, and the cable impacts the fault loop impedance seen by the distance relays. More precisely, the grounding of a cable's screens, the installation layout or the cable's bonding configuration influence the sequence impedance of a cable, which mean that the conclusions made in [1, 2] have to be validated for hybrid cable-OHL. Protection of hybrid lines takes these and other aspects into account, but it seems that no studies exist for the case of faults between voltage levels in the OHL section(s) of the line. This paper will analyse the impact of the following:

- Cable's bonding configuration (cross-bonding or both ends bonding) and installation layout (flat or trefoil formation);
- Location of the cable(s) sections;
- Grounding impedance of the cable's screens;
- Presence of an earth continuity conductor (ECC);

The objective is to assess if the proposed protection philosophy from [1, 2] is still applicable. It is only considered the presence of a cable section in the line section of the lower voltage (LV) level, as such is more likely to occur than the presence of a cable section in the higher voltage (HV) line.

2 Protection philosophy

Faria da Silva and Bak [1] proposed a formula for estimating the positive-sequence current of a fault between voltage levels. Fig. 1 shows the equivalent scheme used to deduced formula (1), where Z_y^x are the sequence impedances, with x representing positive, negative or zero sequence and y the voltage level, Z_G is the grounding impedance, Z_F the fault impedance and Z_M the mutual impedance between the two faulted phases. The formula assumes that the fault current is so high when compared with the sound currents, that the latter are considered to be 0 A.

The positive, negative and zero sequence currents are equal and thus, the fault current is equal to three times the positive-sequence current from (1).

A multiple-circuit tower with two voltage levels in a horizontal configuration, i.e. where a fault between voltage levels may occur, has a layout that minimises unbalance created by inductive coupling. This means that if one of the voltage levels has phase R to the left, the other voltage level has phase R in the centre or to the right. As a result, one of the phases leads the other to a fault between voltage levels. Faria da Silva and Bak [1] concluded that the leading voltage level sees the fault in the forward direction, whereas the lagging voltage level sees the fault in the reverse direction. The reference also shows that seen from the HV level, the magnitude of the fault current for a single-phase-to-ground fault (SPTG fault) is expected to be similar to that of a combined fault between voltage levels at the same location, if the HV level leads the LV level and the network short-circuit power is not too low (see (1)) Faria da Silva and Bak [2] investigated whether the relay's settings for a SPTG are able to detect a fault between voltage levels and operate properly (notice the similarity between the equivalent scheme of Fig. 1 and the one for a SPTG fault). It concludes that it should be assured that the HV level leads the LV level. Additionally, the short-circuit power of the network has a larger influence than for a SPTG fault and it is recommended to increase the resistive reach of the protection zone, as well as the angle separating forward/reverse zones if installing the lines in

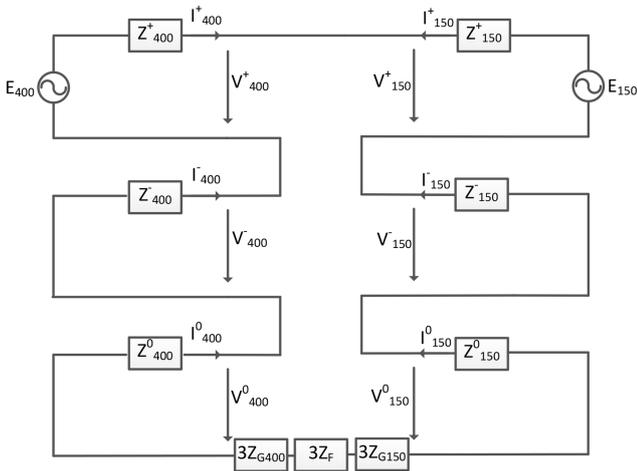


Fig. 1 Equivalent scheme for a combined fault between voltage levels

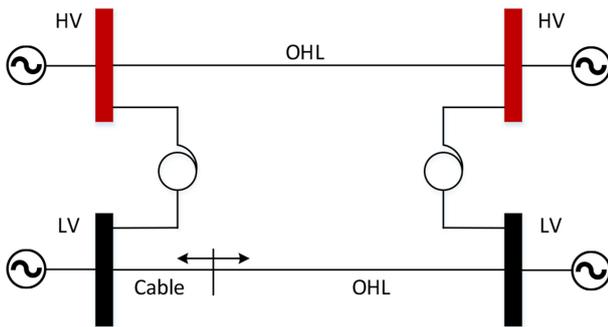


Fig. 2 Single-line diagram of the system used for simulations in this paper

weak networks, as unexpected scenario. In these conditions, the relay of the HV level is expected to detect the fault as a SPTG fault and operate accordingly.

The presence of a cable section in the line may invalidate the conclusions presented in the two references. The impedance of a cable is normally lower than of an OHL for the same power and voltage level, which may result that the simplifications made in (1) are no longer acceptable when estimating the short-circuit current (Section 3) or that the distance protection relays no longer see the fault as a SPTG fault (Section 4).

3 Influence of a cable on the estimation of the short-circuit current

Equation (1) is valid independently if it is applied to cables or OHLs. However, the calculation of symmetrical impedance in a cable depends on several aspects that should be assessed. More specifically, one should assess:

- Cable's bonding configuration (cross-bonding or both ends bonding) and installation layout;
- Grounding impedance of cable's screens;
- The impact of an ECC.

Fig. 2 shows the single-line diagram of the system used in the majority of simulations and calculations performed in this paper. The HV line is fully OHL, whereas the LV line is partly cable, partly OHL. The length of the cable plus the length of the OHL is equal to the length of the OHL at the HV (100 km). The busbars nominal voltages are 400 and 150 kV, with a connection via an autotransformer at both ends. If nothing else is stated, the short-circuit power of the four nodes is infinite.

3.1 Influence of cable's bonding configuration

Land cables can be bonded using one of two configurations: both ends bonding, where the screens are grounded only at the two ends, or cross-bonding, where the screens are regularly transposed and grounded along the cable. A cable can also be installed with single-point bonding and variations, but it is not usual for cables with more than 3–5 km and thus, not considered in this paper.

Table 1 shows the root mean square values of short-circuit current in kA for a fault at the transition point from OHL to cable, with the cable being 10 km long (case A). Table 2 shows the results for a fault again at 10 km from the substation, but with a cable of 5 km (case B). Both cases are for a cable bonded at both ends installed in trefoil formation.

The differences between calculated and simulated short-circuit currents are small and in-line with those obtained in [1], demonstrating the applicability of the equation in presence of cables. The differences are explained by the distributed nature to the line impedance that is not considered in the equation, which is based on lumped parameters.

The magnitudes of the short-circuit currents for a cross-bonded cable are similar to those of Tables 1 and 2. The similarity is explained by the zero-sequence impedance being equal for the two bonding configurations [3], whereas the positive sequences are not very different for typical installations.

Table 3 shows the ratio between the positive-sequence impedance of the two bonding configurations for five different cables. The data for the first four cables is from [4], for two 66 kV (95 and 2000 mm²) and two 400 kV (630 and 2500 mm²) cables, chosen with the intention of showing two extremes cases for each voltage level; cable E is from a real 150 kV system [1]. The results are for flat formation, which gives larger variations, with a 0.4 or 0.1 m distance between phases.

The biggest difference between the two positive-sequence impedances occurs for cable E, but the impact on the short-circuit currents is much smaller than the 28% variation for cable E – 0.4 m. The short-circuit current for case A and a distance between cables phases of 0.4 m is 48.3 kA for cross-bonding and 51.5 kA for both ends bonding, a 6% difference. For case B, the values are 49.8 and 52.7 kA, a 5% difference; all results are for a cross-bonding with one major section. The both ends bonding results are different from Tables 1 and 2, because of changing the formation from trefoil to flat. The installation of the cable with a shorter distance between phases would further decrease the difference between the short-circuit currents, as it would not have a solid grounding of the screens, because it leads to a larger zero-sequence impedance, reducing the weight of the positive-sequence impedance in the current magnitude. These results also show that the differences between a flat or trefoil formation are not considerable.

In conclusion, the differences in the bonding configuration and cable layout have a small influence in the magnitude of the short-circuit current.

3.2 Influence of the screen's grounding

The simulations for the different cable bonding configurations performed in the previous section were with the screens grounded via a 10 μΩ resistance, in order to minimise the influence of the grounding impedance. In reality, this grounding resistance can be of some Ohms and it depends on the location: as an example, the grounding impedance is expected to be larger at a transition point between OHL and cable than at a substation where a grounding grid exists.

Fig. 3 shows the magnitude of the short-circuit current in function of the grounding resistance of the cable's screen for case A; the value of the resistance is equal at both ends. The results show that the current's magnitude decreases as the grounding resistance increases, starting to stabilise for a grounding impedance

$$I_{400}^+ = \frac{E_{400} - E_{150}}{Z_{400}^+ + Z_{150}^+ + Z_{400}^- + Z_{150}^- + Z_{400}^0 + Z_{150}^0 + 3(Z_F + Z_{G400} + Z_{G150}) - 2 \times (3Z_M)} \quad (1)$$

Table 1 Fault current in kA obtained via simulations and using (1) for the relay at the HV level for case A

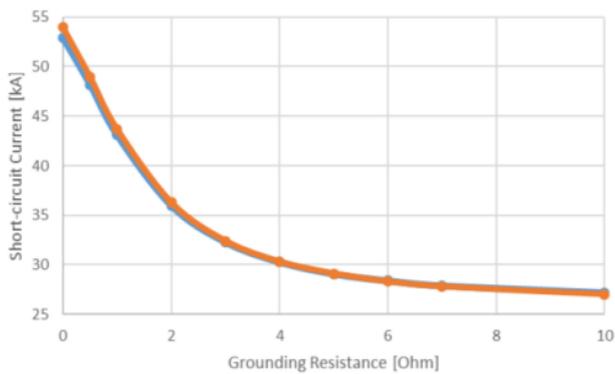
	Line connected
close end relay (simulation)	52.5
close end relay (calculation)	54.0
far end relay (simulation)	7.1
far end relay (calculation)	5.8

Table 2 Fault current in kA obtained via simulations and using (1) for the relay at the HV level for case B

	Line connected
close end relay (simulation)	51.6
close end relay (calculation)	53.4
far end relay (simulation)	6.4
far end relay (calculation)	5.8

Table 3 Ratio between the positive-sequence impedance for both ends bonding and cross-bonding

	Cable A	Cable B	Cable C	Cable D	Cable E
0.4 m	1.05	0.99	0.87	0.84	0.72
0.1 m	1.03	1.00	1.00	0.99	0.97

**Fig. 3** Short-circuit current in function of grounding resistance. Blue: simulation; orange: calculation

around 10 Ω (this value depends on the cable geometry and its length). The behaviour is explained by a decrease of the circulating current in the screen as the grounding resistance increases, which also corresponds to an increase of the zero-sequence impedance. As an example, for the 10 km long cable used in the example and a grounding resistance of 2 Ω at each end, the zero-sequence impedance increases ~ 7.4 times, when compared with solid grounding.

Fig. 3 presents results obtained using (1) and considering grounding impedance, showing a good match. The correction of the zero-sequence impedance requires changing a variable of the equation used when estimating zero-sequence impedance, meaning that it is not possible to perform direct alterations to a reference zero-sequence value. The zero sequence of a cable is estimated by (2) [3], where Z_a is the conductor's self-impedance, Z_x is the mutual impedance between cables, Z_m is the mutual impedance between phase conductor and screen and Z_s is the screen's self-impedance

$$Z_C^0 = Z_a + 2Z_x - \frac{(Z_m + 2Z_x)^2}{Z_s + 2Z_x} \quad (2)$$

The grounding impedance is accounted by increasing Z_s as given in (3), where Z_G is the summation of the grounding impedances at both ends. This change is also going to impact the calculation of positive-sequence impedance of a cable bonded at both ends, but the changes are minor: around 3% for a grounding impedance of 2 Ω at each end and the 10 km long cable considered in this paper

$$Z_s^{\text{Ground}} = Z_s + 3Z_G \quad (3)$$

Some utilities perform measurements of the zero-sequence impedance when installing new cables and the result can be applied directly in (1) for a more accurate estimation.

The use of cross-bonding instead of both ends bonding would result only in small differences in the results. The zero-sequence impedance is calculated using the same formula for both cable configurations and thus, the differences are for the reasons explained in Section 3.1. It is important to refer that when performing the correction presented in (3) only the groundings at the ends of the cables should be considered, neglecting the groundings at the major sections of a cross-bonded cable, because the current flows almost all in the cable's screen.

In conclusion, the grounding impedance of the cable's screen has a strong impact on the magnitude of the short-circuit current and it should be considered. The proposed formula (1) is still able to estimate the fault magnitude accurately, if the zero-sequence impedance is corrected.

3.3 Impact of an ECC

ECCs are used in some installation to reduce the screen-to-earth overvoltage and protect the sheath from earth potential rise, being common when applying single-point bonding [5]. ECC is sometimes installed with other bonding configurations and it is more likely to be present when a lightning strike can reach the cable, as it happens for hybrid cable-OHLs. In this paper, only insulated ECC is considered.

The influence of the ECC in the magnitude of the short-circuit current is rather difficult to assess analytically, as the current loops depend on both the ECC and screen's grounding impedances, the number of grounding points and the transposition of the ECC; as an example, there may be cases where the current flows into the ECC at one of its groundings points and out at another. Thus, instead of comparing the results from (1) with simulation, as done in the previous sections, this section provides a qualitative comparison.

The grounding impedance of the ECC is expected to be equal or larger than the grounding impedance of the screen. Using this assumption, Fig. 4 shows the results obtained for case A, for a grounding impedance of the ECC equal to the screen, and with four or seven grounding points.

Some hybrid line configurations may have a cable connected to an OHL at one end and to a substation at the other end. Such configurations may result in the grounding of the screen at the OHL termination via an impedance noticeable larger than at the substation termination. Fig. 5 shows the short-circuit current when varying the grounding resistance of the ECC and the screen at the OHL end, while keeping a 1 Ω grounding resistance at the substation.

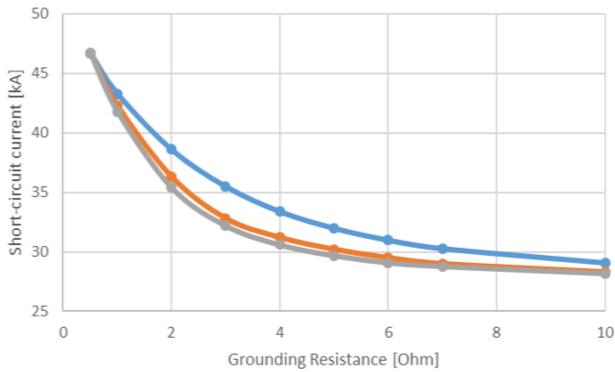


Fig. 4 Short-circuit current in function of grounding resistance. Grey: without ECC; orange: ECC grounded every 3.33 km; blue: ECC grounded every 1.67 km

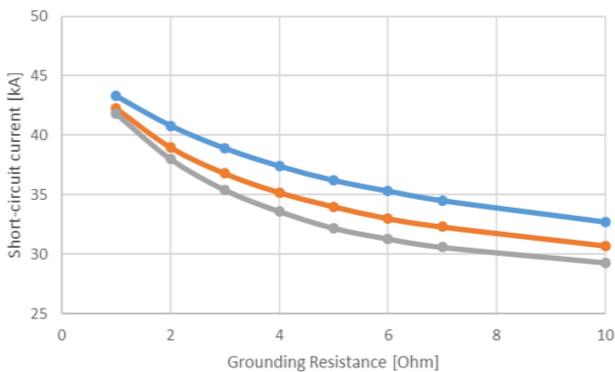


Fig. 5 Short-circuit current in function of grounding resistance with a fix grounding resistance of 1 Ω at substation. Grey: without ECC; orange: ECC grounded every 3.33 km; blue: ECC grounded every 1.67 km

Both figures show that the variation in the magnitude of the short-circuit current introduced by the ECC is noticeable and affected by the number of times that the ECC is grounded. However, there are parameters not included in the simulations for being very system dependent that would decrease the differences. It is likely that the grounding impedance of the ECC is larger along the ECC than at the terminals, because the grounding is better done at the ends of the cable, reducing the current in the ECC. In this simulation model, the screen is grounded to the ground and not to a grounding grid at the substation, which increases the current flowing in the ECC in relation to the screen.

Moreover, case A is an extreme case where the fault is at the transition point, the difference decreases as the OHL portion of the line increases. As an example, the largest difference between having/not having ECC in Fig. 5 is of 12.8%, but it would be reduced to 9.7% if the fault was 10 km away from the transition point.

In conclusion, the presence of an ECC increases the magnitude of the short-circuit current and changes on the ECC have an impact, e.g. the number of grounding points.

4 Use of SPTG protection settings

The work in [1, 2] shows that distance protection relays from the leading voltage level (which should be the HV level) are likely to see a combined fault between voltage levels as a SPTG fault inside of the first zone and operate accordingly. One of the steps for reaching this conclusion was comparing the magnitude of fault currents for combined and SPTG faults and showing that they were similar for typical layouts, because the increase in the voltage from phase-to-ground to phase-to-phase was similar in magnitude to the increase in the loop impedance. This section assesses if the presence of a cable section changes this expectation. The voltage between voltage levels does not depend on the presence of a cable section and cables tend to have lower resistance and reactance than equivalent OHLs, because of the larger cross-section area and shorter distance between phases, respectively. As a result, a cable is

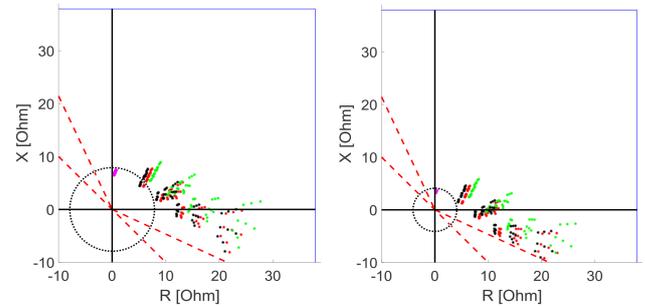


Fig. 6 Fault loop impedance seen from closest relay for Fault A (left) and Fault B (right). Magenta: SPTG fault OHL system; Black: Composite fault OHL system; Blue: SPTG fault; Red: Solid grounding of screen; Green: Grounding via 3 Ω

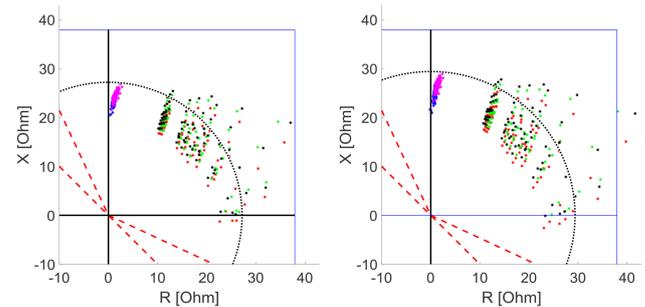


Fig. 7 Fault loop impedance seen from far away relay for Fault A (left) and Fault B (right). Magenta: SPTG fault OHL system; black: composite fault OHL system; blue: SPTG fault; red: solid grounding of screen; green: grounding via 3 Ω

expected to have lower positive and zero-sequence impedances than an equivalent OHL, which would make it easier for the relays to interpret the fault as a SPTG; on the other hand, there is no coupling between a cable and the OHL from the HV level, or if exists it is much smaller than between OHLs in the same tower, which may increase the fault loop impedance seen by the relay closest to the fault.

The first test case consists of two lines of 100 km as shown in Fig. 2 and voltage levels of 400 and 150 kV. The short-circuit power of four Thévenin equivalent at the nodes changes between three values, chosen to represent a realistic range of variation: 6000, 2000 and 500 MVA, all with a X/R of 10. A case where both lines are solely OHL, plus five different fault scenarios including a cable section (as defined in Fig. 2) are simulated. In all five cases, there is an OHL between the fault and one of the LV substations, being the line between fault and the other substation as follows:

- Fault A: 20 km from substation, with 10 km of cable and 10 km of OHL in-between;
- Fault B: 10 km of cable from substation;
- Fault C: 20 km from substation, with 10 km of OHL and 10 km of cable in-between;
- Fault D: 20 km of cable from substation;
- Fault E: 80 km of cable from substation;

As proposed in [2], the 400 kV level leads in relation to the 150 kV level. The cable is considered bonded at both ends, without ECC and with a screen's grounding is solid or via a 3 Ω resistor. An ECC is not considered because it leads to larger short-circuit currents, as seen in Section 3.3. Therefore, if the relays operate correctly for the cable without ECC, they operate correctly for a cable with ECC.

Figs. 6 and 7 show the fault loop impedance at the two relays from the HV line for Faults A and B, respectively. Fault C presents results virtually identical to Fault A, showing that the location of the cable section is of no relevance, as expected. Fault D is similar to Fault B, with variations caused by the change in the fault location. Fault E is analysed later.

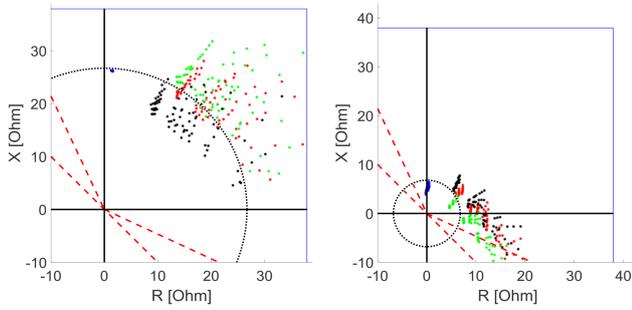


Fig. 8 Fault loop impedance seen from closest (left) and far away (right) relays for Fault E. Blue: SPTG fault; black: composite fault OHL system; red: solid grounding of screen; green: grounding via 3Ω

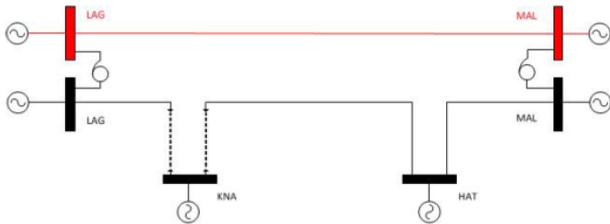


Fig. 9 Single-line diagram of the combined multiple-circuit line. Red: 400 kV; black: 150 kV. Solid line: OHL; dashed line: underground cable

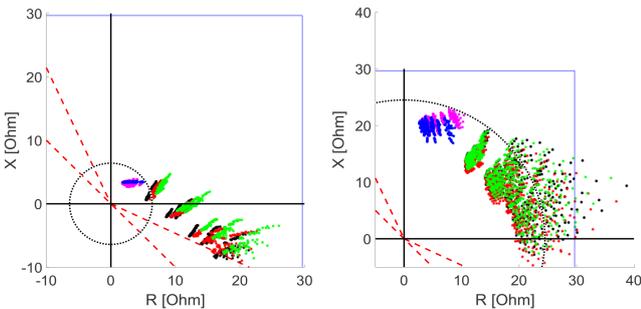


Fig. 10 Fault loop impedance seen from closest (left) and far away (right) relays. Reference system: magenta: SPTG fault; black: composite fault; system with cable: blue: SPTG fault; red: solid grounding of screen; green: grounding via 3Ω

The horizontal blue line shows Z_1 extended protection zone for the reactance, corresponding to 120% of the line reactance, as autoreclosure is normally the first step when protecting OHL against faults. Usually, hybrid lines with cable section(s) do not apply autoreclosure to the full line, because a fault in a cable is permanent, but in this case the cable is in the LV line and the relays expected to react in the HV line (it is considered that the HV line leads the LV line), which is purely OHL and thus, it employs autoreclosure with a normal reach. The vertical blue lines correspond to the resistance, which is set considering a R/X relation of 1. The separation of forward and reverse zones (red dashed line) is considered with an angle of 45° and 25° , but it is important to notice that the angle may be lower in some cases. To better visualise the changes in impedance magnitude when comparing the combined fault with a SPTG fault at the same location, a circle of radius equal to the maximum impedance of the SPTG fault is also presented in the figure. The values of the zero-sequence compensation factor 'k0' used to estimate the fault loop impedance are those that would be used for SPTG faults.

The influence of the short-circuit power on the fault loop impedance is relevant and the stronger the network, the lower the fault loop impedance seen from the relay closer to the fault. The black, red and green points in Fig. 6 can be grouped in three areas, as the resistance increases, with the last area being more spread. The first area with lower resistance corresponds to 6000 MVA at the closest substation, the second area to 2000 MVA and the last area to 500 MVA. Faria da Silva and Bak [2] explained this

behaviour in detail, which can be summarised by the fault current flowing in the Thévenin equivalent impedance.

The simulations show only small differences between having a cable or OHL, which have to be understood. The cable has lower positive and zero sequence impedances, when compared with the OHL, a reduction of 2.7 and 6.1, respectively, for this specific system line was calculated. Therefore, it would be expected that faults in the lines with cable sections had lower fault loop impedances than lines without cable sections, but the opposite happens from the relay closer to the fault. This is explained by the effect of the coupling in the short-circuit current (see (1)). No coupling exists between the HV OHL and LV cable and thus, the denominator of (1) is bigger for the case with cable, resulting in a larger fault loop impedance. If the system with only OHL does not consider coupling for the OHL section equivalent to the cable in Fig. 6, the fault loop impedance is larger for the system with only OHL, which was verified via simulations, but not shown here due to space limitations. The screen's grounding impacts the results and the fault loop impedance is larger if the screen is grounded via a resistance instead of a solid connection, because of the increase in the zero-sequence impedance, as explained in Section 3.2.

Fig. 8 shows the fault loop impedance for Fault E, where 80% of the line is cable. The differences for the system with just OHL are larger than for the other four faults, especially for the relay further away. However, the tendencies are as before and the relays will still react, unless the short-circuit power becomes very low (500 MVA) in several busbars.

Given these results, it can be suggested that the conclusions of [2] are also valid in case of presence of cable sections. However, it would be relevant to perform also the comparison in a real system and not just one where the lines of the two voltage levels have equal lengths. Fig. 9 shows the single line diagram of a real 400 kV/150 kV line in Denmark [6]. The line already has two cable sections connected to busbar KNA, but they are short. To assess the impact of a cable section, 10 km of the 33.84 km MAL-HAT line are underground and a fault is simulated at the cable-OHL transition points. The short-circuit power of all six nodes are changed as previously indicated, the screen's grounding is solid or via a 3Ω resistor.

Fig. 10 shows the fault loop impedance for the reference system and for the system with 10 km of cable between MAL and HAT. The results are in accordance with those obtained for the previous system (Figs. 6–9), with the difference between having cable or OHL sections even smaller, because of the shorter length of the LV line when compared with the HV line.

The relation between the sequence impedances of a cable and OHL are not fixed, but it is expected that the impedances for an OHL are larger than for a cable; as an example, a relation of 1.5 for the positive-sequence impedance of a typical 400 kV OHL and cable is given in [3]. In conclusion, the presence of a cable section in the LV line has a minor influence in the fault loop impedance, when compared with an equivalent of OHL of equal length. As a result, the conclusions from [2] are still valid in the presence of a cable section.

5 Conclusions

The paper intended to study the impact of a cable section in multiple-circuit lines with different voltages. The work is based on [1, 2], which presented a formula to calculate the short-circuit current magnitude for combined faults (1) and proposed that the distance protection relays from the HV level see combined faults as SPTG faults, if the HV level leads the LV level.

The formula for estimating the fault current magnitude continues to be valid for lines with a cable section, being necessary to correct the positive and zero-sequence impedances to account for the cable. It is demonstrated that the bonding configuration and the cable layout have a small influence in the short-circuit current, assuming realistic scenarios, contrarily to the screen's grounding impedance, whose increase leads to a decrease of the fault current magnitude, in the test case it decreases 33% when going from solid grounding to 2Ω . The presence of ECC increases the magnitude of

the fault current and similar to the screen, it depends on the grounding impedance.

The fault loop impedance is barely affected by the substitution of an OHL section by a cable section at the LV level. The cable is expected to have a lower positive-sequence and zero-sequence impedances, but the coupling between the OHL from the HV and the cable is much smaller than between two OHLs in the same tower, which compensates the lower impedance and results in a small change of the fault loop impedance seen by the relays. As a result, the relays of the HV level are expected to see a combined fault as a SPTG fault and act accordingly.

6 References

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