Deploying correct fault loop in distance protection of multiple-circuit shared tower transmission lines with different voltages

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Abstract: Combined faults occurring between different voltage levels in overhead lines present a challenge for distance protection. Previous work has shown that such faults most often appears as single-phase-to-ground (SPTG) faults in a normal type of overhead line. However, it is not obvious that distance relays will identify and select the correct fault loop according to being similar to SPTG, as all six fault loops get excited when combined faults occur. A study where two distance relays of different manufactures are tested using transient replay and secondary test equipment is presented, in order to reveal which fault loops are activated and whether a safe trip for combined faults happens.

1 Introduction

Combined faults between voltage levels represent a challenge when using non-pilot distance protection schemes. This was initially shown in [1], which discussed the distance relay's operation during a series of inter-circuit faults between 400 and 150 kV on a winter's day in 2013, at the system shown in Fig. 1.

The distance relays will not interpret all inter-circuit faults like a typical fault, as for instance the single-phase-to-ground (SPTG) fault within one circuit.

The authors of [2, 3] made a thorough theoretical analysis of the generic type of inter-circuit faults, which showed, among other findings, that the leading or lagging of the circuits towards each other plays a major role for the measured fault loop impedance.

Another issue showed in [1] is that the fault loop impedance is different for all six fault loops (three Ph-Ph and three Ph-E), see the example in Fig. 2, which is from one particular fault in the combined system shown in Fig. 1. As can be seen, only one fault loop impedance is seen in the forward direction.

Usual zone settings for SPTG can in most cases cover also the inter-circuit faults, if correct fault loop is selected, i.e. the fault loop for inter-circuit faults where the measured impedance falls into the same region as for SPTG faults. This is only the case for one of the three Ph-E loops.

Similar scenarios can occur in connection with long, heavily loaded lines with fault resistance taken into account [4], where one fault loop can be leading other loop(s). The challenge is usually overcome by blocking the fault loops having a misleading reach. The same question is important for inter-circuit faults as each fault loop measures different impedances having a different location in the *R*–*X* diagram. Only one, as described above, will measure the correct impedance, which is similar to an SPTG fault. The purpose of this research is to investigate the distance relays deployment of the correct fault loop during inter-circuit faults in order to assure a safe trip for inter-circuit faults. Validated PSCAD simulations from a real system [1] will be used for transient replay case studies with two brands of numerical distance relays and their selection of fault loop will be analysed and discussed.

2 Selection of fault loop

The fault loop is usually defined using an equivalent circuit.

Faults in combined overhead lines will inevitably include a change in all phase voltages and all phase currents at both voltage levels, as the higher level is interconnected with the lower level by transformers [1].

This leads to the fact that both the forward impedance as well as the return impedance in the fault loop consist of a mixture of the impedances from the higher level and the lower level, as shown in Fig. 3. Furthermore, mutual couplings play a role for such highly non-symmetrical situation.

Zero sequence compensation (k_0 or R_E/R_L and X_E/X_L) normally adapts to the protected line zone 1, which means that faults including earth return current will reflect impedance being the same as for non-earth fault faults. In other words, the zero sequence compensation makes the reach of the distance protection independent of the type of fault. When considering combined faults, both positive and zero sequence impedances are combined from both the higher and the lower levels in a way depending on the location of the fault. Therefore, normal zero sequence compensation cannot assure that such type of fault is being seen by the distance relay in the same way as a positive sequence fault. This challenges the reach and zone settings.

This is described in (1) from [4], as it is obvious that the loop impedance will vary as a function of the actual composition of Z_{SC1} and Z_{SCE}

$$Z_{\mathrm{Ph-E}} = Z_{\mathrm{SC1}} \cdot \frac{\left(I_{\mathrm{ph}} - (Z_{\mathrm{SCE}}/Z_{\mathrm{SC1}}) \cdot I_E\right)}{I_{\mathrm{Ph}} - k_E \cdot I_E} \quad (1)$$

Here $Z_{\text{Ph-E}}$ is the measured loop impedance, Z_{SC1} the positive sequence impedance, I_{Ph} and I_E phase current and earth return current, respectively, Z_{SCE} earth return impedance (not zero seq.) and k_E is the zero sequence compensation factor. k_E is one preset parameter in the distance relay, whereas the ratio Z_{SCE}/Z_{SC1} varies widely with the location of the fault and network conditions in general. Therefore, no consistent conversion of the physical distance of combined faults to positive sequence is possible.

Several simulation studies [2, 3] and real cases [1] have shown that such combined faults lead to all six fault loops being activated and measuring an impedance when the fault occurs. These six loops (three Ph-Ph loops and three Ph-E loops) will due to the varying magnitudes and angles of voltages and currents in both higher and lower levels lead to six different fault loop impedances, whereof only one is representative for correct fault detection as similar to an SPTG fault, as described in [2, 3]. Therefore, it becomes mandatory to test whether a certain distance relay calculation algorithm is capable of selecting this fault loop leading to an efficient trip.

Most relays adopt some way of assuring selection of the correct fault loop and thereby avoid unfaulty loops. In the case of the

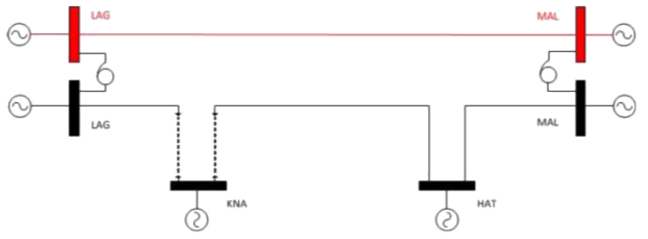

Fig. 1 *Single-line diagram of the combined 400/150 kV line Landerupgaard-Malling LAG-MAL. Black parts 150 kV and red parts 400 kV [1]*

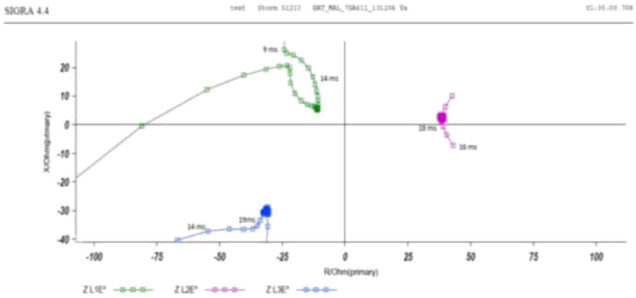

Fig. 2 *Example of the differently measured fault loop impedance in inter-circuit faults for fault loops L1-E, L2-E and L3-E. Measurement origins from fault record in distance relay during the inter-circuit faults described above [1]*

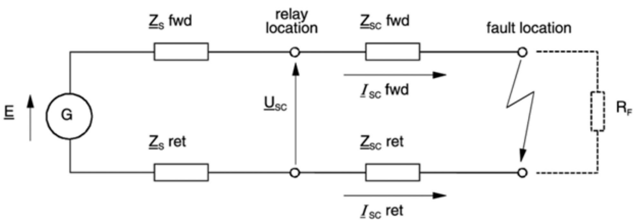

Fig. 3 *Equivalent circuit of the fault loop [4]*

combined fault, the problem is almost the opposite. It is necessary for the relay to select the fault loop that corresponds to the SPTG fault in order to enable autoreclosure (ARC), thereby switching either the higher (recommended) level or the lower level off during deadtime, which will eliminate every non-permanent fault between the two voltage levels. Relay manuals have some information on these internal procedures, although it is not possible to discover whether a correct operation will take place for the highly non-symmetrical combined fault.

In this paper, two distance relays are subject to a thorough testing with the purpose of discovering which fault loop is deployed during combined faults under varying conditions.

3 Description of the tested distance relays

Two distance relays from different manufacturers are tested (only issues related to the combined fault recognition are described):

3.1 Relay A: Siemens 7SA610

This is a state-of-the-art numerical distance relay, which is possible to set to cover almost any thinkable application related to distance protection. The manual [5] states in page 75 the following features to assure correct fault loop selection during combined faults being superimposed on top of load currents

- When using impedance pickup all six fault loops are released.
- So-called 'apparent impedances' are stated to 'usually be larger' than the faulted loop (in combined faults the one including the high level phase and the low level phase rather than the ground) thereby giving a selection using the fault loop with the smallest impedance.
- Phase selectivity is assured using a loop verification procedure, which compares the measured impedance to a line replica. If this replica and measured impedance match within some interval the loop is deemed valid.
- If the impedances of more than one loop are now located within the range of the zone, the smallest is still declared to be a valid loop. Furthermore, all loops that have an impedance which does not exceed the smallest loop impedance by >50% are declared as being valid. Loops with larger impedance are eliminated.

In this manner, unfaulty 'apparent impedances' are eliminated on the one hand, whereas on the other hand, unsymmetrical multi-phase faults and multiple short circuits are recognised correctly.

3.2 Relay B: VAMP 259

This relay is a simpler (and cheaper) type of distance relay, which seems to have a lesser degree of setting freedom. It includes six fault loops (three Ph-Ph and three Ph-E) and the zero sequence compensation is a standard one like described in (1). The manual [6] does not describe any procedures for selecting the correct fault loop during any conditions and therefore, neither for combined faults. It is not disclosed how 'apparent impedances' are treated.

4 Test setup for testing deployment of correct fault loop

The system from Fig. 1 is simulated in PSCAD using data provided by the Danish TSO, Energinet. The validation of the model was previously done and presented in [1]. In order to make the simulated faults realistic and their detection more challenging for the distance relays, a load $S = 400 + \mathrm{j}75$ MVA is connected to LAG-400 kV and a fault impedance of 2 Ω is used.

The phase to earth voltages and the line currents at the locations where the relays are installed are simulated and exported using Comtrade format. The Comtrade files are opened using an Omicron CMC 256-6 with advanced transplay module, which replicates the waveforms, as seen by virtual CT and VT, into the relays.

Two types of faults are simulated: SPTG fault and combined fault between different voltage levels. For both faults, it is considered a scenario where the higher voltage (HV) level leads the lower voltage (LV) level, as well as the opposite. For the former, it is expected that the two relays in the HV level (LAG and MAL) react to the fault, whereas to the latter two relays of the LV level (HAT and MAL) should operate. The faults are both 1 km from the MAL end, corresponding to 98.7% of the line length seen from LAG and 97% seen from a HAT. This location was chosen to have a worst-case scenario, as the fault is at an almost maximum distance from one relay, being very close to the other. Both cases may present challenges to distance relays in case of combined faults, as shown later.

All four cases are simulated considering two different short-circuit power levels at the six nodes. In one scenario all six nodes have a short-circuit power of 6000 MVA, with the value being 500 MVA for the other. These values are chosen, because Faria da Silva and Bak [3] showed that the fault loop impedance of a composite fault is more affected by variations in the network short-circuit power than the fault loop impedance of a SPTG fault. As a result, a total of eight cases are tested for each relay.

For both relays only the extended protection zone (Z1B) is used, corresponding to 120% of the line, as autoreclosure is normally the first step when protecting overhead lines against faults. Other zones would react with a delay and thus, if zone Z1B sees the fault, it means that the distance relays operate as desired. The reach of R is equal to the one of X, in order to account for changes in the angle of the fault loop impedance of combine faults, when compared with SPTG faults, caused by the 120° phase difference between faulted phases. This is explained in detail in [3].

For the Siemens relay, the log file is checked to see which phase(s) is triggered and the circle diagrams (i.e. R–X diagrams) are inspected to obtain the fault impedance seen by the relay and their trajectories.

Table 1 *R* and *X* values of the fault loop impedance for the relays at MAL

	R, Ω	*X*, Ω	|*Z*|, Ω
Com_HV	2.1/8	−2.2/−12.3	3.0/14.7
SPTG_HV	0.9/1.3	0.3/0.6	0.9/1.4
Com_LV	2/9	0.6/2.2	2.1/9.3
SPTG_LV	0.9/1.6	0.3/0.5	0.9/1.7

Left values: strong grid. Right values: weak grid.

Table 2 *R* and *X* values of the fault loop impedance for the relays at LAG or HAT

	R, Ω	*X*, Ω	|*Z*|, Ω
Com_HV	7.3/11.4	13.6/−4.1	15.4/12.1
SPTG_HV	3.8/2.8	21.6/22.4	21.9/22.6
Com_LV	8.5/–	7.2/–	11.1/–
SPTG_LV	6.8/–	9.6/–	11.8/–

Left values: strong grid. Right values: weak grid.

The VAMP relay informs which phase(s) are triggered by a fault, but it does not provide *R–X* diagrams; instead, values for the resistance and reactance of the fault loop impedance are provided, but it is not clear in the manual on how these values are estimated. However, it is possible to export the voltage and current waveforms and then plot the respective *R–X* diagrams. For a better comparison, the *R–X* diagrams are plotted using the same software (SIGRA) doing it in the Siemens relay.

It is important to refer that a small error is associated with all this process. The sampling frequency in the PSCAD simulation is larger than the one of the signals generated by the Omicron, which in turn is larger than the acquisition frequencies of the two relays. In addition, there is no information on the exact acquisition process and treatment of the data by the relays. The repetition of the same cases for the relays showed that there was a small variation in the fault loop impedances seen by the relays when repeating cases.

5 Combined fault test cases

The following cases are prepared:

- Com_HV_Strong: combined fault, HV leading, high short-circuit power;
- SPTG_HV_Strong: SPTG fault, HV leading, high short-circuit power;
- Com_HV_Weak: combined fault, HV leading, low short-circuit power;
- SPTG_HV_Weak: SPTG fault, HV leading, low short-circuit power;
- Com_LV_Strong: combined fault, LV leading, high short-circuit power;
- SPTG_LV_Strong: SPTG fault, LV leading, high short-circuit power;
- Com_LV_Weak: combined fault, LV leading, low short-circuit power;
- SPTG_LV_Weak: SPTG fault, LV leading, low short-circuit power.

5.1 Relay A

5.1.1 Relay at LAG/HAT: The relay does not see a fault for the two weak network cases, when having the LV leading, for both the combine and SPTG faults. This happens, because in these two cases the low short-circuit power increases the fault loop impedance, mainly the reactance, bringing it outside of the protection zone. A similar situation was observed in [3].

For the other six cases, the fault is seen as only an SPTG fault by the relay furthest away to the fault, meaning that the relay operates as desired and sees the combined fault as an SPTG fault.

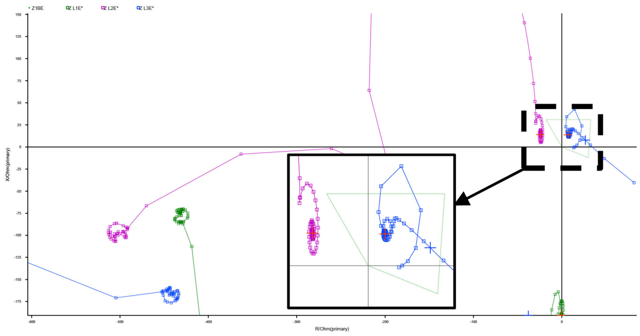

Fig. 4 *Fault loop impedances for L3-E (blue), L2-E (magenta) and L1-E (green) for Com_HV_Strong and relay at LAG*

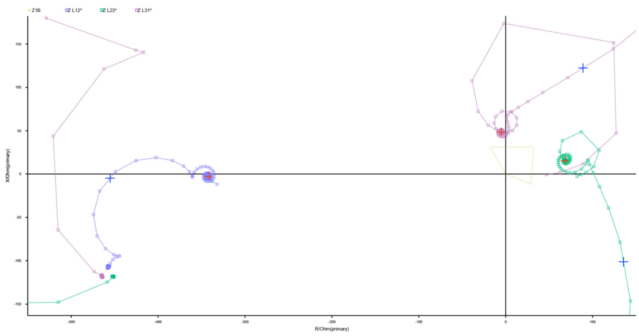

Fig. 5 *Fault loop impedances for L1L2 (blue), L3L1 (magenta) and L2L3 (green) for Com_HV_Strong and relay at LAG*

5.1.2 Relay at MAL: The relay sees seven of the cases as an SPTG fault in the correct phase and operates accordingly. The exception is Com_LV_Strong, where the relay sees the fault as phase-to-phase-to-ground. This means that the relay still clears the fault, but it also sees the fault in another phase (i.e. having trip activated from more than one fault loop).

Tables 1 and 2 show the *R* and *X* values of the fault loop impedance for the relays at MAL and LAG/HAT, respectively. The results are in accordance with those of [3], which performed PSCAD simulations for more scenarios. There are some differences between the *R* and *X* values, mainly the former because the relay reduces the *R* value to half in order to account for the fault impedance [5]. However, the relative behaviour between the fault loop impedances is in accordance with the conclusions from [3]. It is possible to notice that

- The short-circuit power has a much larger impact for combined faults than SPTG faults.
- The fault loop reactance of an STPG fault is higher (higher meaning first quadrant and larger) than a combined fault at the same location, with the latter seeing values in the fourth quadrant if the combined fault is close to a relay.
- As a result, if possible one should increase the angle separating forward and reverse zones in the fourth quadrant, to improve selectivity for faults very close to a relay.
- The *R* reach should be defined as at least equal to the *X* reach, or even bigger, and not be defined by the line resistance, because of the phase shifting in the fault loop impedance.
- To have the HV leading is more reliable for fault detection.
- The relay closer to the fault sees an increase in the fault loop impedance for combined faults, when compared with SPTG faults, whereas the relay further away sees a decrease (the latter is not always true, but it is expected for real short-circuit power levels). This means that it is easier for the relay further away to detect the fault.

Figs. 4 and 5 show the fault loop impedances seen by the relay at LAG for Com_HV_Strong. The combined fault is between L3 of the HV level and L1 of the LV level, which for this case means that the HV level leads with 120°, because of an autotransformer

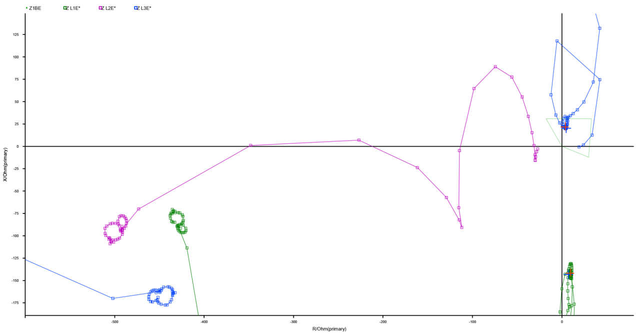

Fig. 6 *Fault loop impedances for L3-E (blue), L2-E (magenta) and L1-E (green) for SPTG_HV_Strong and relay at LAG*

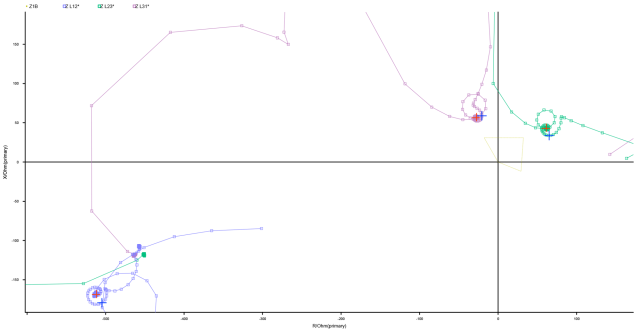

Fig. 7 *Fault loop impedances for L12-E (blue), L31-E (magenta) and L23-E (green) for SPTG_HV_Strong and relay at LAG*

linking HV and LV. Figs. 6 and 7 show the same fault loop impedances, for an SPTG fault at the same location and phase.

The comparison of the figures shows that the differences in the fault loop impedances are not considerable and are in line with the theoretical descriptions and expectation from [2, 3].

5.2 Relay B

5.2.1 Relay at LAG/HAT: The relay does not see a fault for the two weak network cases, when having the LV leading, for both the combine and SPTG faults, alike with the other relay. For the other six cases, the fault is seen as only an SPTG fault by the relay furthest away to the fault.

5.2.2 Relay at MAL: The relay sees six of the cases as an SPTG fault in the correct phase and operates accordingly. The exceptions are Com_HV_Strong and Com_LV_Weak, where the relay sees the faults as phase-to-phase-to-ground. This means that the relay still clears the fault, but it also sees the fault in another fault loop.

Tables 3 and 4 show the R and X values of the fault loop impedance for the relays at MAL and LAG/HAT, respectively.

The values are slightly different from those of Tables 1 and 2, especially for the relays at LAG/HAT, but this is expected as the two relays acquire and process the data differently. Nevertheless, the tendencies previously describe are also observed for this relay and it is again able to clear the combine faults successfully.

6 Discussions

An interesting case, worthy of a more detailed discussion is the operation of relay A at MAL for the Com_HV_Strong case. As previously stated, the relay managed to detect the fault, but the inspection of the R–X diagram shows that although the fault goes through the protection area, it ends outside of it, as shown in Fig. 8. The final fault loop impedance is very close to the limit of the protection area, there is an error associated to the data acquisition and it is unknown in detail how the relay decides to send a trigger signal, which could explain this behaviour. This case also supports the recommendation for increasing the angle between forward and reverse zones, in order to increase the selectivity of the relay.

Table 3 *R* and *X* values of the fault loop impedance (using *R*–*X* diagram) for the relays at MAL

	R, Ω	*X*, Ω	|*Z*|, Ω
Com_HV	2.0/7.1	−2.6/−14.5	3.3/16.1
SPTG_HV	0.9/1.3	0.1/0.3	1.3/0.9
Com_LV	2.7/9.1	0.5/0.0	2.7/9.1
SPTG_LV	1.2/1.6	0.3/0.2	1.2/1.6

Left values: strong grid. Right values: weak grid.

Table 4 *R* and *X* values of the fault loop impedance (using *R*–*X* diagram) for the relays at LAG or HAT

	R, Ω	*X*, Ω	|*Z*|, Ω
Com_HV	8.0/11.0	11.4/−8.2	13.9/13.7
SPTG_HV	5.4/4.2	18.6/21.2	19.4/21.6
Com_LV	9.9/–	5.7/–	11.4/–
SPTG_LV	7.5/–	8.1/–	11.0/–

Left values: strong grid. Right values: weak grid.

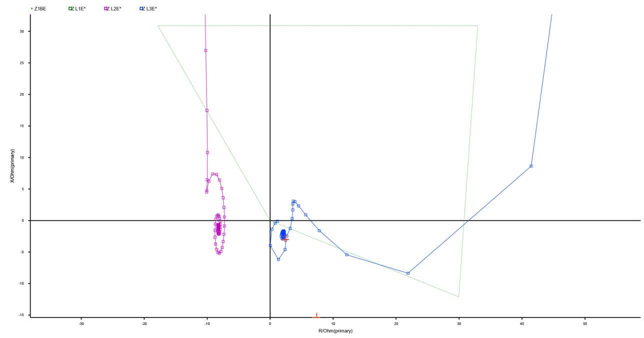

Fig. 8 *Fault loop impedances for L3-E (blue), L2-E (magenta) and L1-E (green) for Com_HV_Strong and relay at MAL*

However, it is important to notice that this parameter cannot always be set, being pre-defined for some relays.

7 Conclusions

Previous studies have shown that a combined fault between different voltage levels in overhead lines presents a somewhat different challenge to distance relays than ordinary SPTG faults. This has been studied intensely and it was proven that in almost all practical cases, the combined fault had a fault loop impedance, making it possible to clear it using standard SPTG fault zone settings.

This paper has shown that two distance relays of different manufacture actually selected the correct fault loop for clearing the combined fault in the same way as the SPTG fault. This finally proves that the proposed philosophy for protecting combined lines using SPTG zone settings works when implemented as settings in the two tested distance relays.

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