ANALYSIS OF PROTECTION MALFUNCTIONING IN MESHED DISTRIBUTION GRIDS

Evita PARABIRSING
TU Delft - The Netherlands
evitapara@hotmail.com

Edward COSTER
Stedin – The Netherlands
edward.coster@stedin.net

Marjan POPOV
TU Delft – The Netherlands
m.popov@tudelft.nl

ABSTRACT- *In this paper, the protective system of an existing sub-transmission grid with a meshed grid structure is studied. Malfunctioning of the protective system in such networks is experienced. The cause of incorrect operation is studied by analyzing relay-fault current detection during phase faults and earth faults. The impact of fault location on the detected fault current is also examined. The different system faults are first analyzed analytically and to assess whether fault current detection takes place or not, the obtained fault current magnitudes are compared with the relay setting values. Furthermore, by making use of developed network modes, simulations are carried out and the simulated results are verified with the analytical results. With the simulation model multi-phase and single-phase-to-ground faults are evaluated. The paper ends up with possible solutions in order to prevent the protective system malfunctioning problem and guarantee fault clearing during a fault in the meshed grid structure.*

INTRODUCTION

Electric power systems are subjected to all kinds of events leading to disturbances of their proper behaviour. Most of these disturbances are small, e.g. anticipated imbalances in generation and load, tolerated overload and voltage deviations, and the power system can withstand these disturbances. Large disturbances, usually related to faults, are accompanied by large current and voltage excursions and can, amongst others, lead to serious equipment damage. This abnormal system condition has to be recognized and an appropriate action has to be taken in order to limit the equipment damage. This is done by the protective system. Proper operation of the protective system and fast and selective fault clearing is very important, however, in some cases the protective system is not able to detect and clear the fault properly. This problem is experienced by the protective system of an existing sub-transmission grid with a meshed grid structure. The sub-transmission grid (25 kV) consists of underground cables only and is schematically depicted in Figure 1. Because of the meshed grid structure, the definite overcurrent relays (IOC) as well as directional relays (DIR) are applied. In the recent past, several faults have occurred in such networks and some of the faults are not sensed and cleared properly by the protective system. If the protection equipment fails to trip, it may have a catastrophic impact on the system performance. In this case, the consequences may be:

- Prolonged fault current which could lead to long-lasting voltage dips
- Possible components damaged due to the long-lasting circulating high fault currents

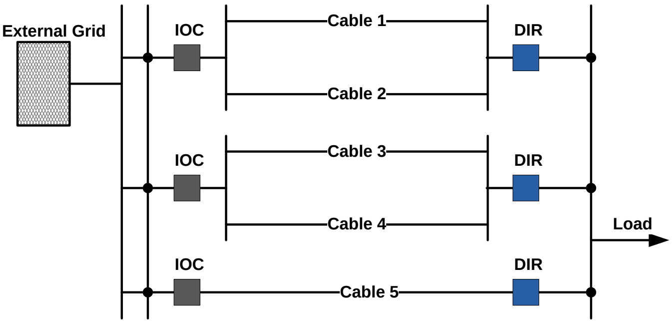

Figure 1: 25 kV underground sub-transmission grid with corresponding protection scheme

POWER SYSTEM PROTECTION

General

The implementation of adequate protection is very important in power system design. The purpose of protective systems is to detect faults or abnormal operating conditions and to initiate corrective actions [1]. Protective systems which make use of protection relays are implemented throughout the system. Protection relays provide corrective action which means that they cannot prevent a fault occurrence but they have to detect the fault, take a correct action as quickly as possible and due to this, minimize the system or component damage.

Principle of overcurrent and directional protection

Overcurrent relays (IOC) are the most common form of protection, which operate when excessive currents that flow in the power system during different system faults. The overcurrent protection operating requirements are the overcurrent unit and the time restraint [2]. The operating requirements of the overcurrent relay are represented by the blocks in Figure 2.

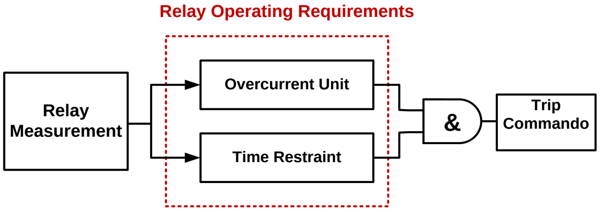

Figure 2: Representation of the overcurrent relay operating requirements

Overcurrent relays are non-directional; the current measurement does not give an indication of the current direction. In case of meshed and loop networks satisfactory discrimination can be achieved by also implementing **directional overcurrent relays** (DIR). They are placed in network locations where fault currents which flow in reverse direction (from load side to source side) must be detected. The directional overcurrent relay contains three operating requirements, namely the overcurrent unit, directional control facility and the time restraint[2]. The operating requirements of the directional protection relay are represented by the blocks in Figure 3. Only if all conditions exceed the relay threshold values, a trip signal is generated.

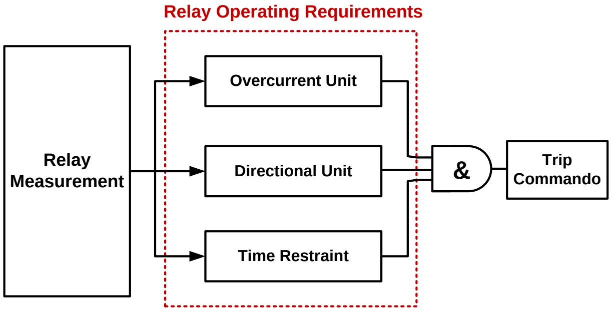

Figure 3: Representation of the direction overcurrent relay operating requirements

SHORT-CIRCUITS AND DETECTED FAULT CURRENT ANALYSIS IN MESHED-NETWORKS

Approach

From the actual network section shown in Figure 1, a simplified model is made, Figure 4, which can easily be analyzed. In this model the impedance Z is the total impedance of all three phases and the external network is represented by the equivalent system impedance (Z net) and a voltage source.

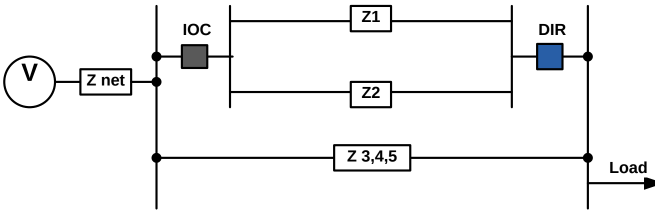

Figure 4: Simplified equivalent impedance model

During short circuits, the total fault current and the circulating fault currents are dependent on a certain distance parameter "k" of the cable where the short circuit occurs. If a short circuit occurs on Cable 1 at a distance L and the total length of Cable 1is L_{tot}, then the distance parameter "k" can be defined as:

$$\boldsymbol{k = \frac{L}{L_{tot}} \times 100\%} \tag{1}$$

The total length (L_{tot}) of the studied cable is 2 km and "k" varies from 0% at the beginning of the cable up to 100% at the cable end.

As shown in Figure 5, when a short circuit occurs on Cable 1 at a certain location with distance parameter "k", the total fault current circulating fault currents through the protection relays (detected fault currents) are analysed as follows:

- IOC detects circulating current $\boldsymbol{I_{IOC} = (I_f - I_{f2b})}$
- DIR detects circulating current I_f $= \boldsymbol{I_{f2b}}$

With:

$\boldsymbol{I_f}$ = the total fault current as function of "k" and

$$\boldsymbol{I_f = I_{f1} + I_{f2}} \tag{2}$$

$$\boldsymbol{I_{f2} = I_{f2a} + I_{f2b}} \tag{3}$$

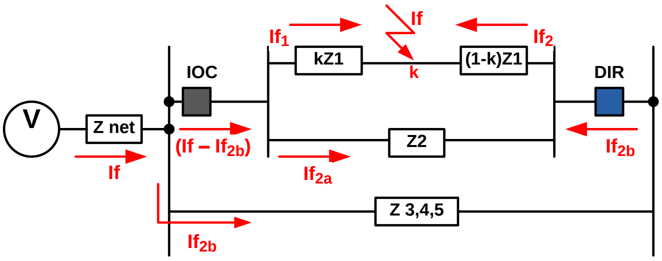

Figure 5: Circulating and detected fault currents during short circuit at "k" on Cable 1

The current $\boldsymbol{I_{f2}}$ can be easily derived from a further simplified model which is shown in Figure 6. In this figure the following holds:

$$\boldsymbol{Z_{2,3,4,5} = 0.25Z \overset{so}{\Rightarrow}}$$

$$\boldsymbol{(1-k)Z + Z_{2,3,4,5} = Z(1.25-k)} \tag{4}$$

Therefore:

$$\boldsymbol{I_{f2} = \frac{kZ}{kZ+Z(1.25-k)} \cdot I_f = \frac{k}{1.25} \cdot I_f} \tag{5}$$

With the help of Figure 5 and formula (5) the current I_{f2b} can be derived as follows:

$$\boldsymbol{I_{f2b} = \frac{Z}{Z+Z_{3,4,5}} \cdot I_{f2} = 0.75 \cdot I_{f2} = 0.6 \cdot k \cdot I_f} \tag{6}$$

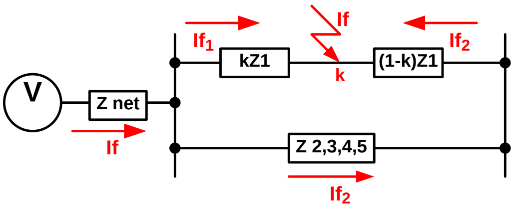

Figure 6: Simplified model for the derivation of I_{f2}

Results: Analysis of Three phase faults

Because a three-phase fault is a symmetrical fault, the total fault current can easily be derived by using Thevenin's Theorem, which creates an impedance model looking from the fault back into the network [3]. In this model the currents produced throughout the network by the fault can simply be found by applying the voltage just before the fault occurs (V_f) to the fault point k. This model is constructed in Figure 7.

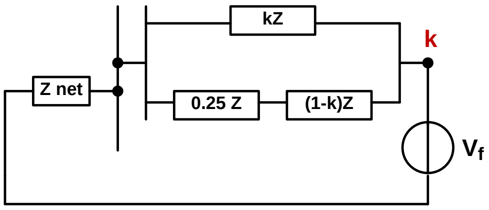

Figure 7: Equivalent impedance model for three phase fault calculation

During a three phase fault occurs the impedance between each line and a common point stays the same. With this fault impedance (Z_f) and the voltage (V_f), the total fault current (I_k) as function of "k" can easily be derived:

$$I_f = \frac{V_f}{Z_f} = \frac{V_f}{Z_{net}+0.75kZ(1.25-k)} \tag{7}$$

By substituting the necessary actual network parameters in formulas (3), (5), (6) and (7), plots can be made from the total three phase fault current (I_f) and the detected fault currents as function of "k". These plots are shown in Figure 8. The analysed fault current magnitudes are compared with the protective system setting values to assess whether the protection relays react correctly upon the fault. The corresponding setting values are given in Table 1 and also plot as I(sett) in Figure 8.

Table 1: protective system setting values

Settings	IOC	DIR
I>>	n/a	n/a
I>	840 A	840 A
t>	2 sec	0.5 sec

It can clearly be seen in Figure 8 that the graph of the fault current detected by the DIR starts at zero Amps if k=0% and as k increases, the detected fault current magnitude also increases. It is also clearly shown in Figure 8 that if 0% < k < 8%, the fault current through the DIR has a magnitude which is lower than the relay current setting value (I(DIR) < 840A). This means that if a short circuit occurs within 0% and 8% cable length, the DIR will not react on the fault as is expected from it. This area is referred to as the *dead zone*.

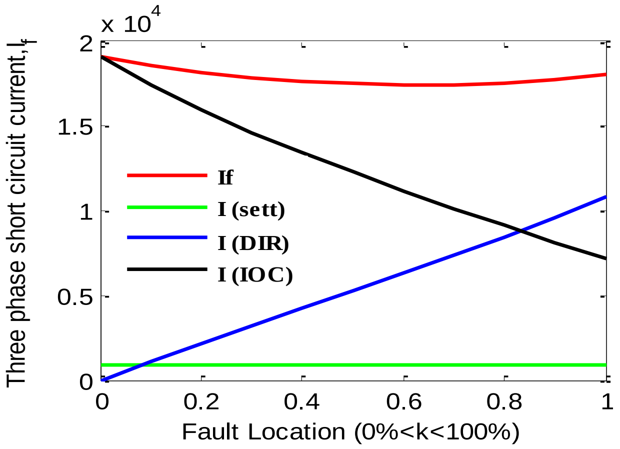

Figure 8: Total three phase fault current (If) and detected fault current magnitudes as function of "k"

Analysis of other phase and earth faults

The same analysis can be used to determine the total fault current and the detected fault currents during the different short circuits which can occur in the network. The results of the analysis show that for all short circuit currents which can occur in the system, there exist *dead zones* within the protection areas. If any system fault occurs within these dead zones, the DIR will not be able to detect the short circuit current. The circulating fault currents can also not be detected by the DIR because of their low magnitude, which is much lower than the DIR current threshold value. The dead zones for all short circuits respectively are given in Table 2. These dead zones in the studied network section are indicated as red areas in Figure 9.

Table 2: Available *dead zones* in the network during different short circuits

System Fault	Dead Zone
Three phase fault	0% < k < 8%
Line-to-line fault	0% < k < 9%
Single line-to-ground fault	0% < k < 15%
Double line-to-ground fault	0% < k < 8%

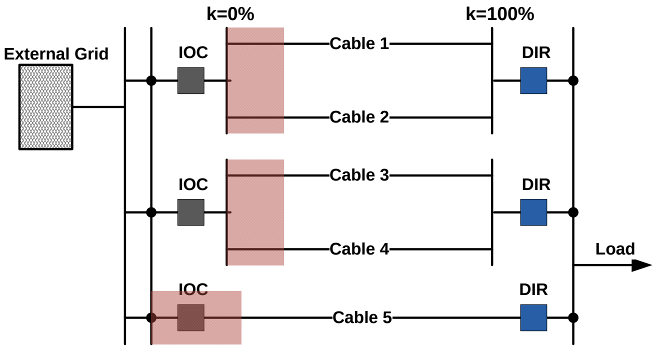

Figure 9: Available dead zones in the studied network section

STRATEGY FOR MITIGATION OF THE PROTECTION MAL-FUNCTION PROBLEM

If any system fault occurs within the available *dead zones*, the results may be a prolonged circulating fault current which can cause long-lasting voltage dips, system component damage and even unnecessary outages. There are possible strategies which can completely mitigate the protection mal-function problem. Due to space limitations only readjustment of IOC settings is discussed in detail.

The I>>, Ie>> and t>>, te>> settings of the currently used protection scheme are not activated in this network section. If coordinated properly, these settings of the IOC relays could be activated and adjusted in such a way that fast selective switching could be obtained when short circuits occur within the *dead zones*. During these system faults the detected IOC fault currents must be high enough to exceed the I>>, Ie>> thresholds of the IOC and instantaneous tripping could be generated with instantaneous tripping times for t>>, te>>. For selective tripping with these settings activated, the following conditions should be fulfilled:

- The detected fault current magnitudes $I_{f(IOC)}$ must exceed the thresholds $I \gg_{IOC}$, $Ie \gg_{IOC}$ during phase and earth faults respectively.
- The IOC relays must not trip for system faults occurring outside their protected zone.
- $t \gg_{IOC}$, $te \gg_{IOC}$ must be lower than $t >_{DIR}$, $te >_{DIR}$ respectively, to obtain selective tripping.

Example three phase faults

When substituting the necessary system parameters in formulas (5), (6) and (7), the detected fault current magnitude ranges for three phase faults occurring within the dead zone and outside of the protected zone respectively are given in Tables 3 and 4. This analysis is visualised in Figure 10.

Table 3: I(IOC) for three phase faults within the dead zone

Fault type	Dead zone	I(IOC) (kA)
Three phase fault	0% < k < 8%	18.5 < I(IOC) <19.0

Table 4: I(IOC) for three phase faults occurring outside the protected zone

Fault type	I(IOC) outside (kA)
Three phase fault	11.4

By proper time grading between the IOC and DIR relays, the *dead zone* problem is completely overcome. With the proposed protection relay settings shown in Figure 11 three phase faults within and outside the protected zone are switched off selectively by the relays. This analysis can be applied for all other system faults. Other strategies to mitigate this protection mal-operation problem are extensively explained in [5].

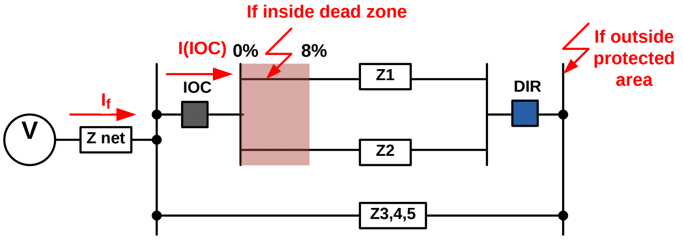

Figure 10: Faults occurring within the dead zone and outside of the protected zone

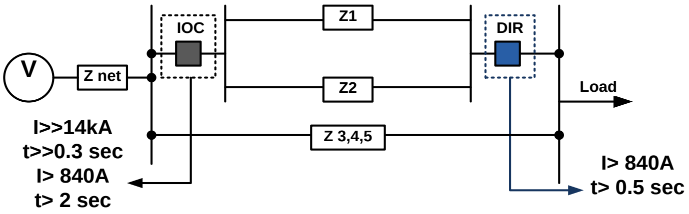

Figure 11: Proposed relay settings for selective switching of three phase faults inside and outside the dead zone

CONCLUSIONS

It is found that incorrect relay tripping occurs due to the presence of certain *dead zones* along the length of the cables. If any type of system fault occurs within these *dead zones*, the circulating fault current magnitudes are found to be lower than the directional relay current threshold. It can be concluded from the analysis that generally this phenomenon will always occur in complex network structures with single source feeding.

It is concluded that selective switching can be achieved when system faults occur within as well as outside the *dead zones* by activating and correctly adjusting the I>>, Ie>> and t>>, te>> settings together with proper time coordination between the overcurrent and directional overcurrent relays in the network section.

An alternative protection scheme which can be implemented in the network to mitigate the ‘dead zones’ is the differential protection scheme. With the proper settings the differential protection scheme will work perfectly, but due to the required pilot wires or optical fibers or other high frequency communication equipment this scheme can be relatively expensive.

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