RETURN PATHS OF EARTH FAULTS CURRENT IN MEDIUM VOLTAGE GRIDS WITH UNDERGROUND SHIELDED CABLES

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ABSTRACT

The design of earthing schemes in Belgian MV networks was established in the past based on the electrical knowledge of the time and has led to the implementation of a certain earthing strategy, around the idea of global earthing. New simulation tools lately have allowed for a more detailed modelling and analysis of the fault current return paths and it appears that the impacts of the conductors' metallic screens have been underestimated.

It appears that in a configuration thanks to which the fault current can return via a continuous path of interconnected screens all the way back to the earthing transformer, most if not all of the fault current will return via this path rather than via the multiple earth connections. This is due to a suction effect induced by the fault current in the conductors, following Lenz law. Several use cases have been investigated and tend to confirm this conclusion.

INTRODUCTION

The earthing of MV networks is primarily designed to limit the fault current during short-circuit and to limit the rise of voltage potential during earth faults locally. New and more performant simulation tools allow for refined calculations of earth faults currents, and notably for their return paths.

In time, the nature of the MV-network in Belgium evolved. Overhead lines are replaced by underground cables in the major part of the country, with the shields interconnected and locally grounded. These shields are either mounted around each separated phase conductor or around the bundling of the three phase conductors for older cables. They are connected at both ends of the cable connection with the local earthing at either the main HV/MV substation or an intermediary MV substation. This architecture resulted in a "global" earthing in the network. The idea is to present a multitude of paths for the return of a fault current to the earthing transformer at the HV/MV substation. More paths introduce a higher repartition of the fault current and thus lowers the individual current in each earthing connection.

When studying the return paths of fault currents thanks to the latest simulation capacities, it appears that the repartition between the different paths composed of the earthing connections and the interconnected metallic screens might have been misconceived. Mostly, it is the effect of the mutual impedance and the consequent suction effect induced by the one-way fault current which seems to have been neglected or largely underestimated.

THEORETICAL BACKGROUND

Lenz law states that a variation in magnetic flux will induce an electromotive force in a direction such that the consequent current induces a magnetic flux variation which opposes the original variation. This is expressed in the following formula via the minus sign:

$$\varepsilon = -\frac{\partial \Phi}{\partial t} = -\mathrm{M}\frac{\partial I}{\partial t}$$

Concretely, an alternative current in a conductor will induce a voltage of opposite direction in an adjacent conductor, thus inducing a corresponding current if said conductor is part of a closed circuit. This is illustrated in Figure 1.

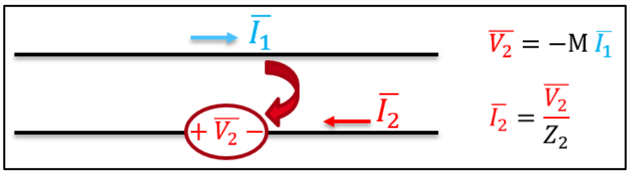
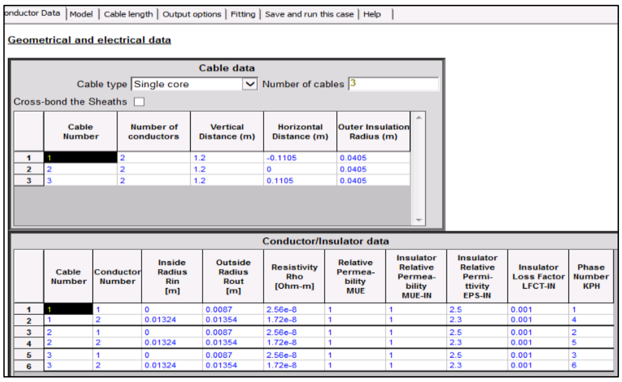


Figure 1: Lenz law applied to two adjacent conductors

In the case of a fault in a MV network with interconnected metallic shields around each conductor, this induces a suction effect which makes a significant part of the fault current return to the earthing transformer via the shields surrounding the conductors through which the fault current flows to the fault. It is worthy to mention that if a parallel pathway of screens is available for the current as well, if it was not part of the one-way path of the fault current, then it won't present the aforementioned suction effect and the current will thus not be attracted into it.

SIMULATION TOOL AND HYPOTHESES

The simulation tool used is EMTP-RV®. Mainly used for electromagnetic transients, but it can also be used for power flow calculations. The specificity of this tool compared to other electrical grid modelling software is the possibility to model the components such as cables or aerial lines in 3D with the specification of the physical materials used. All the electromagnetic interactions between conductors are thus totally taken into account without having to simplify the problem by calculating equivalent impedances such as the zero impedance Z_0. This eliminates one risk of error by reducing the abstraction level of the modelling. An example of inputs for a cable data is shown in Figure 2. The first table is used to enter the geometrical data (positions and sizes of all conductors with respect to one another) while the second one is used to enter the electrical data for each conductor.



onductor Data | Model | Cable length | Output options | Fitting | Save and run this case | Help

Geometrical and electrical data

Cable data

Cable type: Single core — Number of cables: 3

Cross-bond the Sheaths

	Cable Number	Number of conductors	Vertical Distance (m)	Horizontal Distance (m)	Outer Insulation Radius (m)
1	1	2	1.2	-0.1105	0.0405
2	2	2	1.2	0	0.0405
3	3	2	1.2	0.1105	0.0405

Conductor/Insulator data

	Cable Number	Conductor Number	Inside Radius Rin [m]	Outside Radius Rout [m]	Resistivity Rho [Ohm-m]	Relative Permea-bility MUE	Insulator Relative Permea-bility MUE-IN	Insulator Relative Permi-ttivity EPS-IN	Insulator Loss Factor LFCT-IN	Phase Number KPH
1	1	1	0	0.0087	2.56e-8	1	1	2.5	0.001	1
2	1	2	0.01324	0.01354	1.72e-8	1	1	2.3	0.001	4
3	2	1	0	0.0087	2.56e-8	1	1	2.5	0.001	2
4	2	2	0.01324	0.01354	1.72e-8	1	1	2.3	0.001	5
5	3	1	0	0.0087	2.56e-8	1	1	2.5	0.001	3
6	3	2	0.01324	0.01354	1.72e-8	1	1	2.3	0.001	6

Figure 2: Example of cable data as inputs in EMTP model

One of the MV network used in this study is illustrated in Figure 4 and shown in details as a model in EMTP in Figure 3. In this example, several MV feeders depart from the same HV/MV substation and are interconnected along the way via either direct connections or via a LV connection thanks to a common PEN conductor (between C & D). Each downward substation is earthed via a 1Ω resistance (arbitrary value for this use case). Each conductor has a metallic shield and all shields are interconnected and grounded at both ends of each feeder. Two fault locations are represented as a red lightning in the schematic and have been simulated in various scenarios. The length of each cable stretch as well as the conductors' layout is displayed in the lower-left corner. Finally, the impedance of the fault's arc is seen in the upper-right corner. The impact of its value on the results has also been studied.

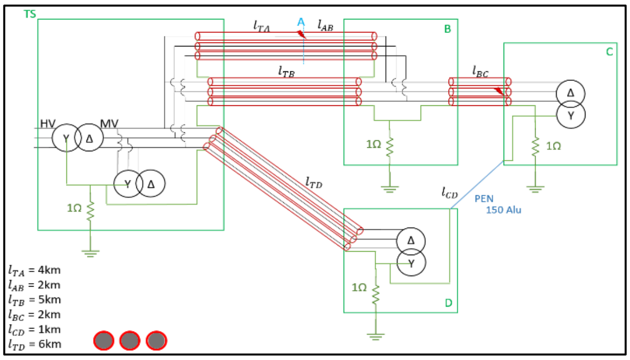


Figure 4: Schematic of an example of MV network under study

The various models studied followed the following hypotheses:

- Ground impedance = 0Ω. This hypothesis is of course an approximation, but in this case it is a conservative one since a zero impedance in the ground will tend to favour the current going back via the earth, while this study aimed to study the share of fault current going back via the shields.
- MV/LV transformers neglected.
- MV cable conductors of 240 mm² Aluminium.
- LV PEN (Protective Earth-Neutral) conductor of 150 mm² Aluminium.
- Earthing transformer with a limit of 1000 or 2000 A (both cases simulated).

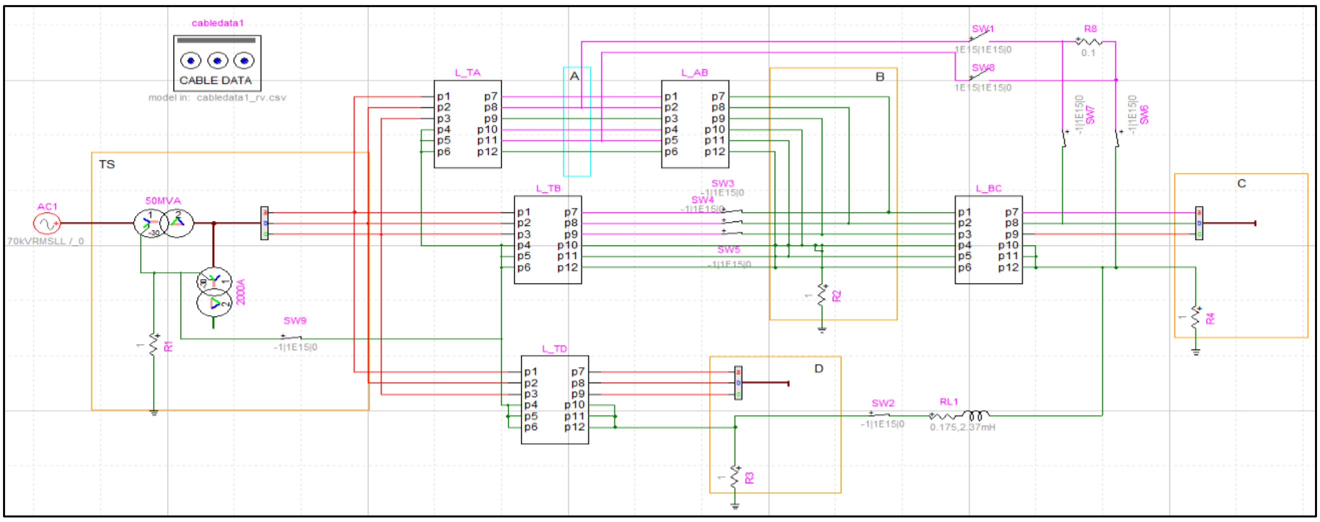


Figure 3: Example of a circuit modelled in EMTP for fault simulations

EXAMPLES OF RESULTS

The results of one of the simulations is shown in Figure 5. A 1-phase fault is applied close to the substation C on phase B (in the middle of the three conductors). It can be seen that a total fault current of 1800A flows through the network and comes back to the earthing transformer. It is worthy to mention that the direction of each current in the schematic is based on a reference for the phase angle of the currents which is the fault current at the fault location (the grey value 1771A).

The fault current returns mostly via the shields, as the one-way current attracts the return current in the corresponding shields via the suction effect (Lenz law). It can be seen that the three shields are concerned, since they are all close to the central conductor which is in fault. The central shield, being closer to the central conductor, attracts more current than the other two. Since the one-way current is split between two parallel feeders, the return path follows the same itinerary. The shields of the "TD" feeder do not present a significant current since there is no suction effect present there and thus the return current does not take that path although it could have via the PEN conductor or via an upward earth connection.

What is even more surprising and counter-intuitive is that in this specific case, the current not only does not comes back via the earth connections, but it even comes from the earth to reinforce the currents in the shields because of the strength of the suction effect in this particular configuration. In most configurations and scenarios, this was not the case although the current returning via the earth connection was always very small if not negligible.

The arc impedance being quite limited in this example, the fault current is mainly limited by the earthing transformer impedance and is thus logically relatively close to the 2000A limit value. Different scenarios with higher arc impedances have been tested (up to 10Ω) and the trends observed in the case displayed are the same, although the global fault current amplitude is lower.

Another circuit modelled and simulated with a fault is shown in Figure 6. In this case cables with one common screen for the three phase conductors and with another conducting area (150 mm^2) were also used. The results are similar and the same trends are observed. In the configuration displayed, a very small part of the fault current goes back via the earth connection at the fault's location, but a significant part of this earth current returns in turn in the shields via the other earthing connections upward in the feeder. This is due to the fact that the latest part of the feeder is a bit shorter than the other ones, thus inducing a smaller suction effect and allowing for more current to return via the earthing connection.

Among the conclusions of this second circuit study were the following:

- Higher earthing resistances do not necessarily imply a lower earth current. It can thus consequently imply higher voltages on said earthing resistances.
- The higher the length of the cables, the higher the suction effect and the lower the earth currents.

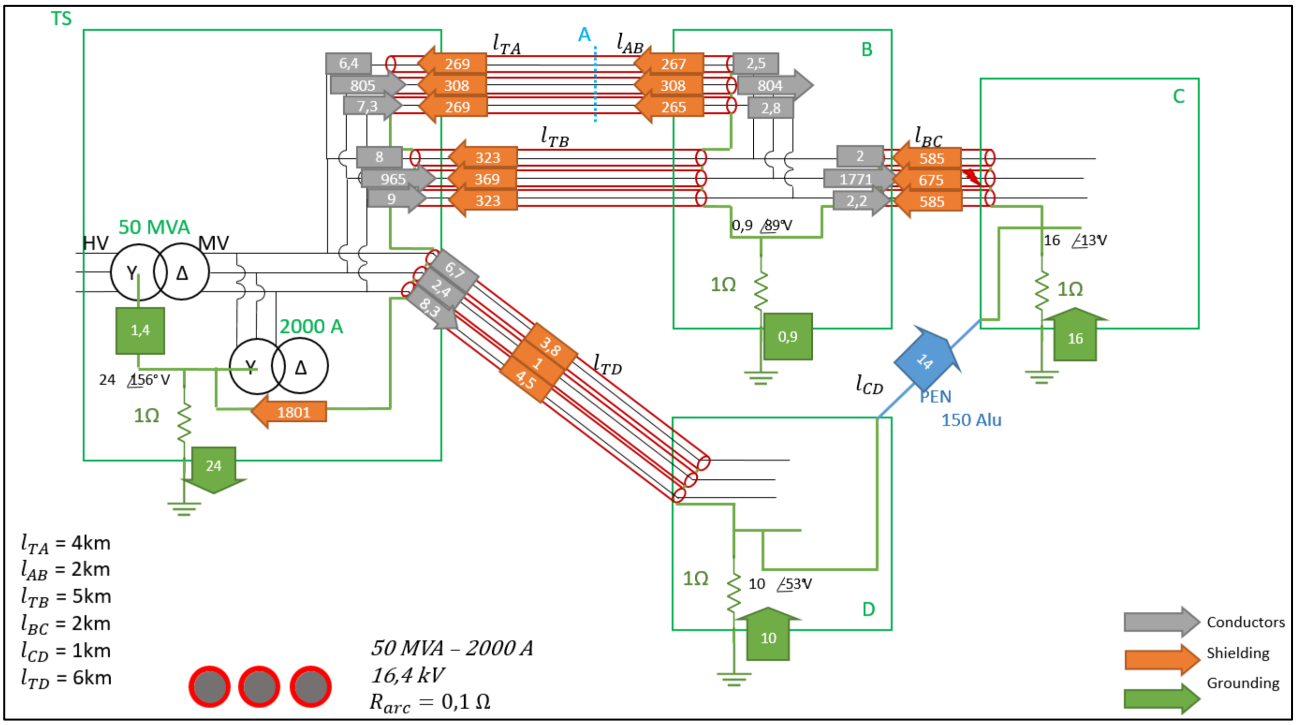


Figure 5: Results of a fault simulation close to substation C in the modelled circuit

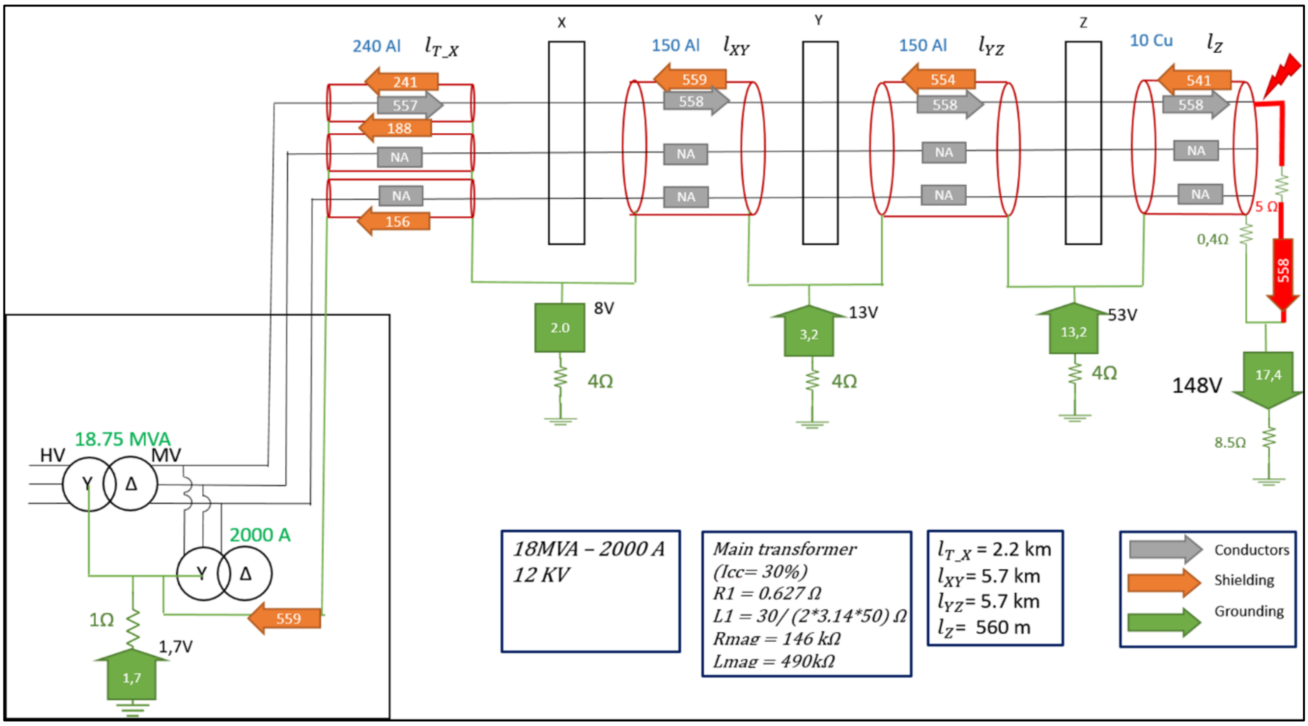


Figure 6: Results of a fault on another circuit modelled

COMPARISON WITH NEPLAN®

In order to assess whether the tool NEPLAN®, used up to now in a lot of faults simulations and analyses for distribution networks, actually provides an accurate fault current estimation, a comparison was made with EMTP results on the first basic case. The main difference between the two tools is that in the first one the user can only indicate the zero impedance Z_0 of each individual elements (cables, transformers, etc.). By doing so, the suction effect cannot fully be taken into account, since it depends entirely on the one-way path of the fault current and thus on the specific combination of the concerned conductors and shields. The details of the mutual impedances are thus lacking in this case.

The circuit modelled is shown in Figure 7. It can be directly observed that the level of details in the fault current return paths is not the same as in the EMTP tool. Apart from that, the same cables and grid elements (transformers, PEN conductor) were used.

The results yielded that NEPLAN® globally gives a fault current which is relatively accurate in magnitude, with differences ranging from 2 to 27% of the global fault amplitude depending on the scenario and the hypotheses. This is due to the fact that the total Z_0 is mainly formed by the earthing transformer and the arc resistance. The current is however given without any indication of the return path. Furthermore, it has been noticed that in order to obtain the exact same current as EMTP, one must change Z_0 drastically.

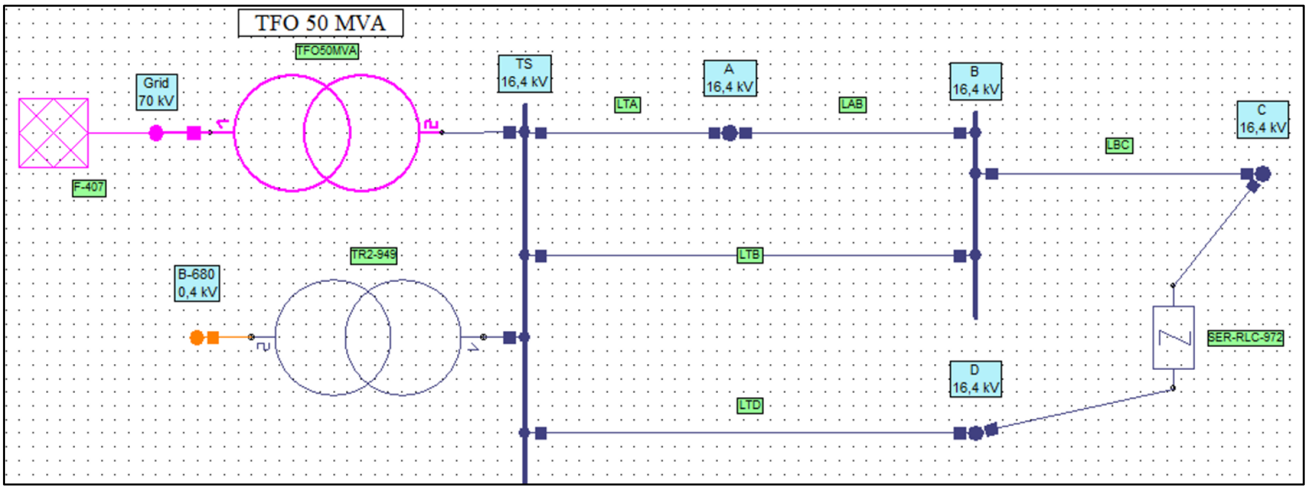


Figure 7: NEPLAN® model of the first MV network studied

CONCLUSIONS

Several use cases of typical Belgian MV networks with underground shielded cables have been studied with the EMTP-RV® simulation tool. The physical details of the cables configuration and the fault current return paths have been modelled and allowed for a finer analysis of those return paths than with more classical tools such as NEPLAN®.

The suction effect induced by the one-way fault current in the conductors on the metallic shields makes most of the fault current go back via the shields instead of via the earthing connections as it could have been thought before when only thinking in terms of least-impedant paths. This can lead to a revised way of seeing the earthing scheme in MV networks which were mostly composed of aerial lines in the past.

Such results on a few selected use cases prompt for further simulations on wider networks with different configurations not yet studied. Notably, the analysis of a mixed MV network composed of both aerial lines and underground shielded cables would be very interesting. In that case it could be expected that the return path of the fault current would highly depend on the fault location and whether it is located on a feeder composed entirely of underground shielded cables, entirely of aerial lines or even of a mix of both.