HIGH CURRENT FAULTS IN RESONANT GROUNDED NETWORKS UNDER ASPECTS OF A GLOBAL EARTHING SYSTEM

Lothar FICKERT
TU Graz – Austria
lothar.fickert@tugraz.at

Thomas MALLITS
TU Graz – Austria
thomas.mallits@tugraz.at

Ernst SCHMAUTZER
TU Graz – Austria
schmautzer@tugraz.at

ABSTRACT

Earth fault tests and measuring in earthing systems in medium voltage networks show that the current distribution is not only depending on the station's local earthing system. Also the connected cable shields, cable support earth electrodes, reduction conductors as well as the connected protective-earth-neutral-installations and foundation earth electrodes, have an influence on the current distribution. Thus in many cases, only a "small" percentage of the total fault current passes through the local earthing system of the station, which is the main cause for the earth potential rise and in consequence for the gradient, the touch voltage during a ground fault.

In this paper, the authors show the influence of grounded conductive structures connected to the earthing system during a ground fault in the station and on the fault current distribution. As result touch and step voltages and potential transfers during an earth-fault and other fault cases can be identified, for example in a transformer station or a cable to overhead line pylon. To round the paper off, some statistical approaches for the evaluation of grounding systems are shown.

INTRODUCTION

The determination of resulting fault currents, depending on the earthing system, is the basis for the calculation and evaluation of the expected step- and touch voltages. In practice the earthing system of general MV/LV-transformer stations can't be treated as a separate closed system. For the implementation of the medium voltage system, today mainly cables with earthed shields are used, which carry a part of the fault current. On the low voltage side in TN-systems also a distribution of the fault current happens, leading to dangerous voltage.

A set of measurements and evaluations of earth faults in urban and suburban middle voltage grids have shown, that a large part of the middle voltage fault current is flowing back through the cable shields (based on inductive and galvanic coupling). Only a small part of the fault current flows over the local earthing system into the soil.

If the fault current distribution is determined by measurement or simulation, it may be possible to identify dangerous locations (e.g. cable to overhead transition pylons) and determine the necessary measures (e.g. isolation of the location).

Specifically in cases with high soil resistivity and potentially high fault currents, the current distribution becomes very important. In this paper a high current fault location method is the reason that in a resonant grounded grid high fault currents (limited artifical double ground fault for 1 s) high EPR and touch voltages can occur.

The objectives of the paper are:

- description of the fundamentals and backgrounds of grounding
- determination of the current distribution and the earth surface potential
- description of the main influencing factors, based on high current fault localization

Structure of the paper:

- basic principles
- determination of the current distribution in the region of MV / LV substation
- calculation of earth surface potential
- outlook (pragmatic assessment approaches and statistical analysis)

BASIC PRINCIPLES

Fundamentals around Grounding

Figure 1 shows the relevant key terms (Current, Earth Potential Rise - EPR) in the case of an earth fault in an electrical grid.

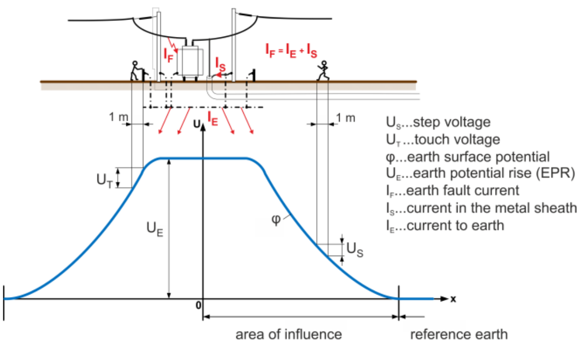

Figure 1 Current and EPR relationships of an earthing system in case of an earth fault

As Figure 1 shows a single phase earth fault in an electrical installation, the resulting fault current I_F is split into different return paths (e.g. current to earth I_E, current through the middle and low voltage cable metal shield).

The current distribution primarily depends on two factors. These are the inductive coupling of the conductors and the current distribution due to the impedance ratio of the individual current return paths.

The basis for calculation of the ground return current distribution is the knowledge of the connected conductor structures (e.g. reduction conductor, cable shields etc.) and their impedances.

Important for the evaluation of an earthing system regarding personal safety in the case of an earth fault are the earth potential rise, touch and step voltage.

The touch voltage U_T is a part of the ground voltage U_E which can be experienced from people when the horizontal distance between the foot and the exposed hand part is 1 m (current flow from one hand to the feet). The definition of the step voltage U_S refers to that part of the ground voltage which can be tapped by a step size of 1 m in case of an fault (current flow through the feets) [8].

Description of the analyzed situation

Figure 2 shows the principle structure which is the base for the analysis in this paper. It consists of an MV / LV transformer station which is supplied by a substation through a combination of cables and an overhead line. For an earthing measurement the percentual current distribution is shown.

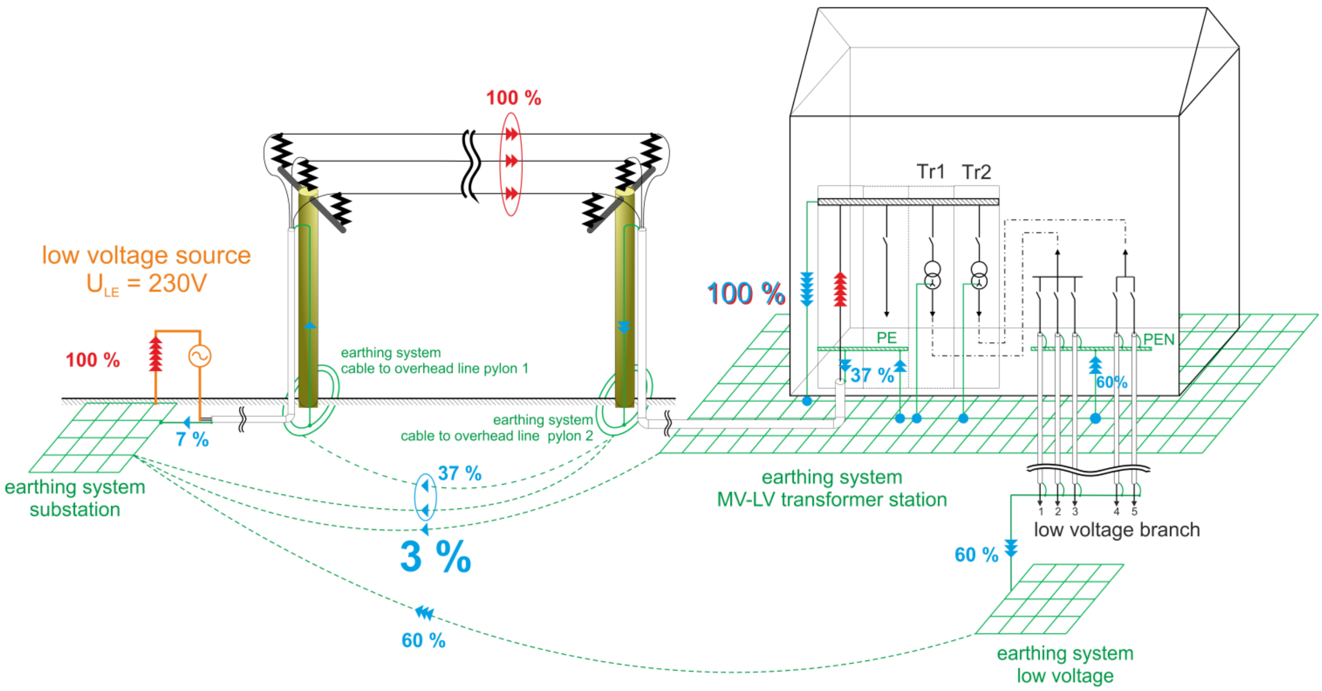

Figure 2 Basic Structure

Function of healthy phase earthing – HPE (high current earth fault localization)

High current earth fault localization provides good in-depth fault localization, in resonant grounded networks. But there is the risk of higher cost to toughten the earthing system and a possible higher personal safety risk because of higher EPR than in the case of resonant earthed systems. Typical fault detection current values in HPE systems are in the order of some hundred Amps to max. 1.25 kA (see Figure 3)

The function of HPE as shown in Figure 3 can be explained in four steps:

1.) t = 0 s: ground fault in L1
2.) t = 3 s: connecting R_{CC}
   - I_F=1.25 kA
3.) t > 3 s: stimulation of overcurrent (directional) relay or distance relay
   - locating the fault with overcurrent indicators
   - tripping the failed branch
4.) t = 4 s: disconnecting R_{CC}

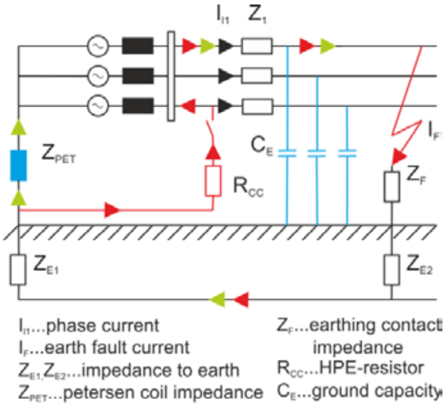

Figure 3 Typical circuit diagram of a Healthy Phase Earthing (HPE) scheme

Figure 4 shows the HPE unit

Figure 4 Resistor R_{CC} (left), Selection circuit and circuit breakers (right)

DETERMINATION OF THE CURRENT DISTRIBUTION

General

The current distribution among the different paths depends on the impedances of the connected conductors (impedance along the lines and cables, grounding impedances etc.), on earthing conditions and inductive couplings (e.g. cable metal shields).

Measurement of the current distribution

During an earthing measurement the current distribution in the structure (see Figure 2) was measured. The results of the measurements are shown in Table 1.

Calculation of current distribution with a simulation model (Simulation of the current distribution)

The calculation of the current distribution was carried out by a three phase model in Matlab® Simulink®. The inductive coupling of the conductors was calculated by the calculation methods of Carson [7] and Pollaczek [8]. The results were used in the phase model [4] to calculate the current distribution. An advantage of the model is that the multiple distributed grounding conductors (e.g. PEN conductor) and their reduction effect can be considered.

The result of the calculation is shown in Table 1.

Influencing Factors

The main factors of the current distribution are the soil resistivity, the geometrical situation of the conductors and in consequence the ratio of the impedances in the system and the inductive coupling [3].

Comparison of measurement and calculation

The comparison of the results in Table 1 shows that a simplified calculation model regarding the inductive coupling of conductors, with consideration of the equivalent resistances of a several times earthed PEN conductor can be used in principle to determine the current distribution.

location	measured		calculated	
	A	%	A	%
medium voltage				
test current	1 250	100	1250	100
∑ cable shields	463	37	475	38
low voltage				
∑ PEN-Leiter	750	60	725	58
station				
earthing electrode of the station	38	3	50	4

Table 1: measured and caclulated current distribution

The results in Table 1 show, that only 3% of the fault current flows from the grounding system of the station into the soil. As might be expected a big part of the fault current returns through the shield of the MV cable (inductiv coupling of the fault loop over the cable metal shield). The second big part of the current returns through the low voltage earthing systems of the LV TN-system. In the next chapter the relevance of the results for the personal safety is explained.

CALCULATION OF THE EARTH POTENTIAL RISE

Global Earthing System

In literature and standards, there are different definitions for a global earthing system GES. Often the phrase "closed housing areas" is representative in use for global earthing systems, without assigning allowable and clear numerical values for the earthing systems resistance or impedance.
In the standard EN 50522 [5] a global earthing system is defined by the touch voltage: For a mains voltage range above 1 kV a grounding system is regarded as globally, if no dangerous touch voltages occur.
In the following section, the influence of the resistive coupling of single earthing is demonstrated by the step- and touch voltage with an example, simply to give a sense of the geometric limits of a global earthing system.

Theoretical Background for the calculation of the earth surface potential

For the calculation of the earth surface potential of earthing electrodes coupled through the stationary flow field in the earth (see Figure 5), the method of potential coefficients [1],[2] is used. The central point here is to determine the potential of a single earth electrode that is generated by its own flow field and the flow fields of further ohmic coupled earthing electrodes in the vicinity. The self-potential of an earth electrode (which has the form as an ellipsoid) is determined by its surface and the current flowing on it into the ground.

$$\varphi(r,z) = \frac{I \cdot \rho}{4 \cdot \pi \cdot l} \cdot ln \left| \frac{z + e + \sqrt{r^2 * (z+e)^2}}{z - e + \sqrt{r^2 * (z-e)^2}} \right|$$

$\varphi(r,z)\ldots$ potential (elliptical coordinate system)
$R_{Sum}(x)\ldots$ sum of earthing resistances
$\rho\ldots$ soil resistivity
$l\ldots$ side length of the earth electrode
$z, r\ldots$ elliptical coordinate system
$e\ldots$ eccentricity

The external potential of another earth electrode is determined by its self-potential and the potential of all the other electrodes at the vicinity of it.

By specifying the current of each single earth electrode, the coupling factors can be calculated.

$$k_{ij} = \frac{\varphi_i}{I_j}$$

$k_{ij}\ldots$ coupling factor in Ω
$\varphi_i\ldots$ potential of a single earth electrode in V
$I_j\ldots$ current of a single earth electrode in A

The total earth surface voltage and thereby the earthing resistance of the hole earthing system can be calculated by superposition.

$$U_E = \sum k_{ij} \cdot I_j$$

$U_E\ldots$ EPR in V

Influencing Factors

As in the former chapter explained the relevant influencing factors of the EPR are [3]:

- the injected current in the earthing system
- the specific soil resistivity
- geometry of the earthing system (number and arrangement of single earth electrodes).

Earth potential rise

For the calculation of the earth surface potential (shown is the absolute value) the current distribution through the earting systems (Table 1) is used. As Figure 5 shows that inside of the global earthing system (village with about 40 single-family homes and foundation earthing electrodes) no high touch voltages have to be expected. The same applies to the area of the substation.

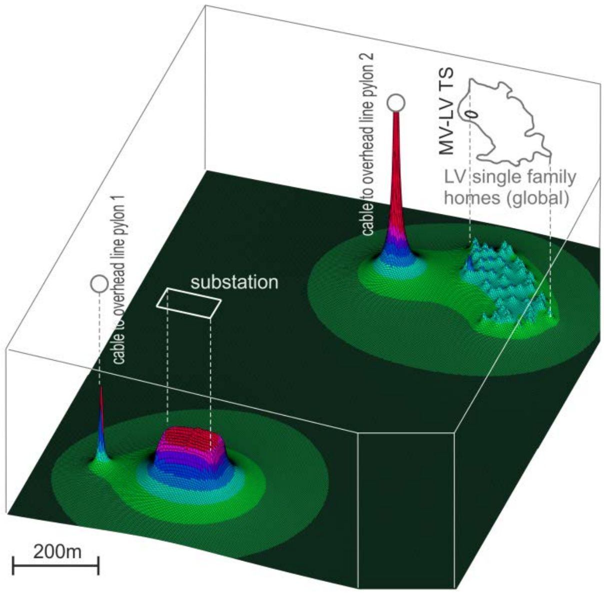

Figure 5 earth surface potential

Because of the impedance ratio and the inductive coupling, the earth surface potential and the expected touch voltage around the cable lifting pylon is much higher then the earth surface potential of the second one.
This example illustrates how important it is to consider the whole system with the focus on touch voltages, if a fault occures and HPE is working. So the maximum of EPR does not occur in the area of the fault but preferably in the area of outlying small earthing electrodes e.g. cable lifting pylons, transformer stations, farmsteads, liftstations, pumping stations etc..

Outlook

Statistical considerations

A statistical approach to the assessment of earthing systems can be found in the Power System Earthing Guide [6]. The likelihood $P_{fatality}$ of a fatality occurring, can be described by the following equation:

$$P_{fatality} = P_{coinic} \cdot P_{fib}$$

$P_{fatality}\ldots$ likelyhood (Propability) of a fatality occurring
$P_{coinc}\ldots$ probability that one or more risk events will occure
$P_{fib}\ldots$ probability of fibrillation

The probability of fibrillation includes body current, contact resistances, fault duration etc.

Example:

Under the assumption that a person touches an outlier every week for 20 seconds and the HPE appears three times a year for 1 s, P_{coinic} can be calculated as:

$$P_{coinc} = \frac{r_{fault} \cdot r_{exp} \cdot (t_{fault} + t_{exp}) \cdot T}{365 \cdot 24 \cdot 60 \cdot 60} \cdot CFR$$

$$P_{coinc} \frac{3 \cdot 52 \cdot (1 + 20) \cdot 1}{365 \cdot 24 \cdot 60 \cdot 60} \cdot 1 = 1{,}04 * 10^{-4}$$

$P_{coinc}\ldots$	Probability that one or more risk events will occur
$t_{exp}\ldots$	average duration of the average exposure in s
$t_{fault}\ldots$	Average duration of the average fault in s
$r_{exp}\ldots$	Rate which the exposures occur in #/a
$r_{fault}\ldots$	Rate at which fault occur in #/a
$T\ldots$	Number of years (exposure duration)
$CFR\ldots$	Is Coincidence reduction factor

In this example an increased risk can be noted. So if the risk is higher than the socially accepted risk ($P_{fatality}$ usually $<10^{-6}$) further measures are necessary.

SUMMARY

In this paper, the influencing factors for the earthing current distribution and the effect onto the earth surface potential during a ground fault are shown.
Under the aspect of the fault location method HPE the fault current reaches up to 1,25 kA throughout the fault clearing time.
The main influencing factors for the current distribution are the inductive coupling as well as the ratio of the earth electrode impedances and earthing resistances. For the earth surface potential the main influencing factors in addition to the fault current are the earth electrode geometry, the resitive coupling and the specific soil resistivity.
The example in the paper shows that in practice only a small amount of the fault current flows through the earth electrode of the station into the soil. Furthermore it is shown that the maximum of EPR does not necessarily occur in the area of the fault but in the vicinity of outliers.
To round the topic off, a small excurse for the evaluation of grounding systems depending on personal safety by help of statistical methods and a pragmatic approach for the local relationship between EPR, earthing impedance and touch voltage are shown.

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