DEFINITION OF CRITERIA TO OPERATE 20 kV NETWORKS WITH ARC SUPPRESSION COILS ACCORDING TO STANDARDS

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ABSTRACT

E.ON Bayern is the largest regional network operator in Germany. The area of supply is 54,000 km² and covers the regions East Bavaria, Upper Bavaria, Upper and Lower Franconia. The utility supplies customers with heat, gas and electrical energy. The total length of medium voltage and low voltage lines is about 140,000 km. In the largest region East Bavaria one hundred and thirty four 20 kV networks are operated. These supply regions are mainly rural and large areas are difficult to access. Nearly all networks are operated with arc suppression coils and are mixed networks with cable and overhead lines. This paper gives the criteria to operate the 20 kV networks of East Bavaria with arc suppression coils according to standards.

INTRODUCTION

Characteristics of the 20 kV networks of E.ON Bayern in East Bavaria

Figure 1 shows the supply area of E.ON Bayern.

Figure 1: Supply area of E.ON Bayern

A maximum residual current of 32 A was given in the guidelines of East Bavaria for the design of equipment. Step by step overhead lines were replaced by cables, which were also used for network extensions. Due to the increasing proportion of cable the capacitive earth fault current, and consequently the residual current during earth fault conditions increased.

As a result, in the future in some areas during earth fault localization and maintenance work the residual current might exceed the given design value of 32 A. Furthermore, the actual design value decisively limits the possible network size and also restricts the possibilities for structural changes in the 20 kV networks.

To ensure the future operation of the 20 kV networks according to standards E.ON Bayern decided to study 8 selected 20 kV systems of East Bavaria with regard to the increased residual currents. A team of E.ON Bayern and Siemens AG employees was tasked to develop a concept based on the investigations of the selected 20 kV systems. The following steps were carried out:

- Check of requirements as defined by standards
- Evaluation of the maximum magnitude of earthing resp. residual currents of the actual 20 kV networks
- Evaluation of the effectiveness of the earthing systems of the consumer substations
- Definition of a new and higher design value for the residual current to be included in the guidelines of E.ON Bayern
- Elaboration of a concept to identify the consumer substations and towers of the 20 kV networks of East Bavaria which do not fulfill the new requirements
- Compiling of a catalogue of measures for improving the earthing systems with respect to the future higher residual current

Operation with arc suppression coils

The capacitive earth fault current at the fault location is compensated by an inductive current fed in by Peterson coils. Due to the small residual current at the fault location this method allows to detect and disconnect the faulted section under earth fault conditions without supply interruptions. Considering the conditions of overhead line systems most arcs automatically extinguish in a very short time without the need for action. The self-extinction of arcs depends on different parameters. One decisive parameter is the magnitude of the residual current. According to DIN VDE 0228 part 2 [3] the flashover in a 20 kV system may extinguish up to 60 A residual current. Considering the conditions of a cable system, each earth fault is a permanent fault. The main risk during operation is that the permanent earth fault might extend to a double earth fault before the faulted section can be located.

At the fault location the residual current leads to damages of equipment and touch voltages. Additionally to the effects at the fault location all parts of interconnected network will be affected during earth fault conditions. In medium-voltage...
overhead line systems resonant earthing has the advantage of self-extinguishing arcs and provides the option of fault clearing without supply interruption. Depending on the value of the capacitive earth fault current and the structure of the network the problems for operation and equipment increase.

Requirements defined by standards
In principle the standards allow the operation of high-voltage networks including medium-voltage networks under earth fault conditions. Typically the operation under permanent earth fault conditions lasts between half an hour and two hours. With respect to standards the main aspects German network operators should consider during earth fault conditions are:

- Operational aspects ( DIN EN 50110-1 [1])
- Thermal aspects regarding the design of equipment (e.g. HD637 [2])
- Interference of telecommunication systems (DIN VDE 0228-2 [3])
- Tolerable touch voltages (HD637 [2], HD384.4.442 [4], DIN EN 50423-1 [5], DIN VDE 0141 [6])

Operation
With regard to operation the standards require equipment to detect the earth fault condition and the immediate start of fault localization to minimize the danger at the fault location. Therefore, protection devices must be installed to detect and indicate the faulted feeder. For this purpose transient earth fault relays or sensitive directional earth fault relays are used. The detection and disconnection of faulted section requires the switching of several circuit breakers and load breakers before clearing the fault. These requirements are fulfilled with the standard equipment used by E.ON Bayern.

Thermal design of earthing system
The standards provide equations to calculate the required cross-sections considering the decisive fault currents. These requirements are fulfilled with the standard equipment used by E.ON Bayern.

Interference of telecommunication systems
Regarding interference during earth fault conditions the standards (DIN VDE 0228-2) do not generally require the verification of compliance with limits. Since the residual current given in the standards is kept (I_{res}<60A), a verification is not required.

Touch voltages
Based on the test procedures given in the standards the check of the touch voltage requirements is rather complex. Regarding tolerable touch voltages different conditions have to be analyzed:

- Touch voltage conditions at the consumer substations
- Touch voltages in the low-voltage networks caused by potentials transferred during earth fault
- Touch voltages at the towers of the 20 kV overhead lines

Impedance values measured with the earth resistance tester were available for all 20 kV consumer substations of the region East Bavaria of E.ON Bayern.

Main task
Considering the above mentioned standards the main task was finding an economically feasible concept to evaluate the earthing conditions of the large number (>18,000) of consumer substations regarding tolerable touch voltages. HD637 [2] requires the compliance with permissible touch voltage limits depending on fault clearing time, considering the individual condition at the high-voltage station. A defined tolerable value of impedance to earth is not given. According to HD637 [2] the single possibility to measure touch voltages of a high-voltage station is performing the heavy current injection test (Annex N of HD637 [2]). On the one hand this heavy current injection test is rather time consuming, on the other hand a calculation of actual touch voltage values is often not possible with the required reliability and within given economical possibilities.

Therefore, HD 637 allows the calculation of ground potential rise and the evaluation of the ratio between calculated ground potential rise (U_E) and the actual permissible touch voltage (U_perm) value in case the ratio fulfills the requirement U_E ≤ 4 U_perm. If this limit cannot be kept the actual touch voltages have to be checked!

Regarding the interconnection of the high-voltage earthing system (operated with arc suppression coils) and the low-voltage neutral, HD637 [2] as well as IEC60364-4-42 [4] define a limit for the maximum ground potential rise depending on the operation of the actual low-voltage system:

- TN-system: \( U_E \leq X \cdot U_{perm} \); \( X = 2 \) for X exceptions are possible depending on the conditions at site
- TT-systems: \( U_E \leq 250V \)

These tasks regarding tolerable touch voltages can be reduced to the determination of ground potential rise: \( U_E = I_E \cdot Z_E \)

\( U_E \): Ground potential rise
\( I_E \): Earthing current
\( Z_E \): Impedance to earth

Based on the concept of HD637 [2] in the evaluation of earthing conditions the following tasks have to be performed:

- Determination of decisive current
- Determination of impedances to earth

The check of the earthing condition of a single consumer substation requires the determination of both values with about the same precision. Considering the future operation of the 134 networks a generalization has to be carried out. It was decided to base this generalization on investigations in 8 different 20 kV systems showing adverse conditions regarding earthing or regarding residual currents and which are located in different supply areas of East Bavaria.
DETERMINATION OF EARTHING CURRENT

According to HD637 [2], in the networks operated with resonant earthing the decisive earthing current is defined as follows:

\[ I_E = r_E \cdot I_{\text{res}} \]

- \( I_E \): Earthing current
- \( r_E \): Reduction factor
- \( I_{\text{res}} \): Residual current

With:

\[ I_{\text{res}} = \sqrt{(I_C - I_L)^2 + I_R^2 + I_H^2} \]

- \( I_C \): Capacitive earth fault current
- \( I_L \): Inductive current of Peterson coil
- \( I_R \): Ohmic part of earth fault current
- \( I_H \): Harmonic part of earth fault current

As the different contributions of residual current are unknown and depend on many different parameters, the determination of the size of the residual current is a difficult task. There are basically three different ways of determining the earthing current:

- By earth fault trials
- Rough approximation according to HD637
- By approximation of different contributions

**By earth fault trials**

By means of earth fault trials the residual currents can be measured directly. The disadvantage of this method is that these trials cause a lot of effort and there is a risk that the first fault caused by the test might trigger a cross-country fault or even a multiple fault at different locations. Furthermore, the test shows only a short period of time and it is difficult to judge if this moment is significant. Even if it was possible to evaluate this value the future behaviour would remain unknown.

**Rough approximation according to HD637 [2]**

In case the exact value of the residual current is not known HD637 allows the approximation based on 10% of the capacitive earth fault current of the considered network.

**By approximation of different contributions**

The remaining reactive contribution as well as the ohmic part can be determined by measurements [7] with little effort. It is known that the harmonic contribution of residual current correlates with the THD of line to ground voltages during normal operation. Some methods for the approximation of harmonic contribution have been published (e.g. in [8]). A closed analytical way has not yet been defined.

**Determination of Residual Current**

Measurements of the resonance curve of the residual voltage were carried out in the 8 investigated networks. Based on these measurements the contributions of the residual currents were determined using the methods published in [7] and [8].

With the adverse parameters found the residual current of the generalized 20 kV network was calculated. Figure 2 shows the residual current of the generalized 20 kV network depending on the value of the capacitive earth fault current. The residual current of the generalized network shows that increasing the design value of the residual current from 32 A to 60 A would increase the possible network size to a capacitive earth fault current of about 730 A. This would result in:

- Increase of operational possibilities in case of parallel operation of 20 kV networks during maintenance work or faults
- Essential increase of possibilities regarding future structural changes in 20 kV networks
- Increased stress at fault location
- Increased ground potential rise and resulting increased touch voltages
- Increased inductive interference

Based on the results of the investigation the project team recommended a new design value of \( I_{\text{res}} = 60 \) A for the residual current.

**CHECK OF EFFICIENCY OF EARTHING SYSTEMS OF CONSUMER SUBSTATIONS**

The existing earthing systems were designed considering a residual current of 32 A. It had to be checked whether the earthing systems are sufficient with respect to the future and increased design value of 60 A, based on the permissible touch voltage of \( U_{\text{perm}} = 75 \) V. The new design value would result in an acceptable impedance to earth of \( Z_E = 2 \cdot U_{\text{perm}} / I_{\text{res}} = 2.5 \) Ω.

Based on the above mentioned statement of HD637 [2] this task can be reduced to determining the impedance to earth. There are different possibilities for the determination of the impedance to earth:

- Calculation based on the area covered and on the measurement of the specific soil resistivity and an approximation of impedances connected in parallel
- Measurement with the earth resistance tester (Expressis verbis according to HD637[2], Annex N not applicable for earthing systems of consumer substations connected to low-voltage systems)
- Measurement with the heavy current injection test (According to HD637[2], Annex N)
In principle the heavy current injection test is required to simulate earth fault conditions and to evaluate touch voltages, e.g. caused by transferred potentials at the PEN-conductors of low-voltage systems. Due to the huge area influenced e.g. by different soil layers and type and size of low-voltage systems connected in parallel the typical measurement with the earth resistance tester cannot involve the entire interconnected system. Therefore the results are not reliable. The problem is that the results are not in any case on the safe side. However, as it is not economically feasible to carry out heavy current injection tests for several thousand consumer substations, utilities all over the world use the earth resistance tester to determine the impedance to earth of consumer substations. As E.ON Bayern can provide the impedance values found by earth resistance testing for all of the more than 18,000 consumer substations of East Bavaria the following points have to be checked:

- Reliability of values
- Possibility of using the existing data base for the identification of those consumer substations which have to be improved
- Measures for improving the earthing systems discussed

To answer the first question more than 120 heavy current injection tests were carried out in the 8 selected 20 kV networks. Then a concept was developed for determining the consumer substations unsatisfactory with regard to the future i.e. higher residual currents. The earthing systems of these substations will have to be improved.

**Comparison of test methods**

Figure 3 shows that when considering the entire number of tests, 73% of earth resistance tests showed impedance values higher than the values measured by the heavy current injection tests. According to this it does not make sense to invest in improving earthing systems based on earth resistance tester impedances only. Considering the values \( Z_E \leq 2.5 \Omega \) based on the earth resistance tester no value measured with the heavy current injection test was higher than the resulting limit of \( Z_E = 2.5 \Omega \).

Therefore, it can be stated that all investigated stations defined as sufficient based on the resistance tester results were satisfactory in practice regarding the new and higher design value. The investigation showed that in case the earthing systems are not sufficient regarding the future design value, in some cases heavy current injection tests are required to find the required measures and to prove that the measures carried out fulfil the requirements of the standards.

**Concept for selecting consumer substations suitable for future requirements**

Based on the data base already available, a screening of consumer substations satisfactory regarding the future design values could be performed. The remaining small percentage of consumer substations had to be checked using a defined procedure, starting with an additional check via earth resistance tester carried out by specialists of the recommended inhouse earthing team. Depending on the results the standard measures for improving the earthing system had to be defined. Nevertheless, in some cases the heavy current injection test could not be avoided.

![Comparison of different methods](image)

**Figure 3: Results of the comparison of different test methods**

A catalogue of different earthing measures was compiled, containing e.g.:

- Additional earth electrodes, like surface electrodes or rods
- Interconnection or separation of high-voltage and low-voltage earthing systems
- Reducing the earthing current by replacement of the feeding overhead line by cables
- Switch-off of faulted feeder if other measures are not successful

**SUMMARY**

Due to the standard concept of E.ON Bayern and the limited size of the 20 kV networks of the elaborated area most of the technical requirements mentioned are fulfilled. The investigation showed that for the tolerable touch voltage the decisive current, as well as the earthing conditions at the sites, have to be considered. With respect to the individual earthing conditions at a consumer substation the heavy current injection test is required. However, the results obtained with the earth resistance tester can be used for the selection of consumer substations satisfactory with regard to the future requirements of \( I_{res} = 60 \) A resp. \( 2.5 \Omega \). The implementation of this elaborated concept allows for the recommended increase of the design value of the residual current from 32 A to 60 A.

The following steps have already been taken:

- Implementation of the defined procedure in the 20 kV networks of East Bavaria
- Training of inhouse earthing expert team
- Extension of investigations to conditions in the regions Franconia and Upper Bavaria of E.ON Bayern
REFERENCES

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[8] Edgar Lüke: Longterm investigation of residual currents in networks operated with arc suppression coils Elektrizitätswirtschaft, Jg. 96 (1997), Heft 19