The BOSES computer program – a tool for calculating harmonics in the residual earth fault current

Preamble

Public medium voltage (MV) mains electricity grids are normally provided with an earth system using resonant grounding, so if there occurs a single pole earth fault the rest of the network will continue to function and the consumer will still have an uninterrupted electricity supply.
In cases of network extensions and the steadily increasing number of cables in the electricity grid as well as the increasing harmonic currents in the medium voltage grid lead to rising residual earth fault currents in this networks. Only a very vague estimation is possible as to which networks have reached or exceeded the permitted limits and as to whether action on the part of the network planner is or will soon be necessary. The reason is that accurate calculation is extremely complex and time-consuming. Indeed, actual measurement is difficult and not without risk. The development of a computer program to calculate residual fault current in relation to the degree of distortion in the supply voltage is potentially useful here.

Necessity of limiting residual earth fault currents

The requirement for high reliability in the electrical supply has combined with the technical and commercial advantages to ensure that Germany's public medium voltage networks are usually operated with a so called "RESPE" system, which stands for resonant earthing of the neutral point [1]. As readers will be aware, the fault current when there is a single pole earth fault in these networks will be reduced at the point of the fault to a value which will permit continued operation of the network for a limited period and may even lead to the automatic extinguishing of any fault current arc. If there is to be no interruption in the consumer's supply in the case of an earth fault it is necessary to keep within a contact voltage limit of U_{Tp} = 75 V for 20 kV networks which have been compensated. Taking all of the following into account

- Contact voltage as per DIN VDE 0101 (VDE: German electrical engineers' association) for any electrical equipment
- Arc to be extinguishable [approx. 60 A in 20 kV-networks]
- DIN VDE 0228 part 2: influence on telecommunication equipment

earthing electrodes are usually set to cope with a maximum residual earth fault current, I_r, of 60 A.

Rise in residual earth fault currents

In recent years, residual earth fault current has been steadily rising in public MV electricity networks. The cause of the trend is largely the extension of the networks and the increased proportion of cable in transmission lines associated this. There is also an increased degree of distortion in the supply voltage.
The following equation for the residual earth fault current (I_r) demonstrates the relations:

$$I_r = I_{CE} \sqrt{v^2 + d^2 + i_{rh}^2} \quad (1)$$

With the fault current $I_{CE} = \sqrt{3}\, U_N\, \omega\, C_E$ (this is the 50 Hz value)

U_n	:	mains voltage
ω	:	angular frequency
C_E	:	capacity between conductor and ground
h	:	harmonic index.

These are the meanings of the symbols in equation (1):

$v = 1 - I_D/I_{CE}$	detuning (50 Hz value) I_D: choke current in the earth coil
$d = I_{Wr}/I_{CE}$	attenuation I_{Wr}: Effective residual current (50 Hz value)
$i_{rh} = I_{rh}/I_{CE}$	Harmonic residual current in relation to I_{CE}.

It is clear from equation (1) that the magnitude of the residual earth fault current is largely determined by the 50-Hz value of the earth fault current itself (I_{CE}) and thus by the area which has to be supplied by the electricity grid. The attenuation is usually in the range between 2 % and 4 % but may reach a figure of 6 % in overhead transmission networks. The detuning level can be set and may, for example, be limited in cable networks to values between 0 and 2 % because of the naturally low displacement voltage. Reducing of harmonics in the residual earth fault current is not simply possible, since the earth fault current choke on the neutral point of the transformer is tuned for a resonance frequency of 50 Hz. For the residual earth fault current to be kept down to $I_r \leq 60$ A, the proportion of harmonics i_{rh} must be known, and this is largely determined from the distortion in the supply voltage. Measurements of the current when an earth fault occurs have shown that it is not only in the large-scale electricity grids that the limit given above for residual earth fault current is being reached or even occasionally exceeded, as might be expected, but also in relatively small networks covering only a small area.

<u>Indispensability of prior calculation of residual earth fault current</u>

Up to now, because of the wide variety of grids and the large number of influencing factors, a reliable decision as to which grids or networks urgently require limitation of the residual earth fault current has been possible only upon carrying out painstaking measurements which are both risky and costly. The use of simplified calculation procedures, derived, for example, in [3] from systematic grid measurements, have produced genuinely reliable values in a number of cases but have also revealed serious deviation between prior calculations and actual measurements. When planning decisions are to be made concerning the extension of medium voltage electricity grids, safety considerations and any possible intention to raise the proportion of cable used mean that it is essential for the residual earth fault current values to be known accurately, i.e., in particular, the proportion of harmonics in these. It must be remembered that the harmonics in the residual earth fault current is dependent on THD U, the degree of distortion in the supply voltage, and that this is subject to considerable alterations in the course of a day, with the highest values being recorded at weekends and the strongest influence being exerted by the 5th harmonic voltage (Figure 1). Measured earth fault currents have also revealed that the harmonic element in a fault near the supply station (in the area of the transformer) is present in a higher proportion than when the fault is in switching stations remote from the transformer. Additionally, the proportion shows no significant relation to the earth fault current.

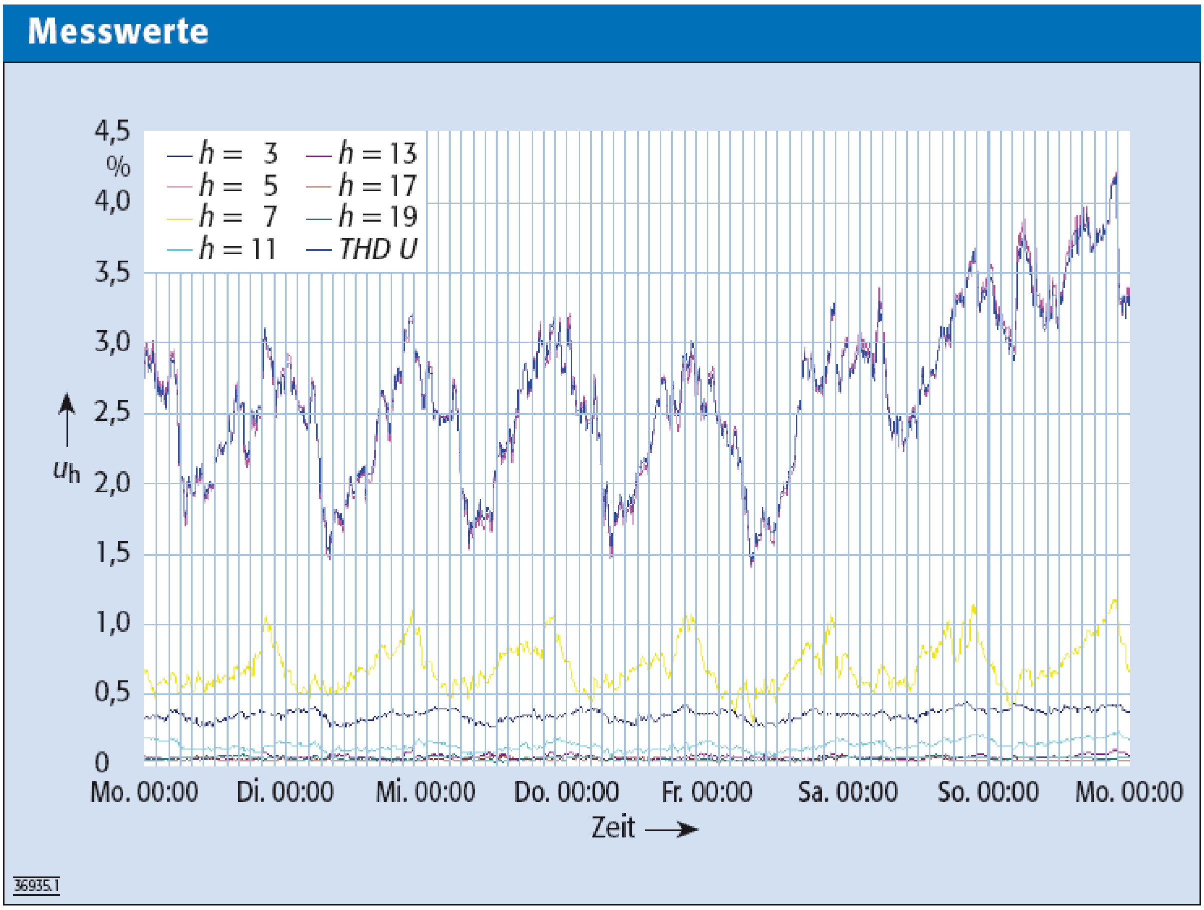

Fig. 1: Distortion in the supply voltage from a public 20-kV network (measured values)

The measurements also led to the significant conclusion that when grids have more or less the same distortion in the supply voltage, it is the “smaller” networks (I_{CE} ≈ 200 A up to 300 A), such as those with two transformers in a transforming station (each supply one smaller and one larger network), which may show greater harmonics in the earth fault current than do more extensive networks. Any calculations for planning purposes must take sufficient account of these factors (i.e. of the maximum voltage distortion in the evening hours of the weekend, of the earth fault current near the transforming stations and of the operation of partial networks).

Useful calculation values instead of rule of thumb

Obviously, an absolutely precise advance calculation of the grid values is a near impossibility. As things are, the variety of forms taken by medium voltage electricity supply networks (the different cross-sections and lengths of wire, the different circuits in transforming stations, and, as shown, the incalculable distorting loads across the various grid levels (which may be downstream, upstream or on the same level as

each other) means that the only feasible way is to reduce the network structure to its basics and to follow worst case scenarios in determining sources of harmonics. For these reasons an attempt has been made to produce a computer-assisted calculating procedure for the residual earth fault currents including harmonics. It is called BOSES. The aim is a “good enough” calculation of the current and voltage for public medium voltage networks when a single-pole earth fault arises.
Public electricity grids in the medium voltage range are, on the whole, structured similarly and it tends to be the 5th harmonic which dominates in the supply.

Figure 2 shows the basic structure.

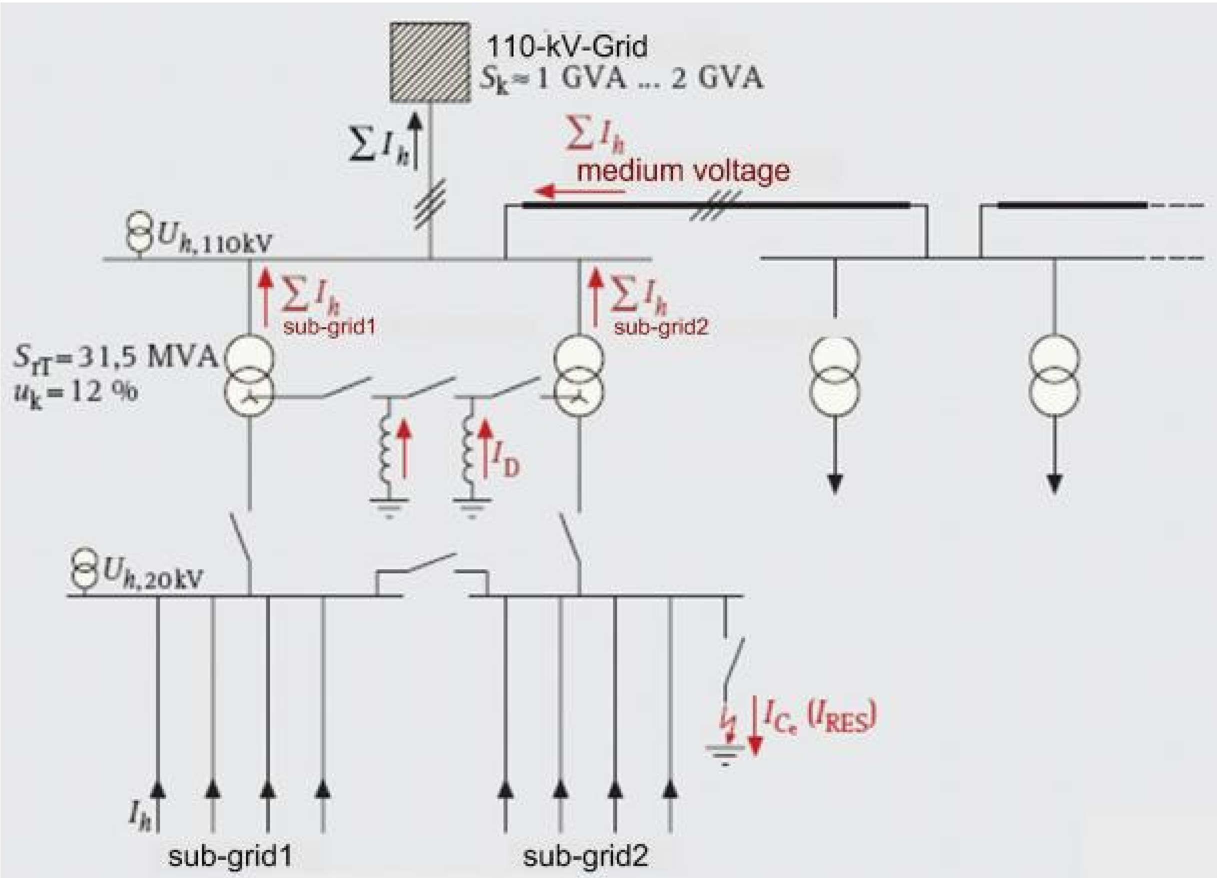

Fig. 2: Simplified basic structure of the MV network

The electricity supply for 20 kV networks of more or less similar form is provided from a 110 kV grid in a transforming station with two transformers providing rated power of (for instance) S_{rT} = 31,5 MVA and relative short circuit voltage u_k = 12 %. The switching station in the transforming station permit either single transformer operation (in which case one transformer supplies all the cable or overhead outputs on the 20 kV side) or dual transformer operation (whereby each transformer supplies one part of a single 20 kV network). There will be an average of 8 to 10 power outputs present, which supply the local (domestic) supply stations and trade and industry via a branched radial system.

The voltage distortion in the 20 kV networks will result from two factors: consumer behaviour on whichever network is affected, and the sum of loads on the 110 kV grid arising from all the medium voltage networks supplied by that grid. In occasional cases there may be distorting loads in the high voltage grid (380-/220-/110-kV) which also determine the prior load on the 20 kV networks.

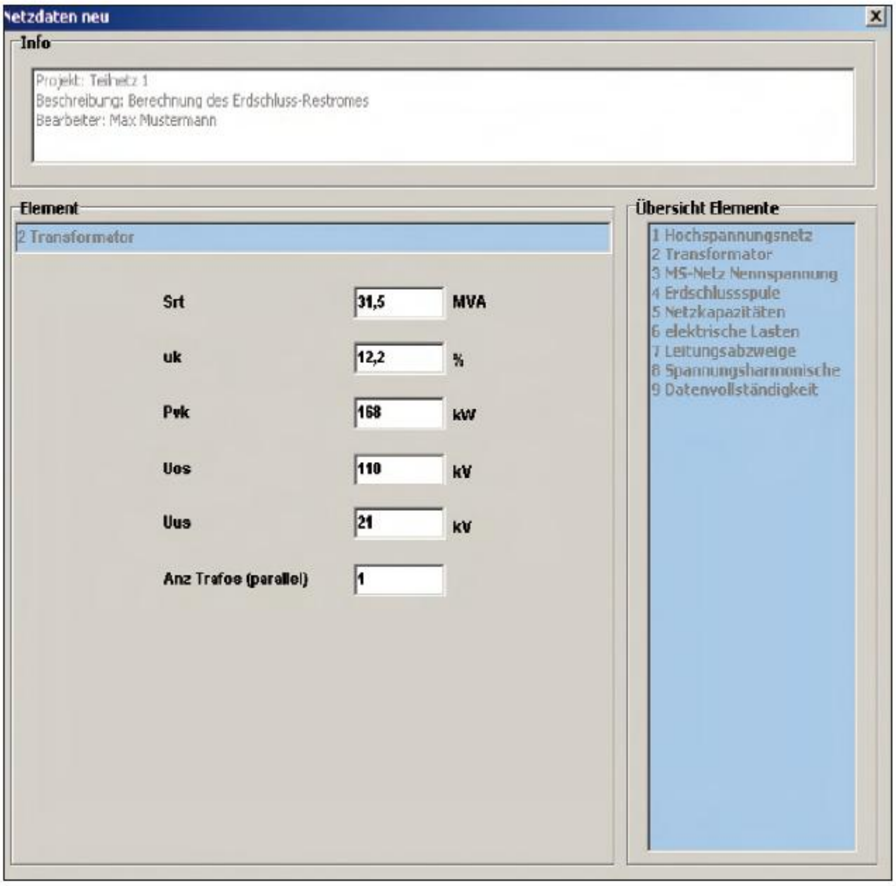

Fig. 3: Entering the grid data into the BOSES program

When the BOSES program is being used, the data for the following elements (with boxes as in Fig. 3) should be entered. They are based on the structure shown in Figure 2 for a medium voltage network.

- High voltage grid (short-circuit power level, resistance vs. reactance relation of the grid impedance)
- Transformer (rated power, short-circuit voltage, short-circuit losses, primary- and secondary-voltage, number)
- Earth coil (detuning, resistance vs. reactance relation, and, possibly, residual current [50 Hz value])
- Grid capacity figures (conductor to ground capacity, conductor to conductor capacity, and, possibly, residual ground current [50 Hz value])
- Electrical loads (average load on grid and displacement factor)
- Line branches (required for each branch: length, zero impedance and any impedance of positive rotating system, ground capacity, line branch on or off)
- the voltage harmonics in normal operation (maximum values of the 5th, 7th and 11th harmonics in the high-voltage grid and the 3rd, 5th, 7th and 11th harmonic in the medium voltage network).

The program will make an automatic check that all data have been entered.

The program will calculate I_r (the earth fault current) and the harmonic residual current for h = 3, 5, 7 and 11, in each case for a single-pole earth fault in the transforming station which is providing the supply. The program contains simple instructions by which individual factors can be varied. An instance would be the setting for the earth choke or the voltage distortion (within certain limits). The influence of the power output points on the earth fault current can be easily calculated by adding or subtracting from their number. There is also the option of determining the residual earth fault current by using the approximation given in [3].

Tafel 1 (Table 1)

Grid (see Fig. 1)	I_{CE}	v	d	$I_{RES,h}$ $h=1$	Messwerte (measured data) u_h $h=3$	u_h $h=5$	u_h $h=7$	$I_{RES,h}$ $h=3$	$I_{RES,h}$ $h=5$	$I_{RES,h}$ $h=7$	$I_{RES,OS}$	Berechnung (simulation) $I_{RES,h}$ $h=3$	$I_{RES,h}$ $h=5$	$I_{RES,h}$ $h=7$	$I_{RES,OS}$
	A	p. u.	p. u.	A	%	%	%	A	A	A	A	A	A	A	A
single transformer	681	0,016	0,033	25	–	1,95	0,61	–	24	2,7	36	–	27	2,5	36,8
double transformer (sub grid 1)	287	0,01	0,044	13	0,18	1,6	0,36	2,7	15,6	7,1	21,5	2,6	17,5	4,7	22,5

Table 1: Calculation and measuring results

<u>Agreement between calculation and measurement</u>

Initial comparison of the outcomes of calculation and of measurement (Table 1) reveals acceptable agreement and confirms that a decision made using this form of computation as to which grids require measures to limit the residual earth current will be a safe decision.

This will be the means of huge savings in the time and trouble which direct measurement costs. These will be necessary in future only in borderline cases and possibly in the preparatory stages of remedial treatment (where the I_r has been calculated as falling in the range 60 A to 70 A).

To reduce the residual earth fault current in any situation, there are various technical solutions. Which one to use must be decided on the basis of definite calculations and expertise and on an estimate of the costs involved. Those in question include:

- extension of existing transforming stations by adding a third transformer or exchanging the existing transformers for three-winding transformers,
- construction of new transforming stations,
- conversion of the neutral-point management for a 20-kV network to low-resistance neutral point earthing and
- reduction of the residual earth fault current using compensatory methods.

In this article, the author has relied upon a selection of investigative results to which staff from the following companies have greatly contributed: E.ON edis Netz GmbH, KEMA IEV Dresden, H. Kleinknecht GmbH & Co. KG Ilmenau.

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Symbols:

h	harmonic index (for the frequency relation: $h = f_H/50$ Hz)
I_h	current of the harmonic h (effective value)
I_{CE}	capacitive earth fault current (effective value)
I_r	residual earth fault current (effective value)
I_{rh}	residual earth fault current of the harmonic h (effective value)
i_{rh}	residual earth fault current of the harmonic h (p.u. value, percentage value)
I_{rOS}	harmonic share of the residual earth fault current (effective value)
I_D	current in the earth fault choke (effective value)

U_h	voltage of the harmonic h (effective value)
U_{nN}	nominal network voltage
u_k	short circuit voltage (p.u. value, percentage value)
U_{Tp}	touch potential
S_{rT}	rated power (transformer)
S_k	short-circuit power (minimum)
THD U	total harmonic distortion factor in the voltage (p.u. value, percentage value)
v	detuning (50 Hz value)
d	attenuation (50 Hz value)
f_H	frequency of the harmonic h
ϖ	angular frequency
C_E	capacity between conductor and ground

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