A STOCHASTIC APPROACH TO INTERNAL OVERVOLTAGES DUE TO EARTH FAULTS IN MV NETWORKS

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SUMMARY

The report brings forth the stochastic approach to the calculation of internal overvoltages due to single-pole faults in medium voltage networks. The application of this model is demonstrated on an actual situation.

INTRODUCTION

Problems connected to the earthing of the supply transformer's neutral point in distribution networks can be found with all electricity utilities around the world. One may say that this is an issue dating as far back as the beginnings of electric energy distribution. There are numerous experiences and theoretical notions relating to the significance of the distribution network operation in the conditions of different neutral point earthings.

As regards the Croatian distribution, medium-voltage networks were in operation up to the 1970-ies with the isolated, i.e. non-earthed, neutral point. Only exceptionally the neutral point was grounded by means of a compensation coil (Petersen coil). But as the network development revealed the disadvantages of such an operation, the 110/35 kV transformer's neutral point gradually became earthed by a resistor limiting the single-pole short circuit current of the 35 kV network, whereby the choice of the resistor size was made based on the experience of the French Electricity Utility (EDF):

- in cable networks the single-pole short circuit current was limited to 1000 A
- in other networks the single-pole short circuit current was limited to 300 A

35 kV network earthing by means of a resistor limiting the single-pole fault current was preceeded by a large number of experiments on internal overvoltages in isolated and earthed networks. The results proved unambigously that the earthed neutral point network operation offered several advantages compared to the isolated neutral point network operation. Among other, these advantages include:

- lower internal overvoltage levels
- high intermittend overvoltage elimination
- double earth fault minimizing
- efficient and selective protection against single-pole faults with a possible application of the fast automatic reclosing system (AR) for overhead networks.

Further experiences regarding the 35 kV networks' operation with the neutral point earthed through the resistor limiting single-pole short circuit currents complitely established the above notions. However, in view of altering 10(20) kV networks from the isolated to the earthed neutral point operation, not always the same criteria can be applied, as is the case with 35 kV networks. This is conditioned by the TN system use as a protection measure against indirect contact of low voltage networks. If the single-pole short circuit current was limited to 1000 or 300 A, unallowably high touch voltages could arise, especially as regards overhead networks located on high resistivity soils.

When determining the resistance value of the 10(20) kV networks' neutral point resistor the following two equally important factors have to be considered:

- internal overvoltage levels appearing with single-pole faults
- technical regulations referring to dangerous touch voltages in 10(20)/0.4 kV transformer stations and the relevant low voltage networks.

However, these criteria have the drawback of being basically contrary. In order to lower internal overvoltages as much as possible it is necessary to limit the single-pole fault current to the highest value possible. The lowest internal overvoltages would be achieved through a directly earthed network. But, growing values of single-pole short circuit currents cause a proportionate growth of touch voltage danger in low voltage networks. This problem may be solved by means of a stronger grounding grid dimensioning, which would then make the neutral point earthing appear economically unacceptable.

In order to find a solution for these contradictions the Croatian Electricity Utility (HEP) conducted comprehensive research experiments within the "Elektroistra" distribution region. The mathematical model for the calculation of internal overvoltages due to single-pole faults, as well as an adequate program support, were developed. The calculation results were confirmed by the conducted measurements and by the comparison of results achieved with the help of EMTP program revealing excellent concordance. The program mentioned is considerably easier to apply than the EMTP and enables further implementation.

This report deals with the stochastic approach to the calculation of internal overvoltages. Such an approach is justified because the value of internal overvoltages depends on a series of mutually independent input parameters. The estimate of the network's susceptibility to internal overvoltages should not be based on the highest expected values of internal overvoltages. Therefore, a mathematical model was developed, based on the generation of pseudo-random numbers which enabled the formation of input data for further calculations. The data displayed were obtained from a typical 10(20) kV network connected to the 110/10(20) kV supply transformer station.

THE MATHEMATICAL MODEL

The mathematical model for the calculation of internal overvoltages was extensively described in [1]. In this part, only its bases will be presented, followed by the stochastic approach to the calculation of internal overvoltages of earthed neutral point networks.

Internal overvoltage calculation model due to single-pole faults

The development of a program enabling a simple calculation of internal overvoltages is justified under at least two reasons:

- internal overvoltage measurements in actual distribution networks are an expensive and complicated task,
- when measuring internal overvoltages in actual distribution networks different input parameters may be altered only within set limits.

After consulting the literature available, it was concluded that this aim could be fully realised by the application of the symmetrical components method in the Laplace domain. Thereby, it was assumed that the medium voltage networks considered were supplied by transformers and that there were no electric power plants (i.e. generators) connected to them. Consequently, the supply network can be modelled based on the data obtained from the value of three-pole short circuit current. It can then be assumed that the network parameters are equal in the direct and inversion systems.

Equivalent network parameters in the direct and zero system include:

- higher voltage network and supply transformers of a medium voltage network,
- equivalent medium voltage network loads,
- capacity of a galvanically connected medium voltage network,
- ohmic resistance and reactance between the supply transformer station and fault location,
- contact resistance at fault location,
- nominal resistance, i.e. coil inductance in the supply transformers' neutral point (zero system).

After defining the model in the Laplace domain, the voltages of healthy phases within the time limit are calculated by means of the inverse Laplace transformation, using numerical routines for polynomials. The most important output values display overvoltage factors on healthy phases:

$$k_B = \frac{U_{max,B}}{U_M}\,;\, k_C = \frac{U_{max,C}}{U_M} \qquad (1)$$

where:

$U_{max,B}$ and $U_{max,C}$ are maximum voltage values of phases B and C during single-pole short circuit of phase A,
U_M is phase voltage amplitudes prior to the occurrence of fault.

In practice it is important to know higher values of overvoltage factors in (1) which are calculated from:

$$k=\max(|k_B|,|k_C|) \qquad (2)$$

Expected distribution of overvoltage factor values in distribution networks

Internal overvoltages due to single-pole short circuits in medium voltage networks include several parameters, among which the following:

a. resistance value of the resistor limiting the single-pole fault current value,
b. zero sequence capacity of medium voltage network, usually expressed through the capacitive earth fault current,
c. impedance of supplying transformer station and upper voltage network, usually expressed through the three-pole fault current on the supplying transformer stations' busbars,
d. medium voltage network's loads,
e. impedance of the line between the supplying transformer station's busbars and the location of fault,
f. voltage value of the faulted phase at the moment of fault occurrence, considered by means of phase voltage shift of the faulted phase,
g. contact resistance at fault location.

The first three factors may be considered constant values for all single-pole faults of a network provided that there are no alterations of the switching scheme of the supply transformer station or the network itself. However, the remaining values (d-g) vary from one fault to the other. This means that for each fault the overvoltage factors assume various values depending on the combination of more influential parameters (d-g).

In order to create a model which would result in the distribution of voltage factors' values of a single network within a set time period (usually a year) the following assumptions were defined:

- The probability of a single-pole fault occurrence at **each** feeder is constant (per km of length). This does not necessarily mean that **all** feeders have the same probability of a single-pole fault occurrence.
- The distribution of overvoltage factors' values is calculated for each individual feeder taking into

consideration the preceding assumption. Fault is located between the limits of:

$$L_{min} < L < L_{max}$$

where, as a rule, $L_{min} = 0$ (supply station's bus bars), and L_{max} electric distance of the farthest feeder point from the supply station.

- Medium voltage network loading is within the limits of:

$$S_{min} < S < S_{max}$$

where S_{min} and S_{max} display the minimum and the maximum expected network loading values within the set time period. The probability function density of this period is uniform.

- Phase voltage shift of the faulted phase is within the limits of:

$$\varphi_{min} < \varphi < \varphi_{max}$$

As the fault probability is much higher when the voltage of the faulted phase is close to the amplitude, it is recommended to define the following:

$$\varphi_{min} = 60^0 \qquad \varphi_{max} = 90^0$$

The probability function density in the above period is uniform.

- Contact resistance at fault location is within the limits of:

$$R_{min} < R < R_{max}$$

where R_{min} and R_{max} represent the minimum and the maximum expected contact resistance values at fault locations. These values depend on feeder type (cable, overhead) and local conditions. As in the previous cases the probability function density in the above period is uniform.

The assumptions relating to uniform probability function densities at defined periods (L_{min},L_{max}), (S_{min},S_{max}), (φ_{min},φ_{max}), and (R_{min},R_{max}) are partly idealised in view of the actual situation. A higher accuracy would be achieved by the division of individual periods into smaller sections within which the assumption of approximately uniform probability function densities could be applied. But, considering how difficult it is to ensure complitely accurate input data for actual medium voltage networks, in this report use was made of the approach based on the first assumption of uniform probability function densities.

Further calculations of internal overvoltages (for supply station feeders) are founded on the selection of input values having a stochastic character, by means of a pseudo-random numbers' generator:

$$L = L_{min} + r_L \cdot (L_{max} - L_{min}) \qquad (3)$$

$$S = S_{min} + r_S \cdot (S_{max} - S_{min}) \qquad (4)$$

$$\varphi = \varphi_{min} + r_\varphi \cdot (\varphi_{max} - \varphi_{min}) \qquad (5)$$

$$R = R_{min} + r_R \cdot (R_{max} - R_{min}) \qquad (6)$$

where r_L, r_S, r_φ i r_R are pseudo-random variables with values between 0 and 1.

Therefore, each calculation of internal overvoltages results in a combination of input parameters having a stochastic character (within the set limits):

$$L_{ij}, S_{ij}, \varphi_{ij}, R_{ij}, \ i = 1,N_j \qquad (7)$$

where N_j stands for the number of calculations of internal overvoltages on feeder "j". Whatever the case, it is necessary to conduct an appropriately large number of calculations, e.g. 1000.

Calculations are performed as described for each of the "j" feeders from the supply station - j=1, N_{izv}, where N_{izv} stands for the feeder number. Thereby, one should consider the fact that each feeder has its own length - L_{max}, and that the contact resistances at fault locations may for different feeders be situated within differing limits.

Having calculated the internal overvoltages for the "j" feeder, the group of N_j overvoltage factors' values is obtained:

$$k_{1j}, k_{2j}.........k_{Nj} \qquad (8)$$

The N_j values' group is then statistically surveyed in order to obtain the following values:

- minimum and maximum overvoltage factors' values - k_{min} and k_{max},
- medium value and standard deviation of overvoltage factors - k_{sr}, σ,
- classification of overvoltage factors' values into predefined sections.

Consequently, based on the statistical analysis results, relative shares of overvoltage factors on feeders for definite sections (r=1,2....N_r) are obtained. Knowing the expected overvoltage factors' values for actual networks, sections are defined between the limits of:

$$1.4 < k < 2.5 \qquad (9)$$

with the step Δk=0.1.

The actual expected number of single-pole faults resulting in a definite overvoltage factor value (according to intervals as in (9)) is determined by the formula:

$$n_{r,j} = \lambda_j \cdot L_{izv,j} \cdot NR_{r,j} \qquad (10)$$

where:

λ_j - probability occurrence of a single-pole fault on feeder "j" (/km, yr.),

$L_{izv,j}$ - total length of "j" feeders; this value is with overhead 10(20) kV lines usually somewhat bigger than the value L_{max}, owing to the presence of spur lines (km).
$NR_{r,j}$ - relative share of calculated overvoltage factors which, according to their value, belong to section "r".

Thereby, the following condition is always valid:

$$\sum_{r=1}^{N_r} N_{r,j} = 1 \qquad (11)$$

After calculating the overvoltage factors for all lines of a supply station it is easy to define the distribution of expected overvoltage factors for the whole medium voltage network galvanically connected to this station. For each interval of overvoltage factors (9), appropriate values obtained from the expression (10) are added up, for all feeders connected to the analysed transformer station. Thus, a realistically obtainable distribution of the number of single-pole faults within a network is calculated according to the **values of the resulting** overvoltage factors.

STOCHASTIC ANALYSIS OF INTERNAL OVERVOLTAGES DUE TO SINGLE-POLE SHORT CIRCUITS

On the basis of the mathematical model previously described a computer program was developed. The calculation is carried out as follows:

- The application of pseudo-random numbers' generator results in random values of varying input parameters within the defined top and bottom limits. As it is necessary to conduct a large number of simulations in order to obtain a realistic allocation of internal overvoltage factors, one thousand was adopted as the number of simulations per feeder. This means that a group of a thousand randomly chosen combinations is achieved for varying input values.
- For each distribution network feeder one thousand calculations are carried out with the previously stated input data and definite other values (neutral point resistor, zero sequence network capacity, supply station parameters). After that, a statistical analysis will reveal the distribution of overvoltage factors due to single-pole faults of the feeder.
- The calculations are conducted for all feeders of the respective network, resulting in the distribution of overvoltage factors for the whole network:

- for each feeder a number of expected faults is determined (permanent, semi-permanent and temporary) and multiplied by the previously obtained statistical shares,
- followed by the summing-up of the results for all lines.

The procedure displayed was applied on a 10 kV network supplied from a 110/10 kV "Velika Gorica" transformer station in the vicinity of Zagreb. Two 20 MVA transformers were installed in the station separated on 10 kV busbars, each transformer earthed by its own resistor. Basic data on the 10 kV network are:

- 8 overhead feeders with the approximate lenght between 9 and 33 kms per feeder and the the cross section of 95 Al/Fe are connected to first 110/10 kV transformer (transformer no. I)
- 8 cable (city) feeders with the approximate length of 8 kms per feeder and the cross section of 150 Al are connected to the other 110/10 kV transformer (transformer no. II).

Apart from the network parameters, the following input data were taken into consideration:

<u>Rural network connected to transformer no. 1</u>
- maximum network loading 13.5 MW,
- minimum network loading 3.5 MW,
- nominal resistor current for neutral point earthing I_r=150 A,
- capacitive earth fault current I_c=36 A,
- contact resistance at fault location within the limits of 1-10 Ω (estimated),
- phase voltage shift of the faulted phase within the limits of 60^o-90^o

<u>Urban network connected to transformer no. 2</u>
- maximum network loading 16.5 MW,
- minimum network loading 4.5 MW,
- nominal resistor current for neutral point earthing I_r=150 A,
- capacitive earth fault current I_c=73 A,
- contact resistance at fault location within the limits of 0-2 Ω (estimated),
- phase voltage shift of the faulted phase within the limits of 60^o-$90\,^o$,
- based on the data, calculations of internal overvoltages were carried out (1000 simulations for each feeder), including the statistical distribution of overvoltage factors' values per feeder.

The expected number of single-pole faults (per 1 km/yr.) was estimated based on the data available:

<u>Overhead lines</u>
- permanent faults: 0.10/km, yr.
- semi-permanent faults: 0.20/km, yr.
- temporary faults: 0.70/km, yr.

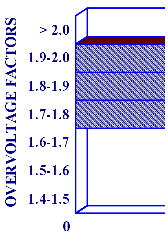

FIG. 1 DISTRIBUTION OF OV
FACTORS (URBAN NET

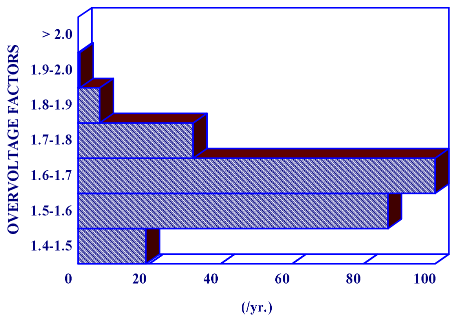

FIG. 2 DISTRIBUTION OF OVERVOLTAGES FACTORS (RURAL NETVORK)

The results obtained are displayed in Figures 1 and 2. The anaylisis of the figures brings about several interesting conclusions:

- Overvoltage factors due to single-pole short circuits in the urban (cable) network exceed the overvoltage factors due to faults on overhead lines. But cable network faults are rare in relation to faults on overhead feeders (where there are frequent instances of temporary faults).
- The largest number of overvoltage factor is to be found within the limits of 1.6 - 1.7 (around 43%), followed by 1.5 - 1.6 (around 34%). Consequently, no significant internal overvoltages due to single-pole faults are expected to occur in the 110/10 kV “Velika Gorica” network's transformer station.
- Rather unfavourable proportions of Ir/Ic values were assumed. The cause of this lies in other factors having damping effects (network loadings, fault locations, contact resistance at fault locations).

CONCLUSIONS

The report briefly presents the mathematical approach to the stochastic calculation of internal overvoltages of medium voltage networks earthed through resistors limiting single-pole short circuit currents. The results display the calculation of overvoltage factors' distribution with a typical 10(20) kV network.

The significance of such an approach primarily lies in the realistic view of the expected overvoltage factors' values for actual networks. Thereby, assumptions can be made as regards general network susceptibility to internal overvoltages due to single-pole short circuits.

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