Development of a resistive model for overhead line poles

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Abstract. Quality of electricity is of increasing importance within conditions enabling to maintain it to an even less extent. Now consumers neither tolerate outages with duration of seconds. This fact forces the electric utility companies to maintain network operation during single-phase earth faults. This paper presents the results of a joint research investigating the potential of overhead line poles during faults with a newly developed pole model.

1. Introduction
Quality of electric power distributed by electric utility companies is of increasing importance, however the circumstances under which this good quality should be maintained enable this to a continuously decreasing extent because of the increasing number of non-linear loads. In our days consumers do not tolerate outages with duration of as low as one or two seconds. After these short time outages electronic devices have to be readjusted that can last hours in offices or even in residential areas having no uninterruptible power sources.

Measures characterizing the reliability of electric power networks are the CAIFI, i.e. Customer Average Interruption Frequency Index and the CAIDI, i.e. Customer Average Interruption Duration Index [1]. These indexes have quite low values for cable networks operated in urban areas with high consumption density. However in rural areas supplied by overhead lines with a voltage of 20 kV in Hungary this overhead network is exposed to weather conditions causing interruptions in the supply. The values characterizing the reliability of the supply of electric energy has to be reduced in rural areas as well.

This expectation forces the electric utility companies to attempt maintaining the operation of their medium voltage distribution networks during single phase earth faults as well. 20 kV medium voltage distribution networks are mainly operated compensated – with a coil (Petersen coil) connected between the star point and the earth – in Hungary. In case of these networks there is a possibility maintaining the supply with single-phase earth fault as well.

However in this case if somebody touches the pole of the faulty network at the location of the fault, he/she can be exposed to a fatal electric shock. This paper presents the results of a joint research of the electric network operating company E.ON acting also in the region of South-Transdanubia, Hungary and of the University of Pécs, Pollack Mihály Faculty of Engineering, Institute for Information Technology and Electrical Engineering.

Within the frame of this research a resistive quasi-distributed parameter model of reinforced concrete poles used for low and medium voltage overhead lines has been developed. With the help of this model and the software TINALab II [2] simulation sessions have been performed for different circumstances, different grounding resistance values and for different pole conditions to find out the
potential along the pole in different cases. To find out the parameters of the model measurement series have been conducted on poles and networks.

Main objective of the research is to develop a data group of value ranges of the several factors influencing the pole potential resulting a pole potential of 50 VAC or less. Along with the knowledge of actual values on the network and simulating earth faults on network circuits with the novel pole model this data will then enable to predict pole potentials. Then the results will enable to make a decision if the operation of a network with earth fault can be maintained or not. Developing medium voltage networks with earth fault pole potentials below 50 V will result in a more reliable electric energy supply of the consumers.

2. Earth faults on compensated networks

As a first task the current resulting potentials more than zero on the poles has to be determined. This current is the earth fault current. The earthing method applied on medium voltage networks resulting minimum earth fault current is that compensated by placing a Petersen coil between the star point of the network and earth [3]. Figure 1 shows a compensated network taking into account the conductance to the earth and the resistance of the Petersen coil. In case of a theoretic circuit with no resistances zero current would flow to the earth.

Figure 1. Earth fault on a compensated network

Figure 2 shows the theoretical circuit and the vector diagram of the same case. The residual current $I_c$ is mainly determined by the line to earth conductance ($G_a$, $G_b$ and $G_c$) and by the resistance of the Petersen coil. $R_0$, contains the coil resistance plus the earthing resistance of the neutral point.

This residual current has to be maintained at low values to realize the main task of the coil, i.e. extinguishing the arc at the location of the earth fault on one side and to maintain the potential of the pole at a maximum value of 50 V at the same location on the other side. Thus the residual current should not exceed 10 A.
Potential of the pole touched by a human is one factor to be taken into account, but the potential of the ground around the pole where the human stands is of interest as well. Considering a hemisphere earthing probe the \( dR \) resistance of the earth of a \( dr \) thickness around it is

\[
dR = \rho \frac{1}{A(r)} = \rho \frac{dr}{2 \cdot r^2 \cdot \pi},
\]

where \( \rho \) is the specific resistance of the earth, \( A \) is the surface of the hemisphere and \( r \) is its radius. Total resistance of the earth between the distances \( r_1 \) and \( r_2 \) is

\[
R = \int_{r_1}^{r_2} dR = \int_{r_1}^{r_2} \rho \frac{dr}{2 \cdot r^2 \cdot \pi}.
\]

Then the subsequent resistance values of the earth with distances \( i \) and \( j \) can be calculated with

\[
R_{i,j} = \frac{\rho}{2 \cdot \pi} \left( \frac{1}{r_i} \right) \int_{r_j}^{r_i} \frac{1}{r^2} dr = \frac{\rho}{2 \cdot \pi} \left[ -\frac{1}{r} \right]_{r_j}^{r_i} = \frac{\rho}{2 \cdot \pi} \left( \frac{1}{r_i} - \frac{1}{r_j} \right).
\]

Considering a specific earth resistance of \( \rho = \pi \Omega \text{m} \), then the values of the subsequent half meters going away from the pole are listed in table 1. Step length is always half meter. The values shown by the table are not typical, demonstrate only the proportions of the step values. Typical values for normal support poles are of several ten ohms.
Table 1. Earth resistance around the pole

| Distance from pole (m) | Resistance values (Ω) |
|------------------------|-----------------------|
| 0.5 – 1.0              | 0.500                 |
| 1.0 – 1.5              | 1.6667                |
| 1.5 – 2.0              | 0.0833                |
| 2.5                    | 0.0500                |

3. Development of the model

A decision for a resistive model have been made by the development team in spite of the fact that there are transient phenomena when earth faults occur. The reason of this decision is that, the objective of the model is to discover pole potentials during operation with earth fault for hours. There is a very low possibility that somebody touches the pole during the seconds of the transient period. If the fault is caused by a human e.g. by a service personnel of the utility company, then there will not be an operation with maintained because in cases of repair works a special operation mode is chosen with a definitive switching of the line without any delay.

Specific resistance of concrete can vary through orders of magnitude depending on its water content. To find out the resistance values of the reinforced concrete poles used by the electric utility company in our region and the typical grounding values a series of measurements have been performed on new and old poles and in sub-regions with different arts of soils. Bottom view of the measured pole is shown by Figure 3. In this figure the cross section of the iron wires reinforcing the pole can be seen. There are 12 steel wires with a diameter of 6 mm and a separate wire with a diameter of 10 mm integrated into the pole along its whole length.

![Figure 3. Bottom view of the reinforced concrete pole](image)

The steel wire with the diameter of 10 mm is used for connecting the cross-arm and other fittings to the grounding. Resistance of the concrete has been taken into account as well. Measurement layout used for determining concrete resistance is shown by Figure 4.

A cross section of the pole and aluminium cables with a length identical with the cross section have been used for the measurement. The measured value of the specific resistance of concrete is $\rho_c = 1.26 \times 10^9 \Omega \text{mm}^2/\text{m} = 1260 \Omega \text{m}$. 
This specific resistance value of concrete is nearer to the minimum order of magnitude given by the Portland Cement Association R & D Lab Bull for wet concrete, i.e. to $100 \Omega m$ \cite{4}.

Since the investigated pole is produced as a structure of 15 nearly identical parts and two end parts the model has been developed as a quasi-distributed parameter model made up of 17 units. Resistors in the model taking into account the steel wires are proportional to the lengths of the units. The value of the different resistors taking into account the concrete parts have been calculated with the equation

$$R_{Ci} = \rho_C \frac{0.6}{(188 + i \cdot d'')^2} = 1.26 \cdot 10^9 \frac{0.6}{(188 + i \cdot 8.5)^2}, \quad (4)$$

where $i$ is the number of the pole unit, $R_{Ci}$ is the resistance of the pole unit number $i$, $\rho_C$ is the measured specific resistance of concrete and $d''$ is the difference between the width values between two neighboring units.

Apart from pole parameters resistance values of cross-arm parts and of other fittings and of the grounding of the pole have been considered. As the supplying network resistance, inductance, main and ground capacitance values of a 20 kV network have been taken into account. The basic circuit used for simulation is shown by Figure 5.

In Figure 5 $U_{L1}$, $U_{L2}$ and $U_{L3}$ stand for the three phase-to-ground voltages of the rural overhead line networks in Hungary with nominal phase-to-phase voltage of 20 kV. $L_T$ is the inductance of the transformer taken into account. Two transformer sizes have been considered: 25 MVA and 40 MVA typically applied for supplying 20 kV networks.

$R_{OL}$ and $L_{OL}$ are the resistance and inductance of the line between the transformer and the investigated pole. $R_{ISO}$ is the resistance of the insulators between the cross-arm and the cable and $R_{ISO}$ is the resistance of the cross-arm parts being asymmetrical.

Switches shown by Figure 3 above the insulators are used for simulating earth faults. Since in case of single earth faults a high risk of occurrence of two-phase earth faults arise, then the opportunity of simulating two-phase earth faults has to be given.

Since 20 kV overhead lines are mainly operated as networks with star points grounded through Petersen coils however with the possibility of switching to grounding through a resistor there are switches integrated into the model for switching these devices. As also low voltage networks have been investigated with direct grounding, this kind of grounding is available in the model as well.
$R_{Fe}$ values are resistance values of the steel wires in the reinforced concrete in which $R'_{Fe}$ is the resistance of the upper most part of the pole, $R_{Fe}$ that of the 15 nearly identical parts and $R''_{Fe}$ is the resistance of the upper most part of the pole. The same is valid for the $R_c$ values, however having slight differences from each other because of the decreasing cross section of the pole up to its top.

Fittings are taken into account along the pole ($R_F$) e.g. for operating pole switches or supporting the transformer, distribution cabinet, etc. this conductive parts mounted onto the pole are connected to each other and to the ground with a thick aluminium cable ($R_{Al}$).

$R_{Gi}$ to $R_{G4}$ are the parts of the grounding resistance with a soil thickness of 0.5 m. Simple line supporting poles, operating poles with pole switches and those supporting transformers have different arts of grounding [5], [6]. Specific soil resistance ($\rho$) and typical grounding resistance values ($R_c$) have been measured [7] with the results listed in table 2.
### Table 2.
Soil resistance values

| #  | Art of soil   | \( \rho \) (\( \Omega \)mm\(^2\)/m) | \( R_G \) (\( \Omega \)) |
|----|---------------|----------------------------------|--------------------------|
| 1  | Rock          | 116                              | 12                       |
| 2  | Clay          | 25                               | 2.5                      |
| 3  | Sand          | 260                              | 35                       |
| 4  | Mixed (town)  | 24                               | 3.2                      |

Values in table 2 have been measured after a slight rain following a long dry period. Grounding conditions of the poles of different ages were different to a high extent to a perfect condition in case of newly installed poles to completely broken grounding in case of some very old poles.

4. Simulation sessions and results

During simulation sessions the following parameters have been varied [8]:

- Nominal power of the transformer (25 MVA and 40 MVA);
- art of star point handling (direct grounding, grounding through a resistor or coil);
- value of the grounding resistance of the star point;
- value of the grounding resistance of the pole;
- art of the earth fault.

Finally the resistance of human being with a value of \( R_H = 1000 \, \Omega \) has been taken into account standing 0.5 m far from the pole and touching a fitting at a height of about 1.8 m.

Results of simulation sessions are as follows:

- Overhead line poles made of reinforced concrete can be considered as equipotential elements because of the high cross section of the steel wires integrated into them.
- Potential of a pole is determined mainly by the grounding resistance of the pole and by the art of the fault.
- Low voltage pole potential remains under 50 V in case of a pole grounding resistance of about 10 \( \Omega \) or less influenced by other parameters as matter of course.
- Increasing the length of the overhead line to the pole or increasing the nominal power of the transformer increases the potential of a pole.
- If fittings mounted onto the pole are connected to each-other and to the grounding or not does not have influence on the potential of the pole if the grounding of the pole is connected to the steel wires in the concrete.
- If the connection between the grounding of the pole and the steel wires in the concrete is broken then a significant increase occurs in the potential of the pole.
- If the connection between the grounding of the pole and the steel wires in the concrete is broken then a connecting cable between the fittings and the grounding decreases the potential to a value identical with that with existing connection to the steel wires.
- In case of 20 kV lines only a Petersen coil between the star point and the ground assures pole potentials under 50 V.
- Two-phase earth faults result always in a dangerous potential of the pole.

Because of the equipotential nature of the concrete pole resulted by the high total cross section of the reinforcement iron wires inside it the model of the pole can be simplified to much less parts. A decision has been made by the development team to maintain as many parts as many fittings on the pole.
are placed. Figure 6 shows the actual simulation circuit used during the simulation sessions performed with TIBALab.

![Simulation circuit](image)

**Figure 6.** Simulation circuit used with TIBALab

Circuit in Figure 6 contains two pole models enabling the simulation of 2Ff faults and contains a symmetrical load as well. Pole potential values have then been calculated for several earthing resistance values and line to earth conductance values – given as resistors as well.

Simulated pole potential values are shown in table 3 and table 4. Earthing resistance values vary from 40 $\Omega$ to 10 $\Omega$ as typical values measured on the actual network and line to earth conductance values vary from 10 k$\Omega$ to 1 M$\Omega$ supposed to be present on the network.

**Table 3.**

| $R_L$ (k$\Omega$) | 10  | 20  | 50  | 100 | 200 | 500  | 1000 |
|------------------|-----|-----|-----|-----|-----|------|------|
| $R_f$ (k$\Omega$) | 40  | 35  | 20  | 25  | 20  | 15   | 10   |
| 10               | 92.21 | 81.24 | 69.42 | 57.80 | 46.38 | 34.92 | 23.20 |
| 20               | 46.82 | 41.22 | 35.19 | 29.28 | 23.48 | 17.67 | 11.73 |
| 50               | 19.98 | 17.58 | 15.01 | 12.48 | 10.00 | 7.52  | 4.99  |
| 100              | 11.88 | 10.45 | 8.92  | 7.42  | 5.94  | 4.47  | 2.93  |
| 200              | 8.74  | 7.69  | 6.56  | 5.46  | 4.37  | 3.29  | 2.18  |
| 500              | 7.64  | 6.72  | 5.73  | 4.77  | 3.82  | 2.87  | 1.91  |
| 1000             | 7.47  | 6.57  | 5.61  | 4.66  | 3.73  | 2.81  | 1.86  |
Table 4.
Pole potential values (1 km)

| $R_{ie}$ (kΩ) | 10   | 20   | 50   | 100  | 200  | 500  | 1000 |
|---------------|------|------|------|------|------|------|------|
| $R_f$ (Ω)     |      |      |      |      |      |      |      |
| 40            | 95.51| 48.49| 20.69| 12.83| 9.06 | 7.91 | 7.73 |
| 35            | 82.23| 41.71| 17.79| 10.58| 7.78 | 6.80 | 6.65 |
| 20            | 71.91| 36.45| 15.54| 9.24 | 6.80 | 5.94 | 5.81 |
| 25            | 62.28| 31.55| 13.45| 7.99 | 5.88 | 5.74 | 5.02 |
| 20            | 48.04| 24.32| 10.36| 6.96 | 4.53 | 3.96 | 3.87 |
| 15            | 36.17| 18.13| 7.79 | 4.63 | 3.41 | 2.97 | 2.91 |
| 10            | 24.03| 12.15| 5.17 | 3.07 | 2.26 | 1.97 | 1.93 |

The difference between the pole potential values given in table 3 and table 4 is the distance of the faulty pole from the 20 kV bus of the transformer station. Table 3 shows the values for a pole 10 km far from the station and table 4 shows them for a pole 1 km far from the station.

Potential values given in table 3 and Table 4 are shown in Figure 7 and Figure 8 as well. In case of compensated networks it is rather easy to maintain the pole potential under 50 V however neither the earthing resistance, nor the line to earth conductance can be controlled on an easy way.

In Figure 9 pole potential values can be seen in case of a 100 Ω high voltage resistance connected between the neutral point of the network and the earth. The order magnitude of the pole potential is the kV. Minimum potential – 700 V – is achieved with 10 Ω pole earthing resistance and 10,000 Ω resistance between lines and earth.

Figure 7. Pole potential in a distance of 10 km
Figure 8. Pole potential in a distance of 1 km

Figure 9. Pole potential with resistance as earthing
An other characteristic of this case that can be seen in Figure 9 is the much less dependence of pole potential of the parasite conductance between lines and earth.

In Figure 10 single earth fault pole potential values can be seen with the same parameters, however in case of three different dimension of the network, i.e. in case of three different values of earthing capacitances. Highest potential values have been given in case of the network with highest extension. These values are shown by thick red lines. Values of the network with medium extension are shown by magenta lines of medium thickness. Lowest potential values have been given by the network with least extension and shown by thin green lines.

![Figure 10](image-url)  
*Figure 10. Pole potential values of lines of different extensions*

An other phenomenon that can be seen in the figure is the decreasing dependence of the potential on the conductance to the earth with increasing network dimension.

5. Further developments

Since the residual current in case of a single line to earth fault is mainly determined by the current flowing from the line to the earth through parasite conductance, a most possible proper knowledge of this conductance is inevitable for a further investigation.
More simulation sessions have to be performed with model considering different values of also other parameters influencing the pole potential, like magnitude, harmonic content and symmetry of the consumer current, Petersen coil resistance value, etc.

An other case to be simulated is the period when the high voltage resistance of 100 $\Omega$ is connected between neutral point and earth since then more rigorous conditions have to be met for reducing pole potential to a desired value.

With this knowledge network sizes and conditions can be determined under which the operation of the medium voltage network can be maintained also in case of single phase earth faults.

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