Analysis of the Characteristics of Grounding Elements and Safety Criteria's of Towers of Overhead Lines Using Monte Carlo Simulation

Nikolce Acevski[1] and Risto Ackovski[2]

Abstract - **In this paper is proposed new method for analysis the main characteristics of a grounding elements, and, furthermore, characteristics of some types of grounding elements of towers of overhead lines, mostly used in middle voltage (MV) power networks are calculated and presented in a different, new way. Main characteristics of each grounding element are set of properties, forming some kind of identity card for those grounding elements, unique and easy for recognizing their characteristics. The set of informations, forming this identity card, are resistivity to ground *R*, potential distribution on the earth surface in the vicinity of the grounding and, as an additional data describing the characteristics of the grounding that can be used further for analysis the safety conditions and risks of hazard shock, the probability density functions (PDF) of the touch and step potentials (i.e. potential differences $\Delta E_t, \Delta E_s$), and finally, risk level of accident (death) due to appearence of dangerous potentials. While calculation the PDF-s and risk level from dangerous step and touch potential differences occuring during the fault arround the transmission towers on which human body might be exposed, using stochastic (Monte Carlo) simulation are calculated number of experiments, produced and analysed by the computer. In each experiment, using random numbers generated from the computer, human body impedance, current of fibrillation threshold and probability of fatal accident, as random variables are calculated.**

Results of the analysis, presented in the paper, suggested some interesting conclusions, relating their safety criteria's and their improvement. They suggested the fact that in some cases the real risks of accidental death due to dangerous step or touch voltages are considerably smaller from those, recommended by the existing technical recommendations and adopted criteria's.

Keywords - **grounding elements, probability density function, step and touch voltages, Monte Carlo simulation, risk level, safety criteria's and probability for deathly accident**

I. Introduction

It is well known that each type of grounding is characterized and might be completely presented by his main parameters: his geometry, resistance to ground *R* in homogenous soil with known specific resistivity ρ, and the shape of the electric field (distribution of potentials on the surface of the ground in the vicinity of the grounding), as well as maximal touch and step potential differences $\Delta E_t, \Delta E_s$, or maximal step and touch voltages, U_t, U_s. The risk of dangerous potential differences appearing during the fault, was estimated deterministic in the past, using the maximum values of potential differences of touch and step $\Delta E_t, \Delta E_s$ only. However, this approach is not correct because in the reality, the probability of being exposed on these maximal values is very small, almost neglecting. In order to obtain more realistic results by these analyses, in the methodology for estimation the mentioned risks stochastic should be involved. In other words, in such analyses we need to operate not only with the maximal values, but also with their actual values and with the probabilities of theirs appearances.

That way, additional data describing the characteristics of the grounding that should be used further for analysis the safety conditions and risks of hazard shock are the probability density functions PDF's of step and touch voltages of the grounding. In the proposed model the human body impedance, being a stochastic variable, is treated as a function of the voltage and the current flowing through the human body. The threshold of ventricular fibrillation is taken as a random function of the electric shocks duration also. In addition, the probability of ventricular fibrillation within the vulnerable phase of the heart cycle is taken into account like in [4], [5], and [6]. For estimation the risk level of total electric shocks, probability of human beings exposure around the tower should be known. This supposes long time observations and good modeling of passing by the people around the tower, like in [7], [8]. Because of the fact that all variables mentioned before are stochastic, the most adequate method for analysis of these problems is the method of stochastic simulation called Monte Carlo method. In this paper are analyzed the main characteristics of some types of groundings of towers of overhead lines, most often used in the MV distribution networks in Macedonia and former Yugoslavia.

II. Human Body Impedance, Fibrilation Treshold

The idea of the proposed methodology will be explained on an example of typical grounding of tower of MV overhead line. Accidental death of a human being near the tower during fault to ground can happen if three independent events occur at the same time: 1) existence of line to ground fault at the

[1] Nikolce Acevski is with the Faculty of Technical Sciences, Bitola, Macedonia, E_mail: nikola.acevski@uklo.edu.mk

[2] Risto Ackovski is with the Faculty of Electrotechnical Sciences, Skopje, Macedonia, E-mail: acko@ieee.org

tower; 2) existence the people around the fault location and 3) occurence the dangerous step or touch voltage and existence of path for the current through the human body to be fatal for their life. The events 1 and 2 aren't analysed in this paper because they are already presented in the literatures. In this case only event 3 is analysed.

For this aim let's suppose that in the moment of the fault there is a human being near the transmission tower touching it and being exposed on touch voltage U_t. According to [5]:

$$U_t = (Z_{50} + R_t) \cdot I_{50} \tag{1}$$

where I_{50} is mean or 50 % value of current through the human body (accidental current path is arm-arm or arm-leg), and Z_{50} is the mean or 50 % value of human body impedance

$$Z_{50} = \frac{293.3}{\sqrt{I_{50}}} + 750 \tag{2}$$

Substituting (2) into (1), we obtain:

$$I_{50} = c^2 \left(\sqrt{1 + \frac{U_t}{119.6 \cdot c}} - 1 \right)^2 \tag{3}$$

with

$$c = \frac{119.6}{R_t + 750} \tag{4}$$

According to [3], the equivalent foot resistances for adults with average foot, are: $R_t = 1.5\rho$ for the self resistance of a foot, and $R_s = 6.0\rho$ for mutual resistance between the two foots.

Body impedance Z is a random variable following the lognormal cumulative probability distribution function ([5], [6]. In the stochastic simulation it can be simulated by means of a uniformly distributed random number R_n, using (5):

$$Z = Z_{50} \cdot 10^{1.086 \cdot R_n} \tag{5}$$

The value 1.086 in (5) has been determined to match approximately with 5% and 95%th percentilies for the total body impedance, given by Working group 4 of IEC TC 64, where R_n is normal distributed random number with mean value 0 and standard deviation 1. The current I through the body, which is also random variable, can be calculated by (6):

$$I = \frac{U_t}{Z + R_t} \tag{6}$$

In a similar way we can calculate the current through the human body when it is exposed on step voltage U_s, but in this case, in the relations (4) and (6), the resistance R_t should be replaced by the resistance R_s.

From the graphs for 5%, 50% and 95% percentile fibrillation tresholds accepted by IEC WG 4, obtained by statistical analyses of numerous experimental results, it is deducted that 50% fibrillating treshold currents depend on the fault duration T and can be represented reasonably well by (7)

$$I_{F50} = \begin{cases} 1.6\,\text{A}, \text{ when } T \le 0.1s \\ \dfrac{0.16}{T}, \text{ when } 0.1 \le T \le 2s \\ 0.08\,\text{A}, \text{ when } T \ge 2s \end{cases} \tag{7}$$

In the stochastic simulation random values for the fibrillation current, following the lognormal cumulative probability distribution function, can be produced using the algorithm (8):

$$I_F = I_{F50} \cdot 10^{1.176 R_N} \tag{8}$$

The fibrillation will occur if

$$p\{I > I_{F50}\} = 0.5 + \frac{1}{\sqrt{2\pi}} \int_0^y e^{-\frac{t^2}{2}} dt \tag{9}$$

where

$$y = \frac{I}{1.176} \cdot \log \frac{I}{I_{F50}} \tag{10}$$

III. Methods for Calculation of the Basic Grounding Characteristics

As mentioned before, each type of grounding might be completely presented by a set of informations forming some kind of its identity card. Resistance to ground R in homogenous soil with known specific resistivity ρ, could be calculated by means of the computer programs based of the current field theory and application of the well known method of medium potentials ([8]), whether by a program based on the Monte Carlo simulation, the PDF's of touch and step voltages e_t , e_s and the probability for deathly accident (risk level p) could be calculated. The probability density function (PDF's) of one grounding depends on its geometry only. Good-shaped grounding has low medians and modes of theirs PDF's, and the most frequently appeared potential differences e_t and e_s are on the left side in the rectangular coordinating system, near the valye 0.

The simulation program produces large number of experiments (hundreds of thousands and more), big enough to calculate accurate result (or results whose error doesn't exceed more then a few %).

For calculation the value e_t, two uniformly distributed random numbers are needed for each experiment. First of them defines the position of the touch point (A) on the perimeter of the object while the second random number define the position of the foots of the human on the surface of the ground (point B), which is at distance of 1 m in a random direction. For calculation the value e_s two uniformly distributed random numbers are also needed, for determining the positions of both of the feet. The distance between the point A and B in this case is again 1m. All simulations are performed in the so called "dangerous area" around the grounding, i.e. in the area where potential φ on the surface of the ground is not less than 20% of the potential U of the grounding.

Furthermore, using (5) in each experiment, the random values of the human body impedance Z is generated, and after that, using the equation (6), the flowing current I through the human body is calculated. By means of (8) the random value of the ventricular fibrillation current are generated, I_F, and then, using (9), probability p (i.e. risk) of death, caused by this current is calculated.

(7)

IV. Grounding's Characteristics Analysis - Example

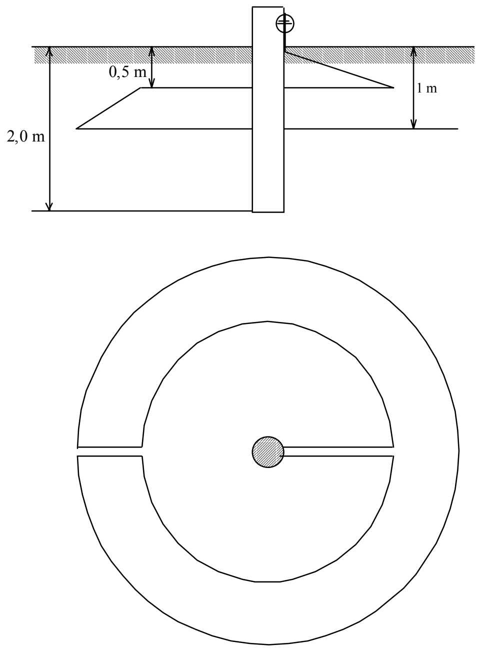

Figure 1. Grounding from the family K2

Using the described stochastic model, characteristics of the most frequently used types of grounding of the 10, 20, 35 kV towers are calculated. According to the recommendations [9], two familias are known, the first one (K1), with just one ring, burried on depth 0,7 m, and the second one (K2), with two rings, where the first one is on depth 0,5 m, and second one, on depth 1 m, with radius 1 m bigger than radius of the previous one. In the adopted denotation here, numbers after the hyphens shows value of radius of the first ring in (m). For ex. K2-1.5 means grounding with two rings with 1.5 m radius of the first one (figure 1), while K1-1.5 is grounding with just one ring with radius 1.5 m.

Fig. 2 presents the dependence of the grounding resistivity, while on figures 3 and 4 are presented dependances of the maximum potential differences of touch and step e_t , e_s , on the radius of the first ring l, for these two types of groundings.

By use of these diagrams everyone can easily choose the type and the necessary dimensions of the grounding, satisfying some technical conditions, limitations and critera's.

Furthermore main characteristics of types K1-1.5 and K2-1.5 are presented.

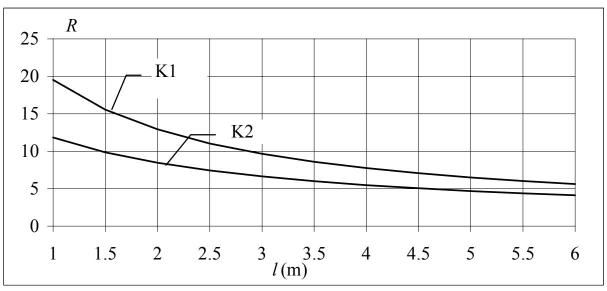

Figure 2. Dependence of the grounding resistivity from the first ring radius *l*, $\rho = 100\Omega$

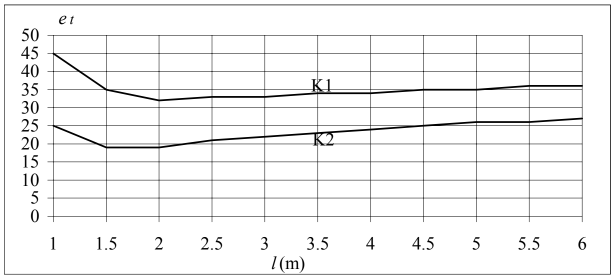

Figure 3. Maximum potential difference of touch e_t in % on which human being might be exposed, for various radius *l*

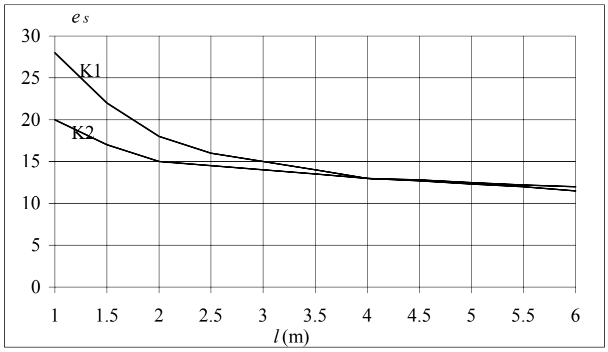

Figure 4. Maximum potential difference of step e_s in % on which human being might be exposed for various radius *l*

Table I. Characteristics of the grounding, type K1-1.5; K2-1.5

Type	R_{100} , Ω	e_t, %
K1-1.5	15,565	35
K2-1.5	9,177	19

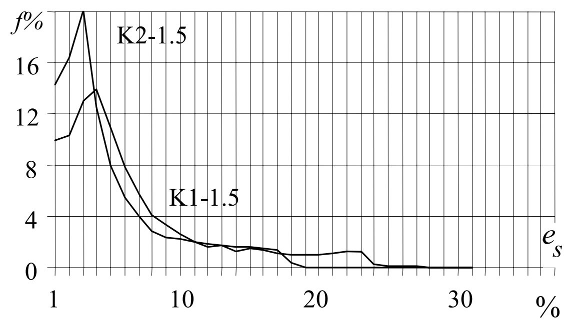

Figure 5. PDF of step potential differences e_s for grounding of the type K1-1.5 and K2-1.5 and its appearence frequency *f*

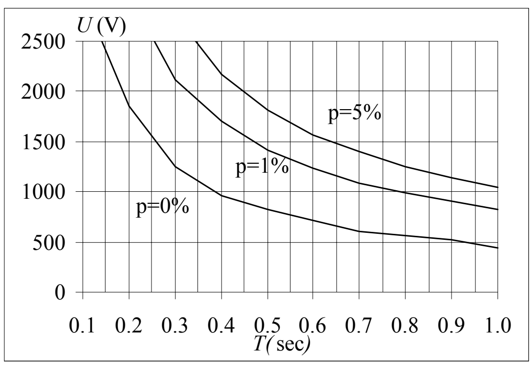

Figure 6. $U=f(T)$, touch voltage, K2-1.5, $\rho = 100\ \Omega$ m

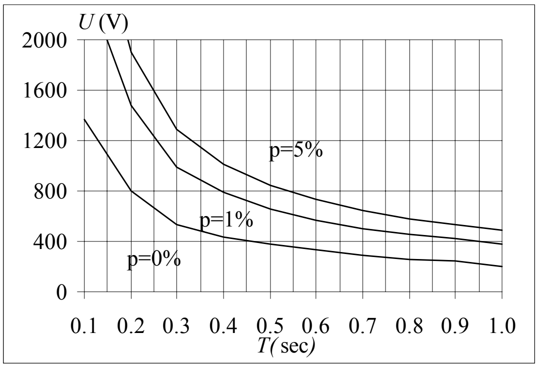

Figure 7. $U = f(T)$, touch voltage, K1-1.5, $\rho = 100\ \Omega$m

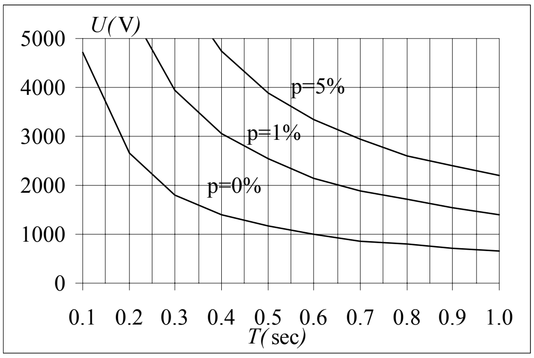

Figure 8. $U = f(T)$, step voltage, K2-1.5, $\rho = 100\ \Omega$m

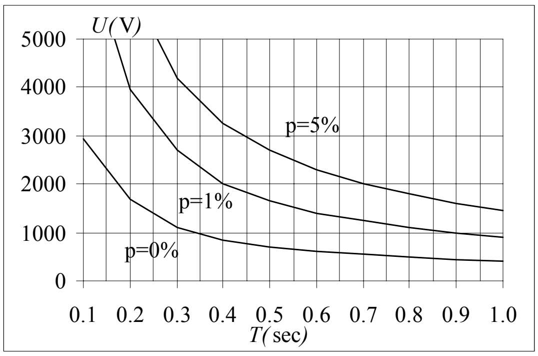

Figure 9. $U = f(T)$, step voltage, K1-1.5, $\rho = 100\ \Omega$m

Because of the simetry of the analysed types, value of e_t is constant in all directions, with the frecuency of appearence f =100 %.

The analyses of the step voltage e_s shows that it is in the interval 0-28 %, (fig. 5) but its bigest valyes are occuring very seldom.

Figures 6-9 present the calculated functions $U(T)$ for various risks's levels p: 0%, 1% and 5%. Figures 6 and 7 are the bigest alowed values of the potentials of the tower U for some chosen risk's levels p for appearing fatal electric shock when touching the tower in the moment of the fault. Fig. 8 and 9 are relating to the dangerous step potential diferences e_s.

Calculations are made for various durations of the fault T.

V. Conclusion

Using the diagrams, presented in this paper, engineers can choose more easily the type and dimensions of the groundings of MV towers that should satisfy some technical conditions and safety criteria's relating the dangerous step and touch potential differences. In the past, the risk of dangerous step and touch potential differences was estimated deterministically, just based on the maximal values of the touch and step potential differences. However, this approach is not correct because in the reality, probability some human being to be exposed on these maximal values is very small, almost equal to zero. In the methodology for estimation of those risks, the stochastic should be involved, as in this paper. In each experiment, using the method of random numbers (Monte Carlo), generated from the computer, human body impedance, current of fibrillation threshold and the probability of death accident, as random variables are calculated. Results of analyses of various types of grounding, suggest the fact that in many cases the real risks of accidental death due to dangerous step and/or touch voltages are considerably smaller than those, are recommended by the existing technical recommendations and adopted criteria's. These criteria's consists too much reserve on the side of the safety, and so, groundings are too expensive. If we accept risk of just 1 %, for instance, the values of the allowed voltage U will be considerably higher, especially for shorter duration of the fault ($T < 0,5$) and for bigger soil resistivity on the surface of the ground.

References

[1] Wang, W., Y.Gervais, D.Mukhedar, "Probabilistic Evaluation of Human Safety Near HVDC Ground Electrode" (85 SM 318-1); T-PWRD Jan 86, pp. 105-110.

[2] M. A. El-Kady, P. W. Hotte, M. Y. Vainberg, "Probabilistic Assessment of Step and Touch Potentials Near Transmission Line Structures", IEEE, Transactions on Power Apparatus and Systems, Vol. PAS. 102, No. 3, March 1983, pp. 640-645.

[3] J. G. Sverak, W. Wang, Y. Gervais, X. Dai-Do, D. Mukhedkar, " A Probabilistic Method for the Design of Power Grounding Systems", IEEE, TPWD, Vol. 7, No. 3, July 1992, pp. 1196-1203.

[4] ANSI/IEEE Std 80-1986, GUIDE FOR SAFETY IN AC SUBSTATION GROUNDING, book, IEEE/John Wiley & Sons, New York, August 1986.

[5] Nahman, J.M, "Assessment of the Risk of Fatal Electric Shocks Inside a Substation and in Nearby Exposed Areas", (89 SM 816-0), T-PWRD Oct 90, pp. 1794-1801.

[6] J. Nahman, M. Zlatanoski, "Risk of fatal electric shocks at distribution network MV/LV transformer stations", IEE Proc.-Gen. Transm. Distrib. Vol. 145, No. 4, July 1998, pp. 463-467.

[7] M. Zlatanoski, "Risk of hazard shocks in HV stations", Ph-D dissertation, ETF-Skopje, 1991.

[8] R. Ackovski, "Grounding of towers of the overhead lines – elements of the grounding system of power networks", Seminar for electrical engineers, Ohrid, 1997.

[9] Technical recommendation TP-9 of ZEPS, Power Transmission, Beograd, 1979.

[10] M. Zlatanoski, R. Ackovski and N. Acevski, N., “Examination of the safety criteria’s of MV/LV transformer stations according the existing technical criteria’s and new recommendations”, III National Conference, MAKO-CIGRE, Ohrid, 2001.