An artificial intelligence system to determine the electrical safety level of power generation facilities

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***Abstract*—The article presents a system of artificial intelligence created for expert assessment of electrical safety level at power generation facilities. This information system based on fuzzy logic methods can more precisely calculate electrical resistivity of the soil in specific conditions. The researchers describe the technique of forming a database and a knowledge base of the expert system including a set of models and algorithms. The article provides a detailed description of fuzzy models of electrical resistivity ρ for different types of soil depending on its humidity, salinity and temperature (both in positive and negative ranges). It offers fuzzy climatic models of soil in a specific area taking into account changes of soil ρ deep into the ground throughout a year. The created artificial intelligence system evaluates the security level of electric power facilities on the basis of different algorithms used to calculate grounding, touch and step voltages; it can more precisely determine soil ρ deep into the ground during a year. The researchers added an option of graphic depiction of modeling results for validation of the solutions offered by the expert system.**

***Keywords*— artificial intelligence system, modeling, multi-parameter dependence, fuzzy logic, soil electric resistivity, grounding devices, electrical safety**

I. Introduction

The percentage of workplace injuries caused by electric shock is relatively small nowadays. However, such injuries caused by electric shock rank the first in the number of deaths and serious consequences for human health. There are many ways to protect the personnel working with electric equipment, including grounding devices[1-7].

The most important parameter of grounding is its resistance calculated on the basis of soil electrical resistivity ρ. However, this parameter varies in a large range depending on the season, weather and climate conditions (from several Ohms to tens of thousands of Ohms)[6]. For this reason grounding was traditionally calculated quite liberally, and in some cases it caused errors in step and touch voltages calculation. For example electrical resistivity of the top soil level rapidly decreases during rain showers, active snow melting, floods or technical accidents. As the result an electric potential that can arise in emergency events may cover considerable distance from the place where a grounding device enters the soil. This may cause an electric shock and serious injuries[7].

II. Solution methods and algorithms

Calculation soil ρ is one of multi-parameter tasks which are difficult to formalize. The issue is that ρ depends on the type of soil, its salinity, humidity, temperature and density, and each of these parameters cannot be determined precisely in real conditions, because soils are not "clean" and the temperature of their layers changes even during the day. This problem can be correctly solved today using modeling on the basis of artificial intelligence methods -soft computing based on the theory of fuzzy sets (and, in its turn, it allows us to solve problems with ambiguous data)[8-19].

This is why we developed an evolutionary information system of artificial intelligence. Such systems allow us to simulate behavior of a certain object in specific conditions stipulated by an operator. In our case the object is a multilayer soil, and each layer has particular characteristics affecting soil conductivity.

The structure of any intellectual system has to include a database and a knowledge base. The database in the created information system is formed by climate parameters of a specific area. And the knowledge base contains logic of the models that describe algorithms and laws according to which the parameters of the examined object can change (in our case the parameters of multilayer soil).

Let's note that the database of the considered information system can be configured for a specific area that requires calculation of grounding devices, touch and step voltages. Climate data include the type of soil, thickness of its layers, ground water level, and values of average monthly temperatures, rainfall, and wind forces for the previous year. As a rule, these data are simple to obtain.

The knowledge base contains the following information:

1. A model of electrical resistivity ρ for different types of soil depending on its humidity and temperature in the positive temperature range[20];

2. A ρ model for different types of soil depending on its salinity[21];
3. A ρ model depending on negative values of temperatures for different types of soil (different salinity and moisture content)[20];
4. model of climatic changes of parameters of soil for determination of unit electrical resistance ρ deep into lands within a year (on the specific area)[22];
5. algorithms for grounding devices calculation of various complexity (on the basis of models 1-4);
6. algorithms for step and touch voltages calculation (on the basis of models 1-4).

The models were developed using a method of artificial intelligence suggested by the Japanese scientists Takagi and Sugeno. Essentially this method means the following: values of output parameters of the examined object are determined experimentally (in the different ranges of its input parameters). Then the system of fuzzy rules is built according to which all calculations are made.

1. The model of soil electrical resistivity. The results of experiments for the examined types of soil showed what in the humidity interval from 0 to 6% the behavior of changing electrical resistivity ρ (ν) differs markedly from the behavior ρ (ν markedly) on the interval from 6% and up to soil saturation with moisture. This is why empirical dependences ρ (ν) were made on the basis of regression modeling for each such interval separately. Then they were united in one mathematical expression using one of fuzzy logic instruments - a system of fuzzy rules.

A direct method was used to determine membership functions, in which (x) μ_A value (a membership function) is set for each $x \in E$ (where x is soil humidity). It is reasonable, because the method is applied to measurable values, such as pressure, temperature etc. Needless to say that humidity is one of such concepts.

The principle of the model is described below. A system of fuzzy rules is developed for each type of soil. It can be written as follows [8,9]

$$\begin{aligned} &\text{IF } (x_1 \in A_{1i}) И (x_2 \in A_{2i}) И \ldots И (x_k \in A_{ki}) \\ &\text{THEN} \quad y = \eta_i(x),\ i = 1, \ldots, N \end{aligned} \quad (1)$$

Where A_{ji} is a fuzzy subset or a fuzzy interval for variable x_j with a membership function $\mu_{Aji}(x)$; N is the number of rules (number of intervals); adjacent μ_1 and μ_2 have non-zero values, and it is always true that: $\sum_{i=1}^{2} \mu_i = 1$, $y=\eta(x)$ is a function defining local solution of the model from the set:$x=(x_1,\ldots,x_k)$.

The solid line in fig. 1 shows a membership function of belonging to a fuzzy "dry" interval, and the dashed line shows the membership function of belonging to a "wet" interval. As the result we got the equations of electric resistivity for sand ρ_s, sandy loam ρ_{sl} and clay ρ_c [20]:

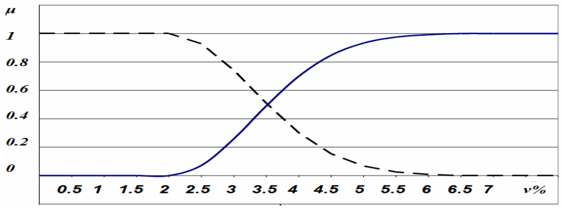

Fig.1 The family of membership functions for fuzzy intervals of humidity

The solid line in fig. 1 shows a membership function of belonging to a fuzzy "dry" interval, and the dashed line shows the membership function of belonging to a "wet" interval. As the result we got the equations of electric resistivity for sand ρs, sandy loam ρsl and clay ρc [20]:

$$\begin{aligned} \rho_s &= 6 \cdot 0.3^{\nu} \cdot \mu_1(\nu) + 1 \cdot 0.7^{\nu} \cdot \mu_2(\nu) \\ \rho_{sl} &= 90 \cdot 0.1^{\nu} \cdot \mu_1(\nu) + 0.3 \cdot 0.8^{\nu} \cdot \mu_2(\nu), \\ \rho_c &= 100 \cdot 0.25^{\nu} \cdot \mu_1(\nu) + 3 \cdot 0.8^{\nu} \cdot \mu_2(\nu) \end{aligned} \quad (2)$$

where ν is soil humidity as a percentage.

To determine electrical resistivity of moist soil at positive temperature values we used a well-known dependence:

$$\rho = \rho_{20} \cdot e^{-0.022 \cdot (t-20)}, \quad (3)$$

where ρ_{20} is soil resistivity at the temperature of 20 ° C and t is soil temperature.

Comparison of the values obtained using this model with reference data showed that the model correctly describes the dependence between electrical resistivity and humidity. Adequacy test of the model using two criteria also gave positive results.

2. The model of ρ for different types of soil depending on its salinity. There are following soil salinity categories of Gradation of salinity of soil are known: not salted (salt content 0.25 - 0.30%), low-salinity (0.30 - 0.50%), medium-salinity (0.50 - 1.0%), high-salinity (1.0 - 2.0%), and saline soils (2.0 - 4.0%).

$$\mu_1 = \begin{cases} 1, & 0 \le salt < 0.4 \\ e^{-0.8 \cdot (salt-2)^2}, & 0.4 \le salt \le 2 \\ 0, & salt > 2 \end{cases}$$
$$\mu_2 = \begin{cases} 0, & 0 \le salt < 0.4 \\ 1 - e^{-0.8 \cdot (salt-2)^2}, & 0.4 \le salt \le 2 \\ 1, & salt > 3 \end{cases} \quad (4)$$

Salinity coefficient was introduced in order to take into account the degree of soil salinity, the value of which is determined by means of fuzzy logic. The behavior of membership functions in fuzzy salinity intervals is similar to functions in fig.1. Their look is presented by the dependences(1).

Values of salinity coefficients are calculated using the following functions[21]:

$$K_{salt} = \sum_{i=1}^{2} \eta_i(salt) \cdot \mu_i(salt),$$

where $\eta_1(salt)=1$, $\eta_2(salt)=0.001$.

For obtaining unit electrical resistance of soil at specific humidity and salinity it is necessary to increase the values received by means of expression 2 on K_{salt}

3. The model of ρ for negative temperature values. Experiments were made to determine the pattern of changes in soil electric resistivity in the process of moisture freezing in the soil and regression dependences were constructed taking into account crystalline or amorphous structure of the soil.

Moist crystalline soils in the temperature range from $0\,^0C$ to $-1\,^0C$ are characterized by an abrupt increase of ρ. The following formulas were developed to calculate the value of such jump for sands and sandy loams [20]:

$$\begin{aligned} \rho_s^1 &= \rho_s^0(-0,03\cdot\nu^2 + 0.86\cdot\nu - 1.9) \\ \rho_{sl}^1 &= \rho_{sl}^0(0.024\cdot\nu^2 - 0.022\cdot\nu + 0.2) \end{aligned}, \quad (5)$$

where ν is humidity expressed in fractions; ρ_s^0 and ρ_{sl}^0 is resistivity for sand and sandy loam at $0\,^0C$, and ρ_s^1 and ρ_{sl}^1 is their resistivity at -1^0C.

Calculation of sand and sandy loam resistivity at temperatures below -1^0C can be done using the following dependences:

$$\rho_s = \rho_s^1 \cdot 0.87^{(t+1)}, \ \rho_{sl} = \rho_{sl}^1 \cdot 0.88^{(t+1)} \quad (6)$$

There is no abrupt increase in ρ happening for clays and loams at about 0 ^{0}C because of the amorphous structure of this type of soil. This is why the following dependence is suggested to calculate electric resistivity of clays in the negative temperature range:

$$\rho_c = \rho_c^0 \cdot 0.88^{(t+1)}, \quad (7)$$

where ρ_c^0 is clay resistivity at $0\,^0C$.

Our analysis of ρ values obtained using the developed dependences shows that they belong to the ranges specified in [6]. Therefore the developed model can be used (with accuracy sufficient for practical work) to determine electric resistivity of any type of soil, taking into account its humidity and temperature.

4. The model of climatic changes of soil parameters. This model was developed in two directions: 1) modeling of temperature changes in soil layers deep into the ground during the year and 2) modeling of humidity changes in soil layers deep into the ground during the year.

4.1. Modeling of temperature changes in soil layers. Creation of this model required analysis of annual temperature changes on earth surface and for different depths in several regions of the CIS. The data were obtained from municipal meteorological stations of Pavlodar (Kazakhstan) and Novosibirsk (Russia) and taken from open sources.

On the basis of the analysis the following dependence was found [21,22]:

$$t = t_P - A_h \cdot \cos\left[\frac{2\pi}{365}(g - 20\cdot h)\right], \quad (8)$$

where A_h is an annual fluctuation amplitude for t (^{o}C) at distance h (m) from the surface calculated as: $A_h = A_P \cdot q^h$, q is a value characterizing temperature decrease deep into the ground: $q = \exp(\ln(A_{PT}/A_P)/h_{PT})$, A_P is an of annual fluctuation amplitude for t(^{o}C) - a temperature of the soil surface, $h_{ПТ}$ is the depth with a permanent temperature during the year (for middle latitudes h=15 meters), coefficient "20" takes into account the delay (in day) in maximum (or minimum) annual fluctuation of temperature t at the depth of 1 m in relation to the temperature of soil surface (for example if the maximum t of the surface is observed in July, then at the depth of 5 m it will be observed 100 days later); g is the number of days starting from January 1, t_P is a temperature of the layer permanent annual temperature, which for middle latitudes is approximately 8 ^{o}C), h – depth from the earth surface in meters; A_{PT} is an amplitude of temperature fluctuation at depths with permanent annual temperature (approximately equals 0.1 ^{o}C), $A_P = (T_{P\,max} - T_{P\,min})/2$, where T_{Pmax} is maximum average monthly temperature, T_{Pmin} is minimum average monthly temperature of the soil surface for a particular year.

4.2. Modeling of humidity changes of soil layers deep into the ground. In the course of analysis of the data from meteorological stations for creation of the second model it was found that climate parameters (rainfall, air temperature, wind force and humidity) affect soil humidity up to 1 m deep into the ground. Only the proximity of subsoil waters has an impact on the humidity of soil layers located more than 1 m deep. Therefore the model of soil humidity has 2 forms: modeling of soil humidity at depths up to 1m) and 2) lower than 1 m.

Modeling of soil layers humidity νon up to 1 m deep was performed using the Takagi-Sugeno method[21]. On the basis of data from meteorological stations for 4 years and their analysis the following multiple-factor models of soil humidity at the depths of 0.2 m and 1 m (meteorological stations register soil humidity at those depths) were developed[22]:

$$v_{20} = 8.06 + 0.03 \cdot o_P - 0.20 \cdot t_{SS} - 0.81 \cdot \upsilon_W;$$
$$v_{100} = -4.10 + 0.03 \cdot o_P - 0.007 \cdot t_{SS} + 1.3 \cdot \upsilon_W, \quad (9)$$

where o_P is an amount of precipitation in mm; t_{SS} is a temperature on the soil surface in ^{0}C, υ_W is an average wind speed in m/s.

$$\mu_1(h) = \begin{cases} 1, & 0 \le h < 20 \\ 1 - \dfrac{h-20}{80}, & 20 \le h < 100 \\ 0, & h > 100 \end{cases}$$
$$\mu_2(h) = \begin{cases} 0, & 0 \le h < 20 \\ \dfrac{h-20}{80}, & 20 \le h < 100 \\ 1, & h > 100 \end{cases} \quad (10)$$

The membership function to determine of soil humidity at depths up to 1 m is described by expressions (10). As a result the expression for humidity at depths up to 1 m looks as follows:

$$v_h = v_{20} \cdot \mu_1(h) + v_{100} \cdot \mu_2(h) \quad (11)$$

For assessment of the model and determination of the percent age of function v dispersion in relation to its mean value depending on accumulated precipitation, temperature on the soil surface and wind speed we calculated determinancy coefficient B_{yx}. For the depth of 20 cm $B=0.9_{yx}$, for the depth of 100 cm $B=0.96_{yx}$ which proves the adequacy of the model to real data.

In order to create the model helping to determine soil humidity in any season of the year at depths up to 1 m we introduced a linguistic variable "month" with two values "cold" and "warm". The first time interval of modeling includes months when air temperature is steadily below zero degrees Celsius (for the considered climatic zone – from November to February), and the second interval is from April to October.

Thus, it can be taken that membership function μ is $\mu_1(m)=1$ and $\mu_2(m)=0$ from November to February for the first interval "cold", and from April to October it is $\mu_1(m)=0$ and $\mu2(m)=1$ for the second interval "warm" where m is the number of the month. Switching intervals are March (the month of active snow melting) and November (the month when soil temperature gets close to negative values).

To the month of active snow melting to the rainfall accumulated during the month we need to add the precipitation accumulated in the form of snow cover during winter months. Membership functions look as follows (see fig. 2, expressions 12):

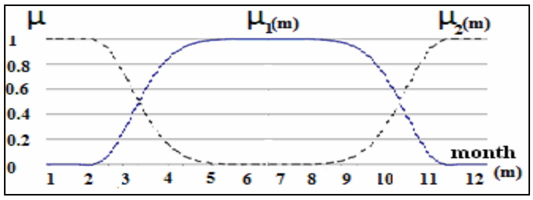

Fig. 2 The family of membership functions to determine humidity by month

$$\mu_1(m) = \begin{cases} 0, & m \le 3, \ m \ge 11 \\ e^{(-3\cdot(m-4)^2)}, & 3 < m \le 4 \\ 1, & 4 \le m \le 10 \\ e^{(-3\cdot(m-10^2))}, & 10 \le m \le 11 \end{cases}$$
$$\mu_2(m) = 1 - \mu_1(m) \quad (12)$$

As a result for depth up to 1 m the humidity depending on o_P, t_{SS}, υ_W and the season (by months) can be calculated using the following formula:

$$v = \sum_{i=1}^{2} \eta_i(m) \cdot \mu_i(m) = \eta_1(m) \cdot \mu_1(m) + \eta_2(m) \cdot \mu_2(m), \quad (13)$$

where $\eta_1(m) = v_h^{(m=10)}$ is the humidity for October calculated by (14) because for the considered region (middle latitudes) in winter months (m=11,12,1,2) v does not change; and $\eta_2(m) = v_h$ is the humidity for warm months (m=4÷10).

The humidity of soil layers located more than 1 m deep from the surface practically does not depend on climate conditions and is determined by the level of ground waters. Therefore to develop the model in this case we used capillary height h_{CR} (water capillary rise): for sand this value is 0.5 m, for sandy loam – 1 m, for loam – 1.5 m, for clay – 2.5 m, and height and rise rate depend on the soil structure.

$$\mu_1(h_{GW}) = \begin{cases} 1, & \text{при} \ 0 \le h_{GW} \le 0.8h_{CR} \\ 1 - \dfrac{h_{GW} - 0.8 \cdot h_{CR}}{0.2 \cdot h_{CR}}, & 0.8h_{CR} \le h_{GW} \le h_{CR} \\ 0, & \text{при} \ h_{GW} \ge h_{CR} \end{cases} \quad (14)$$
$$\mu_2(h_{GW}) = 1 - \mu_1(h_{GW})$$

In humidity modeling we introduced a fuzzy variable "proximity of subsoil waters" with two values: the first is "nearby" with membership function $\mu_1(h_{GW})$ and the second is "far" with $\mu_2(h_{GW})$. The value of $0.8h_{CR}$ was selected because the soil starts drying starting from this distance from water level.

The formula for v definition looks as follows:

$$v = \sum_{i=1}^{2} \eta_i(h_{GW}) \cdot \mu_i(h_{GW})$$

The dependence $\eta_1(h_{GW})$ is built according to the data from a geological prospecting center in the form of a curve obtained using the least-squares method. So, for example, for sand $\eta_1(h_{GW}) = 18 - 27 \cdot h_{GW}$, and $\eta_2(h_{GW})$=4.5 (4.5 is the humidity of a natural sand bedding as a percentage). As a result the model of soil v definition looks as follows:

$$\begin{aligned} v_{sandi} &= (18 - 27 \cdot h_{GW}) \cdot \mu_1(h_{GW}) + 4.5 \cdot \mu_2(h_{GW}) \\ v_{sandi\_loam} &= (23 - 19 \cdot h_{GW}) \cdot \mu_1(h_{GW}) + 3.8 \cdot \mu_2(h_{GW}) \\ v_{clay} &= (50 - 12.8 \cdot h_{GW}) \cdot \mu_1(h_{GW}) + 18 \cdot \mu_2(h_{GW}) \\ v_{clay\_loam} &= (45 - 25 \cdot h_{GW}) \cdot \mu_1(h_{GW}) + 7.5 \cdot \mu_2(h_{GW}) \end{aligned} \quad (15)$$

Here coefficients 18, 23, 50, 45 are maximum moisture capacities of sand, sandy loam, clay and clay loam respectively. Thus, knowing the number and the type of layers and the depth of subsoil waters, we can determine soil humidity according to model (15) at depths below 1 m with accuracy sufficient for practical work in any season of the year. The error of humidity modeling does not exceed 20% for dry soil and 10% for wet one.

The adequacy to the received model is confirmed by the Fischer criterion that is 3.34 for dry soil and 3.59 for wet one which is higher that tabular 3.26 (at significance level α=0.05).

5. Algorithms for grounding devices engineering. The suggested expert system contains algorithms allowing calculation of the following types of grounding devices: simple vertical, simple horizontal, grounding in the form of connected vertical electrodes and in the form of a grid. Each type of grounding is calculated depending on relative positioning and geometrical sizes of its elements[23,24], depth of its installation and electric resistivity of soil layers (calculated using models 1-5).

In addition to grounding devices calculation, the suggested expert system can carry out different modeling and create diagrams. For example, it is possible to simulate how the resistance of a grounding device will change at different depths of its installation in the worst period of the year (in terms of soil electric resistivity). Or to construct a model which will show how grounding resistance will change during a year taking into account climatic peculiarities of the area.

A graphic interpretation of the modeling processes clearly demonstrates and explains the obtained solution. Thus, for example, fig. 3 shows the diagram of changing soil electric resistivity deep into from the earth surface for a specific area during a specific time period. Its results are easy to compare with the real data.

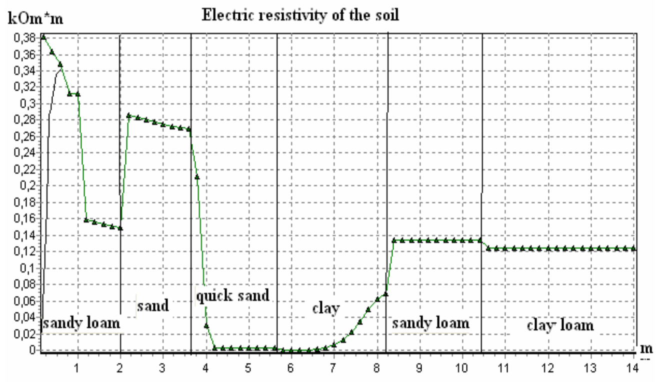

Fig. 3 — Changes in soil electric resistivity by depth (up to 14 m).

There are 5 layers of soil in the examined area at depths from 0 m to 14 m. The top layer 2 m thick is a sandy loam, and beneath it there lies a layer of sand 3.2 m thick, the next layer is water-bearing sand 2.8 m thick, and below it is a clay layer 4.3 m thick. At the depth of 4.65 m the value of electric resistivity resistance of the sand begins to fall sharply because below it there is a water-bearing layer, whose ρ is close to zero or more precisely 0.5 Ohms · m.

The curves on fig. 3 characterize the electric resistivity of soil layers at the beginning of December (the line with markers) and in March, during active snowmelt (the solid line).

The figure shows how ρ of the top soil level falls practically to zero at the beginning of spring (the solid line) and how ρ of the top soil level increases in December when temperature stays below zero (the line with markers). The depth of ground freezing in this climatic zone is about 1.1m. This is why ρ value below this level abruptly falls to the value corresponding to positive temperatures.

6. Algorithms of step voltage and touch voltage calculation in case of accidents at electric power plants. Touch and step voltages are calculated taking into account non-uniformity of the soil and electric resistivity of its layers, because its values differ depending on the season and climate conditions. The suggested expert system has a block helping to analyze electrical safety for electrical installations. Such analysis is carried out on the basis of the following provisions[7]:

– resistivity of modern continental precipitation is 1-3 Ohms · m;
– melt waters and rainfall resistivity in industrial zones is less than 1 Ohm · m.

On the basis of therse values we calculated distribution of the potential on earth surface from its entry point (see fig. 4). Calculation for a point located at the distance of x meters from the grounding was carried out using a well- known formula[7]:

$$\varphi = \frac{I_3 \rho}{2 \pi l} \ln \frac{\sqrt{x^2 + l^2} + l}{x}, \quad (16)$$

where ρ is soil resistivity (1 Ohm·m for abundant rains and active snowmelt), x is the distance from the entry point of the potential, l is the thickness of the layer having resistance ρ.

Hazardous voltage is 36V (this parameter can be reduced subject to certain conditions). Thus, a dangerous distance for the working personnel can be determined by means of the suggested models 1-5 and expression 16:

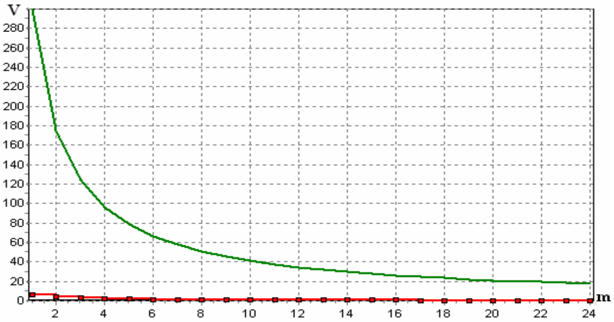

Fig. 4 Change of potential on the earth surface in case of phase-to-ground short circuit during active snowmelt (top curve) and during the period without abundant moisture

Provided that step length is 0.8 m, a dangerous distance from the entry point of the potential will be 2.5 m. The personnel have to be informed about it by the general announcement system at the enterprise. In this case all conducting objects at the distance of 10 m from the point where the potential enters the ground will have a dangerous touch voltage. No dangerous potential arises in case of normal soil moistening level (fig. 4, the bottom curve).

III. Conclusion

The intellectual system presented in the article determines the level of electrical safety at power generation facilities on the basis of more accurate calculation of electric resistivity ρ and other affecting it soil parameters. Modeling is carried out using the methods of artificial intelligence and fuzzy logic in particular.

Fuzzy models of soil ρ depending on such parameters as soil type, humidity, salinity, as well as temperature change and humidity of soil layers under the influence of climatic factors in the specific area were obtained on the basis of the Takagi-Sugeno method. They were used to create the knowledge base of the intellectual system.

The suggested fuzzy models make it possible to determine soil parameters for any season of the year and at any depth with sufficient accuracy for practical purposes. At the same time graphical representation of modeling results is quite convenient because it visually explains the solution given by the expert system.

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