ELECTRIC AND MAGNETIC FIELD COMPUTATION OF 35 KV VOLTAGE LEVEL OF TRANSFORMER SUBSTATION 35/10 KV USING THE CDEGS SOFTWARE

Marinko STOJKOV[*], Damir SLJIVAC[**], Lajos JOZSA[**]

[*]University of Osijek, Faculty of Mechanical Engineering, Trg Ivane Brlić Mažuranić 2, 35 000 Slavonski Brod, Croatia, tel.: +385 35 446 188, e-mail: marinko.stojkov@sfsb.hr

[**]University of Osijek, Faculty of Electrical Engineering, Kneza Trpimira 2b, 31000 Osijek, Croatia, tel.: + 385 31 224 600

ABSTRACT

Paper presents electric and magnetic field computation of 35 kV voltage level of transformer substation 35/10 kV using CDEGS software. Based on well known theoretical considerations of electric and magnetic fields, a realistic simulation model of transformer station 35/10 kV was develop. All calculations are made for horizontal plane with height of 1,5 m above the soil changing coordinates along x and y axes. The simulation results indicate that the values of electric and magnetic fields of the transformer station 35/10 kV are within the limits of regulations in Croatia. Furthermore, the simulation yields symmetric spatial distribution of the electric and magnetic fields on the observed plain, with maximal values at the points of geometric overlapping of conductor resultant fields.

Keywords: *electric and magnetic fields, 35/10 kV transformer station, simulation models, horizontal plane, spatial distribution*

1. INTRODUCTION

Electromagnetic fields are closely associated with development of technology and proportionally with new discoveries and number of widely used electric devices, the number of man-made electromagnetic sources increases. Starting from large power plants up to the finest home appliances and mobile phones, the number of sources of electromagnetic fields is increasing every day. Scientist's interest and deep attention on the impact of electromagnetic radiation on human health are increasing proportionally resulting in specified regulations on the limits of electromagnetic fields.

Republic of Croatia adopted the Legislations on Non-Ionizing Radiation Protection defining decision-action rules (article 10) and permitted levels of marginal electric and magnetic fields (Narodne Novine - Official Gazette 204/03). Legislations enact obligation of power object's owners to perform measurements of electric and magnetic fields of existed transformer substation as the non-ionizing radiation sources and to perform electric and magnetic field computation for almost all new planned transformer substations.

Norms divided the overall affected population and thus limits of exposure, in two different groups: professional population (working population) and general population. It is presumed that a part of the population is more sensitive to electromagnetic radiation (patients, pregnant women, children, elderly) and that this group should be protected carefully. On the other hand, occupational exposure is defined as an exposure to electromagnetic radiation that occurs during planned activities and it is presumed that workers are aware of the risks, undergoing regular health checks which control any harmful effects on their health.

In general, 35/10 kV transformer station generates continuous electromagnetic field at frequency of 50 Hz, so the marginal levels of intensity of electric field E and magnetic flux density B are defined according to the so called Book of regulations, namely:

- For the professional exposure (8 h/day) E_{M8h} = 5000 V/m and B_{M8h} = 100 µT
- Increased sensitivity exposure (24 h/day) E_{M24h} = 2000 V/m and B_{M24h} = 40 µT

Subject of this paper is therefore comparison of calculated values of electric and magnetic field in the near proximity to energized power lines and transformer substations, particularly in the close neighborhood (outside the protective fence) where human exposure is expected to above listed limits according to Croatian regulations.

2. THEORETICAL MODEL

The author presents his main ideas, mathematical Fundamental source of electric and magnetic fields on 35 kV voltage level of transformer station 35/10 kV are overhead power lines 35 kV and 35 kV parts of transformer substation's busbars and equipment. Analyzed transformer substation 35/10 kV has rather simple "H" shape of 35 kV power lines and it is presented by three-dimensional model to compute claimed electromagnetic parameters. Electric and magnetic fields calculation are conducted for quasi-static states at the rated frequency of power system in Croatia (50 Hz).

Results of computation of electric and magnetic field are calculated as spatial distributions in horizontal planes at different coordinates z along the points on x and y axes. Maximum densities of electric and magnetic fields are induced by coordinate components of a vector potential caused by maximum currents of each segment of the busbar. The maximum current I, flowing through the segment impedance Z of the busbar, is defined by voltage drop U between marginal points of the conductor segment:

$$\int_{P_1}^{P_2} \vec{E} \cdot d\vec{l} - \int_{P_1}^{P_2} ZI dl = 0 \qquad (1)$$

2.1. Conservative electric field

The density of conservative electric field can be computed only on the base of known potentials of busbars. Although all electric charges are on the surface of conductors and it should be imperative duty to be acquaint with charges distribution. Here, an assumption is made to simplify calculation: busbar geometry is neglected and only one-dimensional wire model is used. Sources of electric fields are three-phase currents along the power lines while influence of ground is considered using the mirror technique. All vectors are summed by superposition theorem in time domain.

The conductor surface is modeled with a thin-wire approximation which means that the conductor diameter is assumed much smaller than the length of the conductor. The phasor of the electric potential of selected space point P (x, y, z) can be presented as an infinite sum of potentials induced by elemental time variable line charges existed on the surface of the conductor and their mirrored images caused by ground-air discontinuity of permittivity parameter. Since the thin-wire approximation is used, an infinite sum of the charge can be represented as phasor of line-charge distribution and electric potential phasor as following integral equation:

$$\dot{\varphi} = \frac{1}{4\Pi\varepsilon} \int_{l'} \frac{\dot{\lambda}(\vec{r}')dl'}{|\vec{r}-\vec{r}'|} + \frac{1}{4\Pi\varepsilon} \int_{l''} \frac{\dot{\lambda}(\vec{r}'')dl''}{|\vec{r}-\vec{r}''|} \qquad (5)$$

Where:

$\dot{\lambda}(\vec{r}')$ - phasor of line charge density of the original busbar/wire (A/m),

$\dot{\lambda}(\vec{r}'')$ - phasor of line charge density of the mirrored busbar/wire (A/m),

$|\vec{r}-\vec{r}'|$ - distance between the observation point P and the phasor of line charge density of the original busbar (wire) (m),

$|\vec{r}-\vec{r}''|$ - distance between the observation point P and the phasor of line charge density of the mirrored busbar (wire) (m),

ε - permittivity parameter of the space electric field is computed in (air and soil),

l' - integration line between observation point P and selected segment of original busbar (wire),

l'' - integration line between observation point P and selected segment of mirrored busbar (wire).

Here, the line charge density is an unknown mathematical function as a source of electric field, so numerical method is used to solve the problem [1].

The total length of conductor is substituted by N segments of finite lengths Δl (j = 1,..,N), where N depends on the desired accuracy. Thereafter, the unknown distribution of electric potentials needs to be approximated with basic mathematical functions λ_j:

$$\dot{\lambda} = \sum_{j=1}^{N} a_j' \lambda_j' \qquad (6)$$

$$\dot{\lambda} = \sum_{j=1}^{N} a_j'' \lambda_j'' \qquad (7)$$

Here, phasor's constant values of line charge densities λ' and λ'' are premised function for each busbar (wire) segment and lengths of each segment must be very short (less than 1 m) due to n high precision needed in the computation. Parameter a_j' is set on 1 if it is observed segment for calculation, otherwise is set on 0. Now, N conductor segments of one phase wire (bus) with its known line charge density functions form a system of N equations with N unknown variables, which has the matrix form of:

$$\left[\dot{\varphi}\right] = \left[p\right]\cdot\left[\lambda\right] \qquad (8)$$

Constituent elements $p_{i,j}$ of the matrix $\left[p\right]$ present electric potential's portion at selected point "i" situated on the surface of the wire (bus) surface with line charge density λ_j. Determination of matrix equation is resolved by iterative walkthrough Gauss-Seidel method until relative accuracy of 10^{-7} is achieved.

Since the electric field is caused by the line charge density phasors of the three-phase system that are phase shifted by 120^0 with variety of possible phase's location in space (phase's distances, phase's heights above the ground and their disposition geometry) each component of the electric field has a different momentary value and phase shift:

$$E_x(t) = E_{x,max} \sin(\omega t + \varphi_x) \qquad (9)$$

$$E_y(t) = E_{y,max} \sin(\omega t + \varphi_y) \qquad (10)$$

$$E_z(t) = E_{z,max} \sin(\omega t + \varphi_z) \qquad (11)$$

Absolute momentary value of electric field vector density is:

$$E(t) = \sqrt{E_x^2(t) + E_y^2(t) + E_z^2(t)} \qquad (12)$$

Effective value of electric field vector (root mean square value) is:

$$E = \frac{1}{\sqrt{2}} \sqrt{E_{x,max}^2 + E_{y,max}^2 + E_{z,max}^2} \qquad (13)$$

2.2. Conservative magnetic field

Open air space around busbars and power lines inside transformer substation is modeled as a linear isotropic half-space (ε₀, μ₀, κ = 0) with discontinuity on horizontal plane (ground), defined by height 0 m (coordinate z = 0). Half-space under horizontal plane (ground) is modeled by the soil's electric parameters (μ₀, κ = 0,01 S/m).

Magnetic field is caused by the phase currents:

$$\underline{I}_R = I$$

$$\underline{I}_S = I \cdot e^{-j\frac{2\Pi}{3}} \qquad (14)$$

$$\underline{I}_T = I \cdot e^{-j\frac{2\Pi}{3}}$$

The magnetic field is then expressed as:

$$\vec{B} = \frac{\mu_0}{4\Pi} \int_0^{l_j} \frac{\dot{I} d\vec{l} \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|} \tag{15}$$

When calculating the electric field CDEGS [8] uses the thin-wire approximation. In order to meet the above approximation, the following conditions must be met:

- transverse currents are neglected relative to axial currents on the conductor,
- circumferential variation of the axial currents is neglected too,
- current can be represented by a line situated on the busbar's axis,
- boundary condition on the electric field need to be enforced in the axial direction only.

As already mentioned, these conditions are met if the diameter of the conductor is much smaller than the length of the conductor and the wavelength.

The calculation of electric and magnetic fields was performed via observation points. Observation points are arranged in a rectangular network of size 20x20 m in x-y plane i.e. the plane parallel to the ground, at height of z = 1.5 m. Higher voltage level (35kV part) of transformer station where the calculations are made, is covered by the whole plane by default. The distance between observation points is 0.25 m which provides sufficient resolution and output data. The height is set at 1,5 m above the ground to be as close as possible to height of an average human. Since in CDEGS point zero on the z-axis is considered buried in the earth, to compute the electromagnetic field on the surface, it is recommended to set the height to 0.1 m in z-axis for the exact result.

3. CALCULATION OF THE ELECTRIC AND MAGNETIC FIELD

Model of 35/10 kV transformer station used in the calculation of the electric field is shown graphically on Figure 1. Whereas distances of calculation points (horizontal plane with height 1.5 m) are much larger then busbar and conductor geometry, all conductive parts are presented as thin one-dimensional wire grid. Notice that the model is set in a way that the negative z-plane is above the ground. After consisted elements with their lengths, inter distances and heights of the transformer substation (busbars, power lines and busbar interconnection) are entered in CDEGS software, physical model is finished.
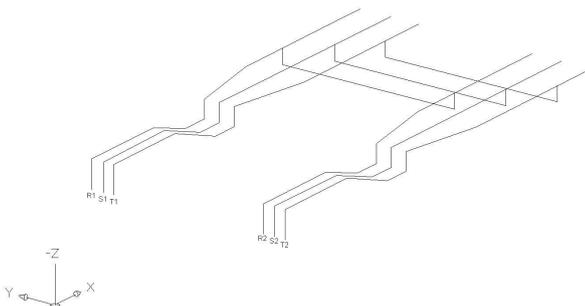

Fig. 1 Physical model 35/10 kV for the calculation of electric and magnetic fields

To define the type of soil, a homogeneous soil profile with resistivity of 100 Ωm and relative permeability and relative permittivity of 1 was used inside air half-sphere space. Analyzed transformer substation 35/10 kV is constituted therefore by two power lines, two power transformers and interconnections of lines and buses. To simulate model of transformer substation by plant design documentation data, HIFREQ [6, 7] module is used. Computation method used in HIFREQ module is based on current distribution along conductor's segments which is kind of mathematical method of moments, taking into consideration changes in conductor's impedances. The highest daily measured currents' value during 15 minutes time intervals is I = 75A. Phase voltages of conductors on the 35 kV side are respectively: $\varphi_A = 20\ 207\ e^{j0}\ V$; $\varphi_B = 20\ 207\ e^{j240}\ V$; $\varphi_C = 20\ 207\ e^{j120}$.

3.1. Normal operational state

Two methods are used for the calculation. The first method is based on the values of current and ground potential rise. Potentials are entered according to the phase voltages and the current value is, the already mentioned, maximal daily current load of I = 75 A. The second way is based on voltage and electrical load in each of the phases. Load is modeled with resistor with predefined value normally attached on the bus conductor. Phase voltages of conductors on the 35 kV side and the load resistance of R_t = 270 Ω (given the current of 75 A) are considered too.

It is important to carefully define the potential because CDEGS currently supports energized conductors type of calculation only for the conductors where initial coordinates are not connected to the network. In both modes, the same results of electric and magnetic fields were obtained.

Spatial distribution and strength of electric field of transformer station 35/10 kV are shown in the figures below. Figure 2 presents the 2D distribution of electric field, at height of 1.5 m (approximation of the average human height).
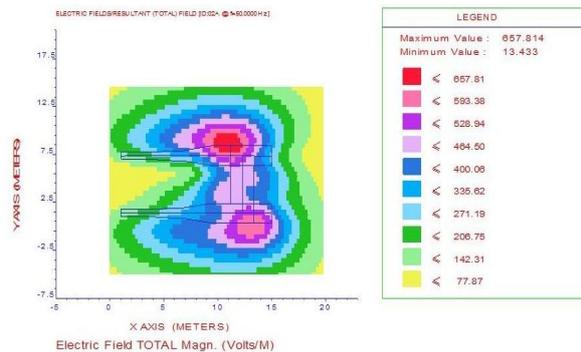

Fig. 2 2D distribution of electric field

It is easy to see that the electric field distribution is symmetric. Note that the maximal values of the electric field are at the points of geometric overlapping of conductor resultant fields. The maximal value of the electric field obtained by simulation is E = 657.814 V / m which is far below the increased sensitivity limit (24 h / day), which is E_{b24h} = 2000 V / m. Mild dissymmetry can be attributed to the power line inter-connection bus geometry.
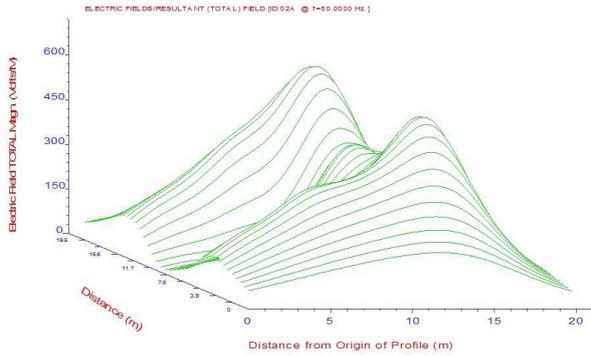
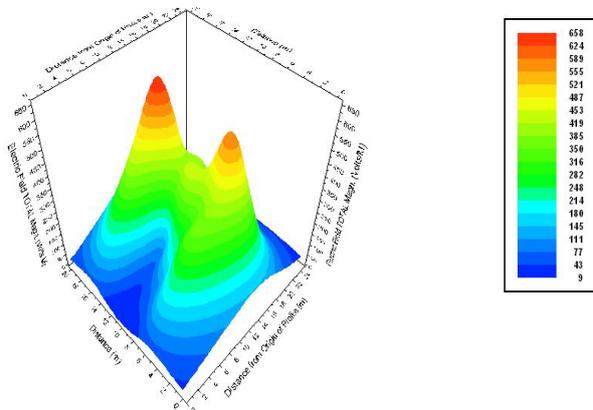**Fig. 3** 3D line distribution of electric field

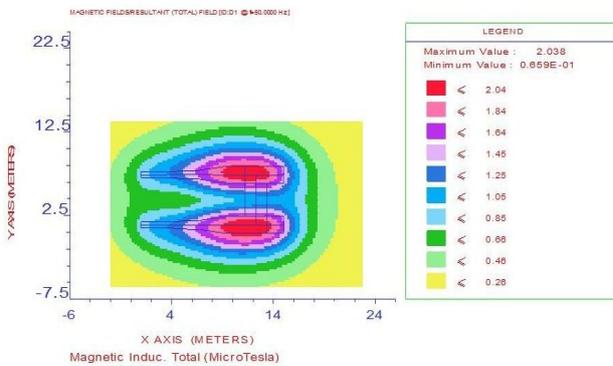**Fig. 4** 3D distribution of electric field

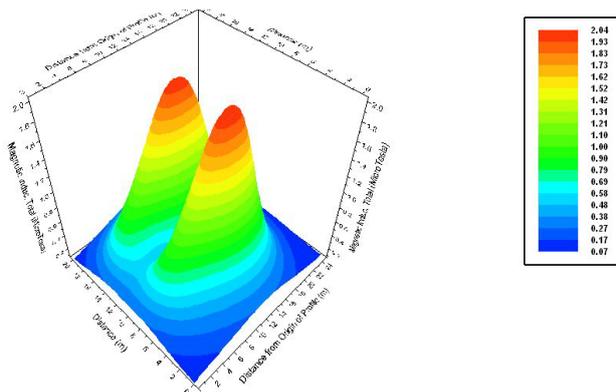**Fig. 5** 2D distribution of magnetic field

Fig. 6 3D distribution of electric field

Distribution and strength of magnetic field of transformer station 35/10 kV are shown in the pictures below. Figure 5 shows the 2D distribution of electric field, at a height of 1.5 m. Figure 6 shows the 3D distribution of magnetic field.

The distribution of the magnetic field is also symmetric. Also, maximal values are noted at the points of geometric overlapping of conductor resultant fields. Results that barely exceed the value of B = 2µT are far below the marginal level of magnetic flux density for the increased sensitivity (24 h / day) $B_{b24h} = 40$ µT.

3.2. Short-circuit conditions

Figure 7 and 8 show the distribution of the magnetic field for the $I_{ef35} = 2.846$ kA, the effective value of short-circuit current.
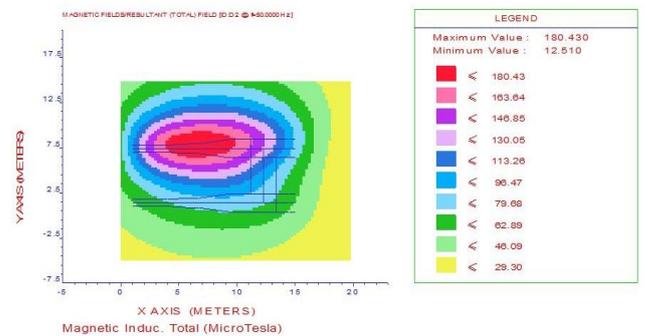

Fig. 7 2D magnetic field distribution for short-circuit in phase R_1 for $I_{ef35} = 2.846$ kA

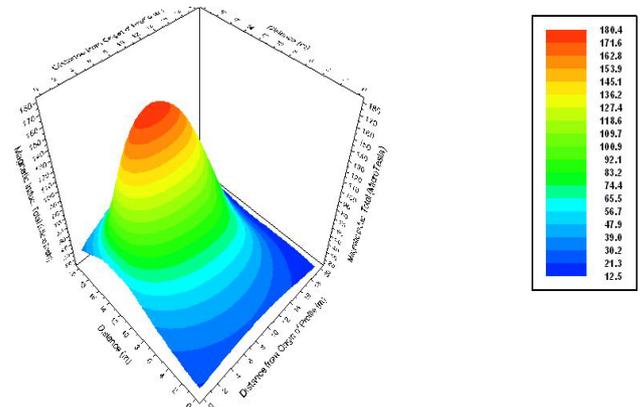**Fig. 8** 3D magnetic field distribution for short-circuit in phase R_1 for $I_{ef35} = 2.846$ kA

It is easy to notice that only in the case of short circuit magnetic field levels exceed the limit of occupational exposure (8 h/day) which is B = 100 µT. However, the magnetic field is significantly decreased with greater distance from the short-circuit phase. For example, in the case of short circuit phase current of $I_{ef35} = 2.846$ kA magnetic field takes on values that are within the boundaries of occupational exposure at the distance of 5 meters Considering the fact that the short circuit current is of very limited duration (until the reaction of relay protection turning the breaker off – within 1 s) one can conclude that there is no explicit danger from magnetic fields in short-circuit conditions.

4. CONCLUSIONS

Results obtained by performed simulation the electric and magnetic field of transformer station 35/10 kV indicated that all values are within the permissible limits of legislation, even for unlikely case of human residential exposure during 24h per day, while reality is that the calculated fields within spatial parameters considered (20 m around the transformer station) will be more suitable for professional population exposure, i.e. the workers. This paper presents results of applied CDEGS software to verify real intensities of electric and magnetic fields inside the transformer substation 35/10 kV according to permissible values for the electric and magnetic field intensity defined in Croatian regulations. In addition, the calculation of magnetic field in short-circuit case have been performed. Although magnetic field exceeds the legal framework in such case, due to the limited duration and the fact that concentration of the magnetic field rapidly decreases already with a few yards away it is not considered as a real threat to human health, at least according to the legislation. Nevertheless, safety and health issues of particularly endangered populations should be a driver for further more detailed analysis and calculation.

REFERENCES

[1] DAILY, W. K. – DAWALIBI, F.: Measurements and Computations of Electromagnetic Fields in Electric Power Substations, IEEE Transactions of Power Delivery, Vol. 9, No. 1, January 1994.

[2] NIKOLOVSKI, S. – ŠLJIVAC, D. – JINXI, M.: Electromagnetic Field Produced by Overhead Power Lines, Proceedings of the 8th International Conference on Operational Research KOI 2000, Mathematical Department, J. J. Strossmayer University 2000.

[3] SELBY, A. – DAWALIBI, F.: Determination of Current Distribution in Energized Conductors for the Computation of Electromagnetic Fields, IEEE Transactions on Power Delivery 9 No. 2 (April 1994), 1069–107.

[4] DAWALIBI, F. – SELBY, A.: Electromagnetic Fields of Energized Conductors, IEEE Transactions on Power Delivery 8 No. 3 (July 1993), 1275–1284.

[5] DAWALIBI, F. – DONOSO, F.: Integrated Analysis Software for Grounding, EMF, and EMI, IEEE Computer Applications in Power 6 No. 2 (April 1993), 19–24.

[6] NIKOLOVSKI, S. – MARIC, P. – BAUS, Z.: Electromagnetic Field Calculation of Transformer Station 400/110 kV Ernestinovo Using the CDEGS Software, Journal of Electrical Enengineering, Vol. 58, No. 4, 2007, 207–213.

[7] NIKOLOVSKI, S. – KLAIĆ, Z. – KRAUS, Z. – STOJKOV, M.: Computation and measurement of electromagnetic fields in high voltage transformer substations, Proceedings of the 33rd International Convention on Information and Communication Technology, Electronics and Microelectronics, Computers in Tecnical Systems, Opatija, Croatia, May 24–28, 2010.

[8] CDEGS User manual, SES technologies, Montreal, 2005.

BIOGRAPHIES

Marinko Stojkov was born in Slavonski Brod, Croatia, on November 18, 1970. Obtained B.Sc. (1990-1994), Master of Science Degree (M.Sc.) (1996-1998) and Ph.D. (1999-2002) from Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. His primary research interests are power systems availability and reliability, power system quality, load modeling and forecasting, real on-line voltage measurements. His employment experience included the HEP group, National Board of Croatia on positions: maintenance manager in 10 kV and 0.42 kV distribution power network, develop manager of power system network including transformer substations. He works as a Associate Professor on the Power System Engineering Department at the Mechanical Faculty of Slavonski Brod and Faculty of Electrical engineering, University of Osijek, Croatia.

Damir Sljivac was born in Osijek, Croatia, on February 4, 1974. He obtained his BSc degree in 1997 from the Faculty of Electrical Engineering, Osijek, MSc degree in 2000 and PhD degree in 2005 from the Faculty of Electrical Engineering and Computing Zagreb, Croatia in the field of the Power System Engineering. Currently he is an Associate Professor at the Power System Engineering Department and vice-dean at Faculty of Electrical Engineering Osijek, Croatia. His main interest is in power system reliability, economics and renewable energy sources. He has published over 50 papers in those fields. He is a member of IEEE Power Engineering Society, IEEE Reliability Society, IEEE Croatia Section, Executive Board of National Council for Energy Of Croatian Academy for Science and Art and Croatian National Committee of CIGRE and CIRED.

Lajos Jozsa was born on 19 December 1945 in Feketić, Serbia. He received the B.Sc. degree 1972, the M.Sc. degree 1978 and the Ph.D. degree 1984 in power engineering, each from the Faculty of Electrical Engineering of the University in Zagreb, Croatia. Dr. Józsa is associate Professor on the Faculty of Electrical Engineering of the Josip Juraj Strossmayer University in Osijek, Croatia. His special fields of scientific interest are hydro-thermal power system reliability, expert systems in reliability analysis of power systems and power quality in electrical systems.