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Electric & Magnetic Field Estimation in the Vicinity of Overhead Transmission Lines Using a Method Based on Multiple Linear Regression

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Abstract. The paper proposes a novel method to determinate the electric field strength and magnetic flux density at an arbitrary point in the vicinity of the overhead transmission line. The method is based on a multiple linear regression model and ordinary least squares estimator. This is a simple method that estimates the electric field strength and magnetic flux density over a lateral profile under overhead transmission lines. Using the method requires no specialist knowledge or software. Determination of the regression parameters is performed in a simple and quick way and only once in a lifetime for any type of the overhead transmission line. A detailed description of the method is given. The method is verified by comparing its numeric prediction values with measurement values and results obtained by other calculation methods. The obtained results show that the method enables a fast and simple estimation of the electric field strength and magnetic flux density in the vicinity of overhead transmission lines with a satisfactory level of the accuracy.

Keywords: Electric field strength, Magnetic flux density, Multiple linear regression, Least squares estimation

Ocena električnega in magnetnega polja v bližini nadzemnih daljnovodov z uporabo metode, ki temelji na večkratni linearni regresiji

V prispevku je predlagana nova metoda, ki omogoča določanje jakosti električnega polja in gostote magnetnega pretoka na poljubni točki v bližini nadzemnega daljnovoda. Metoda temelji na modelu multiple linearne regresije in navadnem ocenjevalcu najmanjših kvadratov. To je preprosta metoda, ki omogoča oceno jakosti električnega polja in gostote magnetnega pretoka preko bočnega profila pod nadzemnimi daljnovodi. Uporaba predlagane metode ne zahteva posebnega znanja ali programske opreme. Določanje regresijskih parametrov izvedemo na enostaven in hiter način in je potrebno le enkrat za vsako izvedbo daljnovoda. V prispevku je podroben opis predlagane metode ocenjevanja. Metodo smo verificirali s primerjavo rezultatov njene numerične napovedi z merilnimi podatki in rezultati, pridobljenimi z drugimi računskimi metodami. Dobljeni rezultati potrjujejo, da omogoča predlagana metoda ocenjevanja hitro in enostavno oceno jakosti električnega polja in gostote magnetnega pretoka v bližini nadzemnih daljnovodov z zadovoljivo stopnjo natančnosti.

1 INTRODUCTION

In order to meet the growing electricity demand, it is necessary to build a large number of transmission lines from production units to consumption centers. In addition to the significant investment costs, power facilities are also characterized by a long life span and high maintenance costs. Consequently, different approaches to reduce the cost of construction and management of power facilities have been considered [1]. This task is somehow simplified by the availability of the typification and standardization in the design of power facilities, especially overhead transmission lines.

High-voltage overhead transmission lines are used due to their cost-effectiveness in the transmission of energy over long distances. However, the increase in the transmission capacity implies higher rated voltages and current values, which causes the problem of generating low-frequency electric and magnetic fields, as well as problems of coupling with metal objects in their vicinity, audible noise and corona impact on the radio interference level [2]. Solving these problems is of a great interest, especially when it comes to electromagnetic environmental problems, due to the existence of the relationship between the level of exposure to their effects and the negative impacts on human health [3]–[5]. Thus, it should be ensured that the generated levels of the electric and magnetic fields in the vicinity of overhead transmission lines satisfy the imposed reference levels [6], [7].

Determining the electric and magnetic fields in the proximity of overhead transmission lines, whether by measurement or calculation, carries certain difficulties with it. The measurement approach is time consuming

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since there is a need to physically go to the measurement location and perform the measurement procedure using an appropriate measuring equipment. Furthermore, this approach is associated with the problem of changing electrical and environmental conditions that can cause significant measurement errors. On the other hand, the calculation approach can be complex and also computationally intensive. In order to overcome these problems, efforts are being taken to develop methods that enable a sufficiently reliable field estimation using a minimum amount of the input data and require the least amount of the computational time [8]–[10].

The paper proposes a novel method to determinate the electric field strength and magnetic flux density at an arbitrary point in the vicinity of the overhead transmission line. The method is based on a multiple linear regression model and ordinary least squares estimator. The multiple linear regression is a statistical technique to model the relationship between two or more explanatory variables and a response variable. The method enables a fast and computationally efficient estimation of the electric field strength and magnetic flux density based on the data available in the dispatch center of the electric power system.

Given the well-known advantages of typification of the overhead transmission lines, it is a common practice to build a large number of overhead transmission lines of the same design. For the proposed method, the parameters of the method for estimating the electric field strength and magnetic flux density for a specific configuration of the overhead transmission line need to be determined only at the design stage. During the design stage, these parameters are determined for a specific overhead transmission line configuration. Once the parameters have been determined for a specific design of the overhead transmission line, these parameters are applicable to all constructed overhead transmission lines of the same design during their complete service life. Therefore, the tables that specify parameters of the method can become an integral part of the technical documentation, together with other important technical parameters of the overhead transmission line. Since these parameters remain constant throughout the transmission line service life, only the engineers involved in the design phase are required to know specific methods for calculating the electric field strength and magnetic flux density. The application of the method does not require the end-users to know the complex theory of the electromagnetic fields and numerical algorithms, nor to have specialized software tools. From the end-user perspective, the method is a simple and much easier to use and understand than either the traditional methods or recently proposed artificial neural network (ANN)-based methods [9], [11], [12].

The rest of the paper is organized as follows. Section 2 presents how the proposed method was developed in detail. The procedure used to form the training datasets and the ordinary least squares estimator are discussed. The coefficient of determination used as the quality indicator is also discussed. The regression parameters and their validation using the coefficient of determination are given. In section 3, validation of the proposed method is presented. The electric field strength and magnetic flux density estimates obtained by the method are compared with field measurements as well as with calculations performed using the Charge Simulation Method (CSM) and the Biot-Savart (BS) law-based method, respectively. Section 4 concludes the paper.

2 The Proposed Electric and Magnetic Field Estimation Method

The basic parameters required for the calculation of the electric and magnetic fields in the vicinity of the overhead transmission line are the applied voltages and current values and a set of parameters that describe the geometry of the overhead transmission line. The geometry of overhead transmission lines is described by the height and horizontal positions of phase conductors and shield wires [13]. The horizontal position of any conductor is defined by the tower head geometry and can be considered constant over time. However, the conductor height depends on a number of parameters, such as load variations, ambient conditions, conductor material, etc. A change in these parameters over time will affect the conductor height [14]. The values of applied the voltages and currents can be read from the Supervisory Control and Data Acquisition (SCADA) system with a satisfactory accuracy at any time.

Determining the conductors height should be done at a specific location of interest. Going to the location to measure the conductors height would nullify all the advantages of the proposed method as it is developed under the assumption that the conductors height are also known in the dispatch center. The height of the conductors at the middle of the span can also be calculated, but this type of the calculations does not take into account all the relevant parameters which affect the accuracy of the calculation [15]. More recently, systems that are able to continuously monitor changes in the conductors height and send information to a remote location are developed [16]–[18]. Therefore, the method, is able to estimate the values of the electric field strength and magnetic flux density using the data available at the dispatch center.

The electromagnetic field laws which deal with the calculation of the electric field strength and magnetic flux density declare that these quantities are in relationship with the square of the distance between the field source point and calculation point [19]. In addition, there is a linear relationship between the applied voltage and electric field strength. A similar relationship exists between the applied current and magnetic flux density [11], [19], [20].

The above mentioned relationships correspond to a single conductor case. When dealing with multiphase overhead transmission lines, additional effects must be taken into account. Specifically, the mutual impact between phase conductors as well as the simultaneous impact of phase-shifted sources on the electric field strength and magnetic flux density at an arbitrary point need to be taken into account. Furthermore, when estimating electric field strength, the presence of shield wires should also be taken into account.

Taking into account the above impacts, a model for determination of the electric field strength and magnetic flux density is proposed. Equations (1) and (2) describe the proposed model for the determination of the electric field strength and magnetic flux density at arbitrary point $P(x, y)$:

$$E_e(x, y) = \alpha_0 + \alpha_1 \cdot U + \alpha_2 \cdot h_a + \alpha_3 \cdot U \cdot h_a + \alpha_4 \cdot h_a^2 \quad (1)$$

$$B_e(x, y) = \beta_0 + \beta_1 \cdot I + \beta_2 \cdot h_a + \beta_3 \cdot I \cdot h_a + \beta_4 \cdot h_a^2 \quad (2)$$

where $E_e(x, y)$ and $B_e(x, y)$ are the electric field strength and magnetic flux density estimates at arbitrary point $P(x, y)$, respectively. Parameter h_a corresponds to the arithmetic mean of the phase conductors height, and U and I denote the root square mean (RMS) values of the line-to-line voltages and phase current values on transmission lines, respectively. On the other hand, (α_0, α_1, α_2, α_3, α_4) and (β_0, β_1, β_2, β_3, β_4) are regression parameters for the two multiple linear regression models that have different values at each considered point.

The method consists of several major steps. First, the location of the calculation points over the considered lateral profile is identified. For each considered calculation point, a training dataset is formed. The target values associated with each sample are evaluated using the calculation methods, i.e. the CSM method [21] is used for the calculation of the electric field strength, whilst BS law-based method [21], [22] is used for the magnetic flux density calculation. For a given calculation point, a dataset is constructed using different values of the line-to-line voltages, phase current values and conductors height that may occur during the operation of the overhead transmission lines, i.e. with a specified range for each input parameter. For each considered calculation point on the lateral profile, a multiple linear regression model is evaluated. The regression parameters are validated using the coefficient of determination values obtained on the test data. The method for the electric field strength and magnetic flux density estimation in the vicinity of overhead transmission lines is validated by comparing the estimation results with the calculation and measurement results.

The overhead transmission lines with a horizontal configuration of phase conductors are investigated. The 400 kV transmission network of the electric power system of Bosnia and Herzegovina consists of 14 transmission lines and 12 substations. Each 400 kV transmission line has horizontal configuration of phase conductors with two conductors in a bundle and two shield wires. Standard tower head dimensions are applied to all transmission lines, except for the substation (SS) Tuzla 4 - SS Višegrad, which has reduced dimensions [23]. This fact contributes to the justification of the development of such a method for the horizontal configuration of transmission lines. Typical geometries of the standard and reduced dimensions transmissions lines of Bosnia and Herzegovina are shown in Fig. 1.

2.1 *Training dataset*

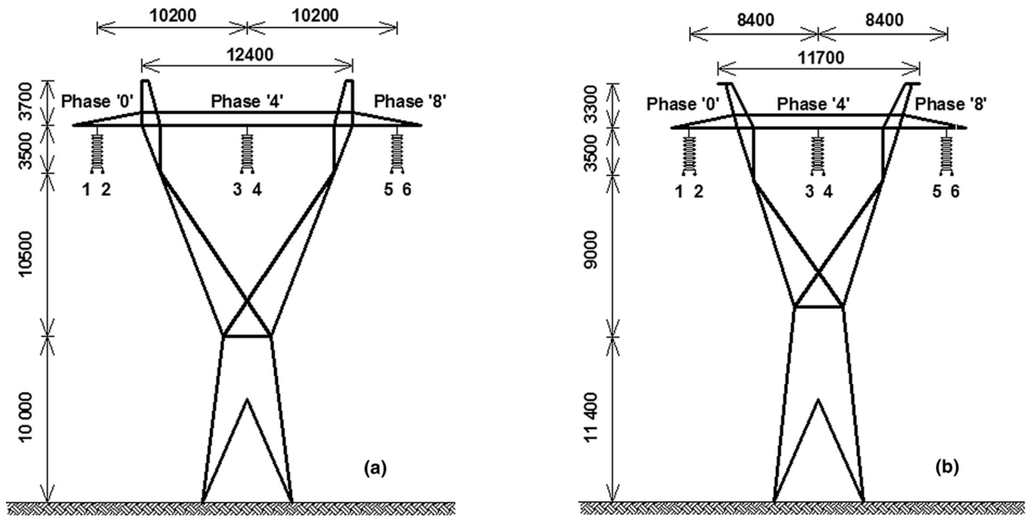
The generation of the training dataset is done by defining the considered range and values for different parameters including: applied line-to-line voltage RMS values, phase currents, and conductors height according to the expectations regarding the operation of the real overhead transmission lines. For all different input parameter values, the electric field strength and magnetic flux density are calculated at each point of interest. A set of training data is generated taking into account the range of changes in the RMS values of the line-to-line voltages of the transmission lines from 380 kV to 440 kV (with an increment of 2 kV) and the range of change in the phase current RMS values from 0 A to 600 A (with an increment of 10 A). The phase conductors height is taken to be in the range from 7 m to 16 m, whereas the considered range of shield wires height is from 15 m to 24 m, with an increment of 0.25 m in both cases. For different overhead transmission line configurations, or expected load states, customized ranges of the line-to-line voltages RMS values, current values and conductors height, are used.

For a set of the input data created in this way, the value of the electric field strength is calculated for each combination of the line-to-line voltage and conductors height. The magnetic flux density is calculated for any combination of the phase current values and conductors height at any point of interest.

The ordinary least square estimator is then employed to ascertain the regression parameters that best explain the input dataset. In this way, the corresponding parameters of the model, defined by equations (1) and (2), are determined for each point of interest.

2.2 *Ordinary least squares estimator*

The regression parameters for the electric field strength and magnetic flux density, calculations are made using the ordinary least squares estimator [24]. The electric field strength and magnetic flux density are



(a) (b)

Figure 1.: Typical geometries of the transmission line towers of the Bosnia and Herzegovina 400 kV transmission network [23]: a) Standard dimensions, b) Reduced dimensions.

described by the following multiple linear regression model:

$$z = \beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4 + \varepsilon \quad (3)$$

Dependent variable z (electric field strength or the magnetic flux density) is linearly related to four explanatory variables (X_1, X_2, X_3, X_4). Random error component ε denotes the difference between the observed and fitted linear relationship. The parameters (β_0, β_1, β_2, β_3, β_4) are the regression parameters. Note that in the case of the electric field strength, the multiple linear regression model assumes the following explanatory variables: $X_1 = U$, $X_2 = h_a$, $X_3 = U \cdot h_a$, $X_4 = h_a^2$. In the case of the magnetic flux density, the multiple linear regression model assumes the following explanatory variables: $X_1 = I$, $X_2 = h_a$, $X_3 = I \cdot h_a$, $X_4 = h_a^2$. The parameters in equations (1) and (2) correspond to the regression parameters of the multiple linear regression model. A sample of the n observations that follows the same model can be represented as follows:

$$\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} = \begin{bmatrix} 1 & X_{11} & X_{12} & X_{13} & X_{14} \\ 1 & X_{21} & X_{22} & X_{23} & X_{24} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & X_{n1} & X_{n2} & X_{n3} & X_{n4} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \quad (4)$$

or alternatively as:

$$\mathbf{z} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \quad (5)$$

The ordinary least squares estimator minimizes function $S(\boldsymbol{\beta})$ which denotes the squared distances between the observed and the predicted dependent variable:

$$S(\boldsymbol{\beta}) = \sum_{i=1}^{n} \varepsilon_i^2 = \boldsymbol{\varepsilon}^T \boldsymbol{\varepsilon} = (\mathbf{z} - \mathbf{X}\boldsymbol{\beta})^T (\mathbf{z} - \mathbf{X}\boldsymbol{\beta}) \quad (6)$$

Assuming matrix $\mathbf{X}$ a full column rank, the columns of $\mathbf{X}$ are linearly independent, the resulting ordinary least squares estimator of $\boldsymbol{\beta}$ is defined as:

$$\widehat{\boldsymbol{\beta}} = \left(\mathbf{X^T X}\right)^{-1} \mathbf{X^T z} \quad (7)$$

Correspondingly, the vector of the fitted values can be defined as:

$$\widehat{\mathbf{z}} = \mathbf{X}\,\widehat{\boldsymbol{\beta}} = \mathbf{X}\left(\mathbf{X^T X}\right)^{-1} \mathbf{X^T z} = \mathbf{Hz} \quad (8)$$

Here, $\mathbf{H} = \mathbf{X}\left(\mathbf{X^T X}\right)^{-1} \mathbf{X^T}$ is a nxn matrix that is commonly referred to as the hat matrix. The regression parameters are obtained by applying equation (7) on the training dataset.

2.3 *Coefficient of determination*

The coefficient of determination (R^2) is a statistical measure used to evaluate the accuracy of the fit in a linear regression model and to judge the ability of the proposed model to predict future outcomes [25]. The coefficient of determination is defined as a proportion of the variance in the dependent (response) variable that is predicted by a linear regression and the explanatory (independent) variables. The coefficient of determination values falls between the range from 0 to 1. In general, a high coefficient of determination value indicates that the model constitutes a good fit for the given data [26]–[28]. When the model predicts all the variations in the response data, the coefficient of determination is

Table 1.: Regression parameters for standard dimensions overhead transmission line

Horizontal distance (m)	Desired variable	Parameters				
		α_0	α_1	α_2	α_3	α_4
		β_0	β_1	β_2	β_3	β_4
0	E (kV/m)	13.16386122	$3.47 \cdot 10^{-5}$	-2.419730733	$-2.10 \cdot 10^{-6}$	0.105205684
	B (μT)	8.264780578	0.049177236	-1.519200426	-0.002501495	0.066052192
5	E (kV/m)	4.307030246	$2.39 \cdot 10^{-5}$	-0.791701863	$-1.25 \cdot 10^{-6}$	0.03442182
	B (μT)	7.949582262	0.047854472	-1.461261874	-0.002442013	0.063533125
10	E (kV/m)	11.7482771	$3.84 \cdot 10^{-5}$	-2.159523463	$-2.11 \cdot 10^{-6}$	0.093892324
	B (μT)	8.380876486	0.042898452	-1.540540733	-0.002211984	0.066980032
15	E (kV/m)	3.760471306	$2.70 \cdot 10^{-5}$	-0.691235485	$-1.28 \cdot 10^{-6}$	0.030053717
	B (μT)	3.032860237	0.025969739	-0.557488795	-0.001184834	0.024238643
20	E (kV/m)	-1.095640513	$1.14 \cdot 10^{-5}$	0.201396458	$-3.24 \cdot 10^{-7}$	-0.008756368
	B (μT)	0.453651588	0.013674768	-0.083388504	-0.000489964	0.003625587
25	E (kV/m)	-1.149804267	$4.65 \cdot 10^{-5}$	0.211352633	$-1.47 \cdot 10^{-9}$	-0.009189245
	B (μT)	-0.018222254	0.007870529	0.003349545	-0.000212952	-0.000145632
30	E (kV/m)	-0.679098928	$2.06 \cdot 10^{-6}$	0.124829373	$7.29 \cdot 10^{-8}$	-0.005427364
	B (μT)	-0.067718115	0.005030459	0.012447685	-0.000102964	-0.000541204

1. Coefficient of determination is defined with equation [26]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (z_i - \hat{z}_i)^2}{\sum_{i=1}^{n} (z_i - \overline{z})^2} \quad (9)$$

where R^2 is coefficient of determination, z_i is the i-th sample in the dataset, $\hat{z}_i$ is its estimation by the model, $\overline{z}$ is the mean value of samples, and n is the total number of the samples in the dataset.

2.4 Regression parameters and validation using coefficient of determination

The method for estimation of the electric field strength and magnetic field density under overhead transmission lines is defined by equations (1) and (2). The regression parameters are obtained by applying the ordinary least squares estimator described in Section 2.2 on the training dataset described in Section 2.1. The obtained regression parameters for the electric field strength and magnetic flux density estimation are presented in Tables 1 and 2. The obtained regression parameters are used in equations (1) and (2) to estimate the electric field strength and magnetic field density. The regression parameters shown in Tables 1 and 2 define the output values of the electric field strength and magnetic flux density in kV/m and μT, respectively. This implies that the RMS values of the line-to-line voltage and phase current values are in Volts and Amperes, respectively. Furthermore, the arithmetic mean of the phase conductors height is used in meters.

Standards which deal with the determination of the electric field strength and magnetic flux density in the vicinity of overhead transmission lines require that these quantities are determined over the lateral profile perpendicular to the transmission line axis [29]–[31]. Taking into account the size of tables in which regression parameters for all points of a lateral profile would be shown, Tables 1 and 2 define the regression parameters for the points distant from the axis of the overhead transmission line for 0 m, 5 m, 10 m, 15 m, 20 m, 25 m and 30 m.

Considering the obtained regression parameters and the associated explanatory variables which multiply them, it can be concluded that all parameters have a significant impact on the obtained field values.

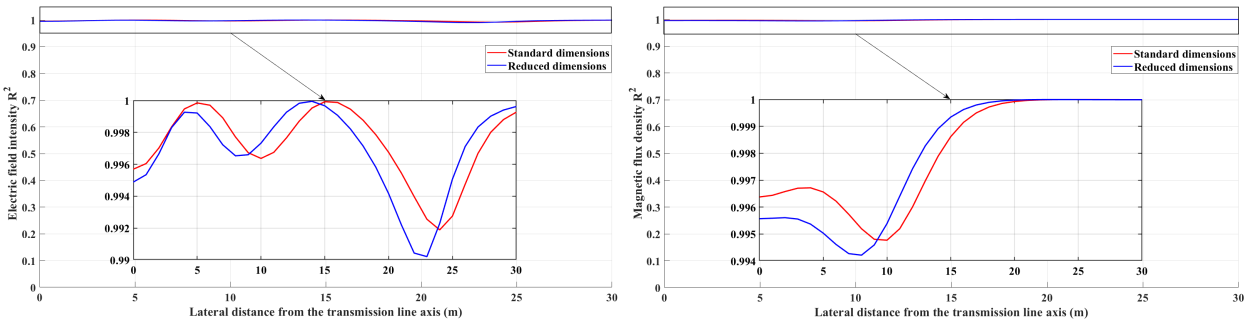
Based on the test dataset and their estimates by the regression model, the coefficient of determination is evaluated for each calculation point over the considered lateral profile. The test dataset includes 500 randomly generated samples. In the process of generating test samples, the input variables are considered to be uniformly distributed over the intervals previously defined in the training dataset generation process. The distribution of coefficient of determination values over the considered lateral profile for the electric field strength and magnetic flux density is shown in Fig. 2a and Fig. 2b, respectively.

The lowest coefficient of determination values for the electric field strength and magnetic flux density, over the considered lateral profile for both considered transmission line configuration types, is presented in Table 3.

The results in Fig. 2 and Table 3 show that for both considered overhead transmission line configurations, the coefficient of determination values are very close to 1. These results demonstrate that the proposed method to determine the electric field strength and magnetic flux density is able to account for a high percentage of the variability of the respective dependant variables. This speaks in favor of the proposed model for determining the electric field strength and magnetic flux density.

Table 2.: Regression parameters for reduced dimensions overhead transmission line

Horizontal distance (m)	Desired variable	Parameters				
		α_0	α_1	α_2	α_3	α_4
		β_0	β_1	β_2	β_3	β_4
0	E (kV/m)	13.09268504	$3.12 \cdot 10^{-5}$	-2.4066474	$-1.94 \cdot 10^{-6}$	0.104636843
	B (μT)	9.049178714	0.049281734	-1.663385498	-0.002589985	0.072321109
5	E (kV/m)	6.496137811	$2.67 \cdot 10^{-5}$	-1.194095262	$-1.47 \cdot 10^{-6}$	0.051917185
	B (μT)	9.162752631	0.047416797	-1.684262222	-0.002505587	0.073228792
10	E (kV/m)	10.78331582	$3.67 \cdot 10^{-5}$	-1.982147962	$-2.02 \cdot 10^{-6}$	0.086180346
	B (μT)	6.87552226	0.036767183	-1.263832264	-0.001885951	0.054949229
15	E (kV/m)	1.228239492	$2.02 \cdot 10^{-5}$	-0.225770296	$-8.76 \cdot 10^{-7}$	0.0098161
	B (μT)	1.69486898	0.019807437	-0.311544348	-0.000855915	0.013545406
20	E (kV/m)	-1.264942556	$8.13 \cdot 10^{-6}$	0.232516913	$-1.74 \cdot 10^{-7}$	-0.010109431
	B (μT)	0.189152893	0.010463088	-0.034769363	-0.000349507	0.001511711
25	E (kV/m)	-0.956008191	$3.34 \cdot 10^{-6}$	0.175729777	$3.14 \cdot 10^{-8}$	-0.007640425
	B (μT)	-0.046337138	0.006164536	0.008517516	-0.000155743	-0.000370327
30	E (kV/m)	-0.537949782	$1.50 \cdot 10^{-6}$	0.098883876	$7.21 \cdot 10^{-8}$	-0.004299299
	B (μT)	-0.059985376	0.004014875	0.011026283	$-7.73 \cdot 10^{-5}$	-0.000479404



(a) (b)

Figure 2.: Distribution of the R^2 over the considered lateral profile: a) Electric field strength R^2, b) Magnetic flux density R^2.

Table 3.: Lowest values of coefficient of determination

Electric field strength R^2		Magnetic flux density R^2	
Standard dimensions	Reduced dimensions	Standard dimensions	Reduced dimensions
0.9919	0.9902	0.9948	0.9942

3 Validation of the Proposed Method

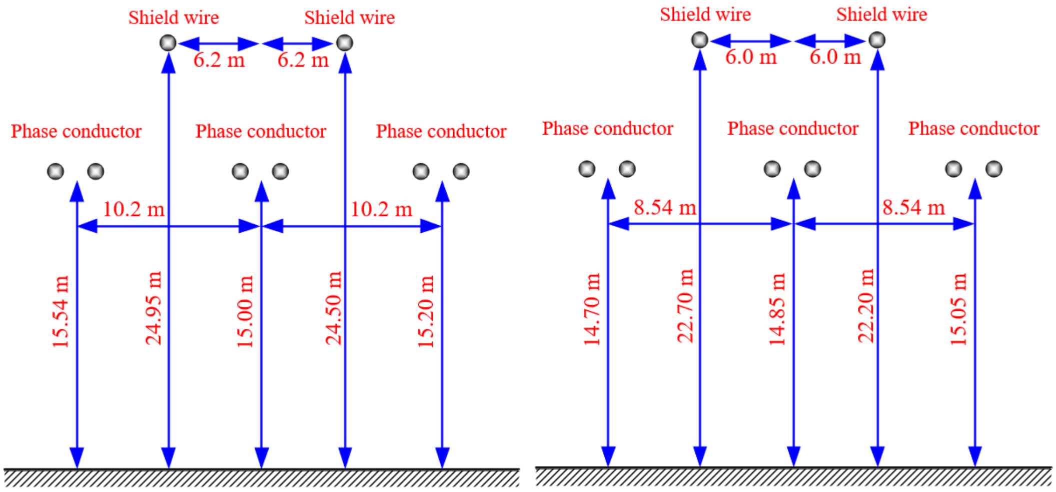
The proposed method is validated by comparing the estimated results with calculations performed using the CSM method and BS law-based method. The results of the proposed method are compared with the results obtained by field measurements.

The values of the electric field strength and magnetic flux density are estimated, calculated and measured at a height of 1 m above the ground level [29]. In each case, the values are obtained for the lateral profile near the midspan, at a minimal conductors height where the highest field values are expected [30]. The considered lateral profile is in the range from 0 m to 30 m, in increments of 1 m, from the overhead transmission line axis.

The paper is focused on the overhead transmission lines with a horizontal configuration of phase conductors. With some adjustments, the same approach can be applied to other overhead transmission line configurations.

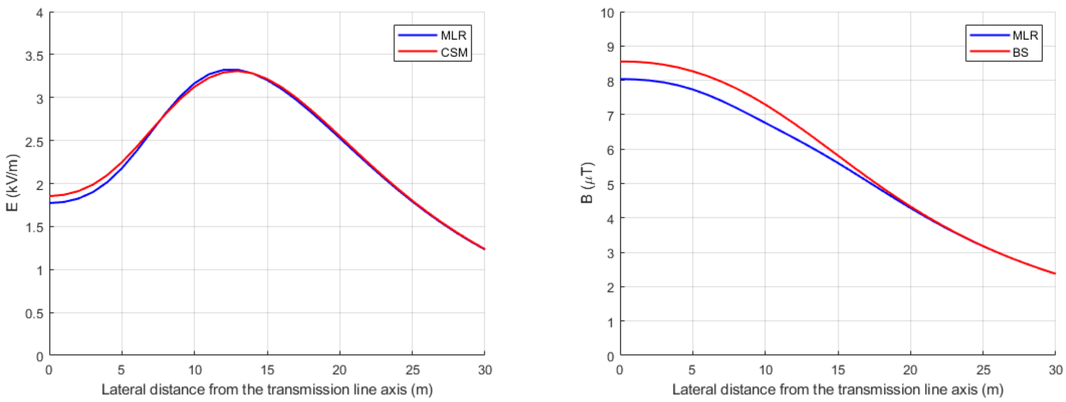
Fig. 3 shows a configuration of a 400 kV overhead transmission line with a standard tower head dimensions (Fig. 3a) and a configuration with a reduced tower head dimensions (Fig. 3b), operating in the 400 kV power transmission network of Bosnia and Herzegovina.

The 400 kV power transmission network of Bosnia and Herzegovina is underloaded and is characterized by very high-voltages and low current values [11].



(a) (b)

Figure 3.: Geometries of the analysed 400 kV overhead transmission lines: a) Configuration of the standard dimensions, b) Configuration of the reduced dimensions.



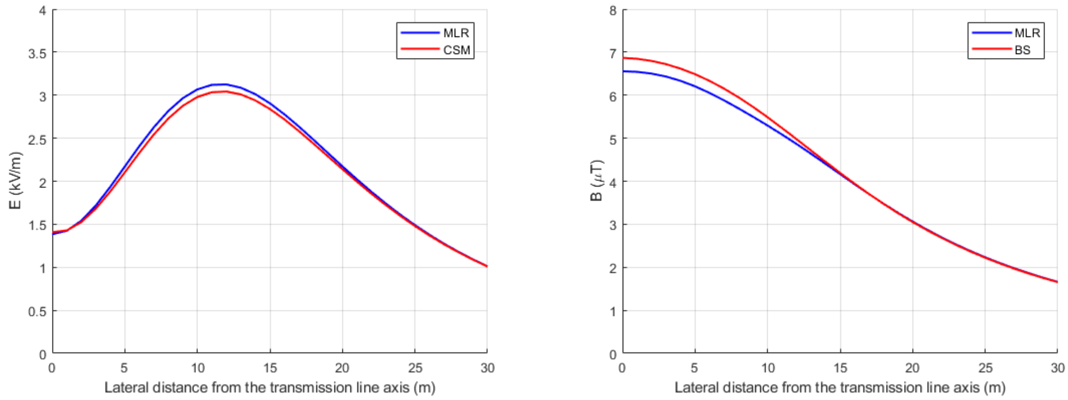
(a) (b)

Figure 4.: Comparison of the estimated and calculated results under a horizontal overhead transmission line of the standard dimensions: a) Electric field strength distribution, b) Magnetic flux density distribution.

Therefore, it is a very rare situation, in the 400 kV transmission network in Bosnia and Herzegovina, that the RMS value of the line-to-line voltage is equal to the rated one [11], [23]. Although such situations are difficult to encounter in practice, the proposed method is able to efficiently estimate the values of the electric field strength and magnetic flux density for the rated values of voltages and higher current values than those usually occurring in the operation of the Bosnia and Herzegovina power transmission network. Therefore, calculations are performed under the assumption that the RMS line to-line voltage is 400 kV for both configurations. The considered phase current RMS value for the overhead transmission line configuration shown in Fig. 3a is $I = 686.88A$ and $I = 580A$ for the overhead transmission line configuration presented in Fig. 3b. The arithmetic mean of the phase conductors height required for the estimation of the electric field strength and magnetic flux density is calculated based on the height of individual conductors for each considered overhead transmission line configuration.

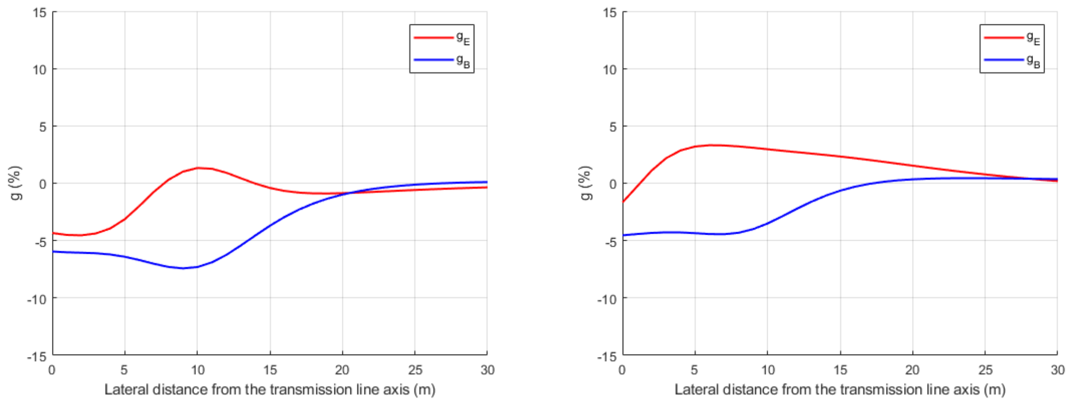
Fig. 4a shows the electric field strength distribution obtained using the proposed method and the CSM calculations over the considered lateral profile for the standard dimensions overhead transmission line. For the standard dimensions overhead transmission line, Fig. 4b shows the magnetic flux density distribution obtained using the proposed method and the BS law-based method calculations over the considered lateral profile.

Similarly, a comparison of the results obtained by using the proposed method with those obtained by the CSM and BS law-based method calculations for



(a) (b)

Figure 5.: Comparison of the estimated and calculated results under a horizontal overhead transmission line of reduced dimensions: a) Electric field strength distribution, b) Magnetic flux density distribution.



(a) (b)

Figure 6.: Distribution of the relative error: a) Configuration of a standard dimensions overhead transmission line, b) Configuration of a reduced dimensions overhead transmission line.

the reduced dimensions overhead transmission line is presented in Fig. 5.

Though it is shown above that the proposed method for electric field strength and magnetic flux density estimation can account for a high percentage of the variability of the respective dependent variables, this doesn't necessarily mean that results of the electric field strength and magnetic flux density estimation will overlap well with the results obtained by other methods. The relative errors between the results obtained by the proposed method and the results obtained by the CSM/BS law-based method are defined by the following equations:

$$g_E(\%) = \frac{E_{Validation} - E_{Reference}}{E_{Reference}} \cdot 100(\%) \quad (10)$$

$$g_B(\%) = \frac{B_{Validation} - B_{Reference}}{B_{Reference}} \cdot 100(\%) \quad (11)$$

where g_E is the relative error of the electric field strength, g_B is the relative error of the magnetic flux density. $E_{Validation}$ and $B_{Validation}$ are the electric field strength and magnetic flux density obtained by the proposed method, respectively. The electric field strength and magnetic flux density obtained by the reference methods (CSM/BS law-based) are denoted as $E_{Reference}$ and $B_{Reference}$.

For both types of the considered overhead transmission line geometries, the relative error distribution corresponding to the electric field strength and magnetic flux are shown in Fig. 6.

As it can be noted from the diagram given in Fig. 6a, the highest values of the relative error between the electric field intensities obtained by the proposed method and the CSM method are 4.54% and 3.31% for the standard and reduced dimensions overhead transmission lines, respectively. On the other hand, when comparing the magnetic flux density results obtained by the pro-

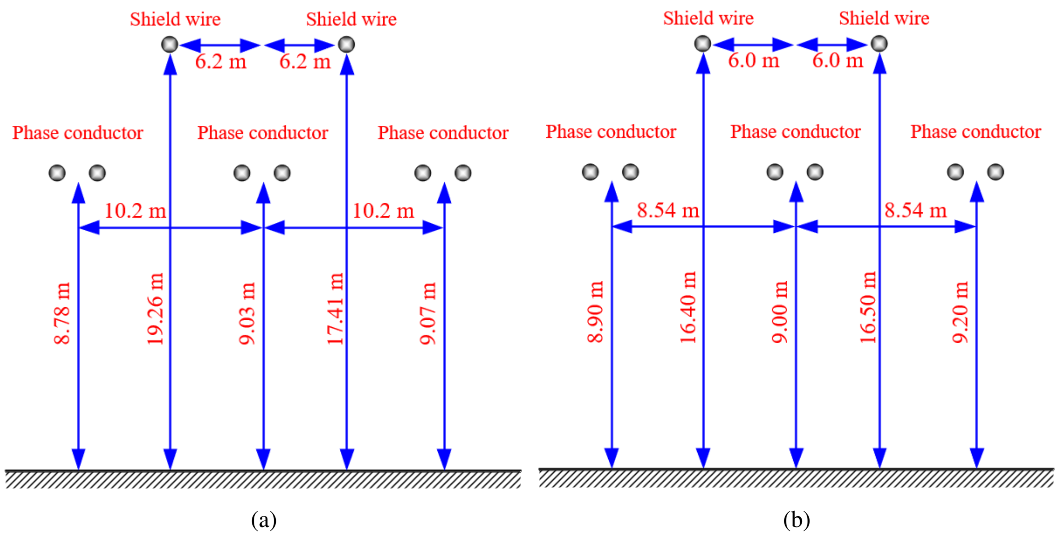


Figure 7.: Geometries of the analysed overhead transmission lines: a) Configuration of the SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line b) Configuration of the SS Tuzla 4 - SS Višegrad overhead transmission line.

posed method and the BS law-based method, the highest relative error value is 7.42% for the standard dimensions overhead transmission line and 4.54% for the reduced dimensions overhead transmission line.

The proposed method is validated also by using the measurements taken for the 400 kV network of Bosnia and Herzegovina. The geometries of the analyzed 400 kV overhead transmission lines of the standard dimensions SS Sarajevo 10 - SS Sarajevo 20 and SS Tuzla 4 - SS Višegrad of reduced dimensions are shown in Fig. 7. A comparison with calculation methods (CSM/BS law-based method) is made on these configurations.

During field measurements of the electric field strength and magnetic flux density, height of each conductor was performed, using the Suparule model 600 device. At the time the measurements were made, the readings of voltage and current values were read from the SCADA system. Measurements of the electric field strength were performed using a 1D sensor (HI-3604 ELF Survey Meter) and the magnetic flux density measurements were performed with a 3D sensor (Narda ELT-400).

For the SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line given in Fig. 7a, the validation of the proposed method based on the calculation and measurement results is shown in Fig. 8. The arithmetic means of the line-to-line voltage and phase current RMS values used as the calculation input parameters, are 426 kV and 85.69 A, respectively.

Figs. 8a and 8b show that for the SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line of standard dimensions the estimated electric field strength and magnetic flux density values agree very well with the results obtained by calculations and measurements.

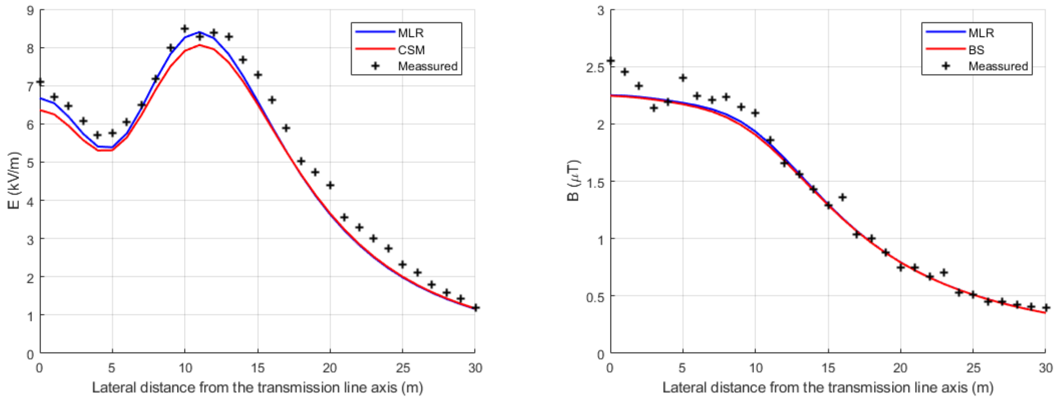
The validation of the proposed method for the SS Tuzla 4 - SS Višegrad overhead transmission line is shown in Fig. 9. The arithmetic mean values of the line-to-line voltage and phase current RMS values used as the input parameters for the calculation are 416 kV [32] and 133.16 A, respectively [11].

As in the previous test case, the estimated values of the electric field strength and magnetic flux density obtained by the proposed method on the SS Tuzla 4 - SS Višegrad overhead transmission line of reduced dimensions closely agree with those obtained using the calculation methods and field measurements (see Figs. 9a and 9b).

There is a significant variation of phase current value during the magnetic flux density measurements. During the magnetic flux density measurements shown in Figs. 8b and 9b, the current value fluctuates. The associated current value fluctuations are shown in Fig. 10. Since the magnetic flux densities for both transmission lines are not measured at the same period of the day, the abscissa of the graph is scaled from 0:00 to 1:00, which represents the hour when measurements were done.

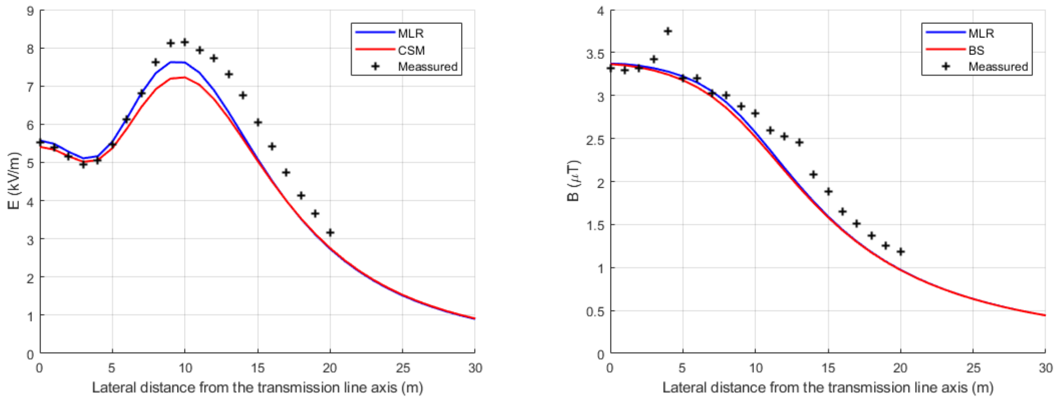
The real overhead transmission line test cases are also used to compare the performance of the proposed method with CSM and BS law-based method. The relative errors are evaluated using equations (10) and (11) and the results obtained by the CSM/BS law-based method are used as the reference values. The relative error distribution over the considered lateral profile for both test cases is shown in Fig. 11.

As seen from Fig. 11, the highest relative error corresponding to the electric field strength estimation



(a) (b)

Figure 8.: Comparison of the measured and calculated values under the horizontal overhead transmission line of standard dimensions SS Sarajevo 10 - SS Sarajevo 20: a) Electric field strength distribution, b) Magnetic flux density distribution.



(a) (b)

Figure 9.: Comparison of the measured and calculated values under the horizontal overhead transmission line of reduced dimensions SS Tuzla 4 - SS Višegrad: a) Electric field strength distribution, b) Magnetic flux density distribution.

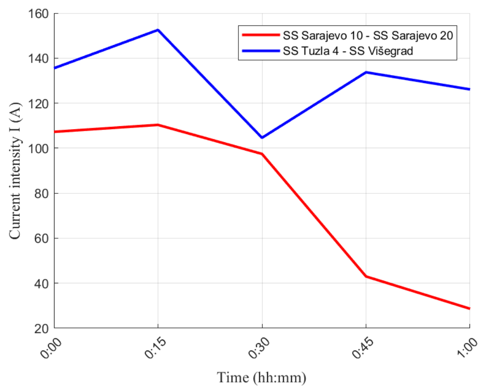
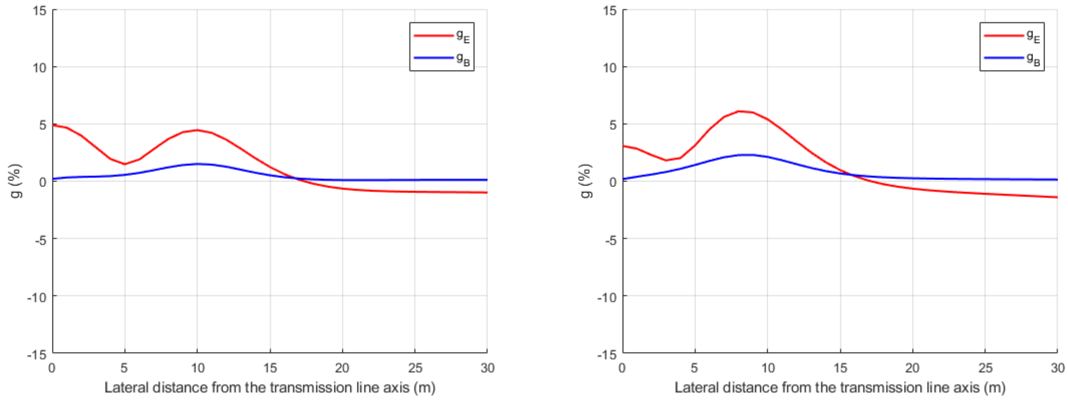


Figure 10.: Variation of the transmission lines current values during the magnetic flux density measurements.

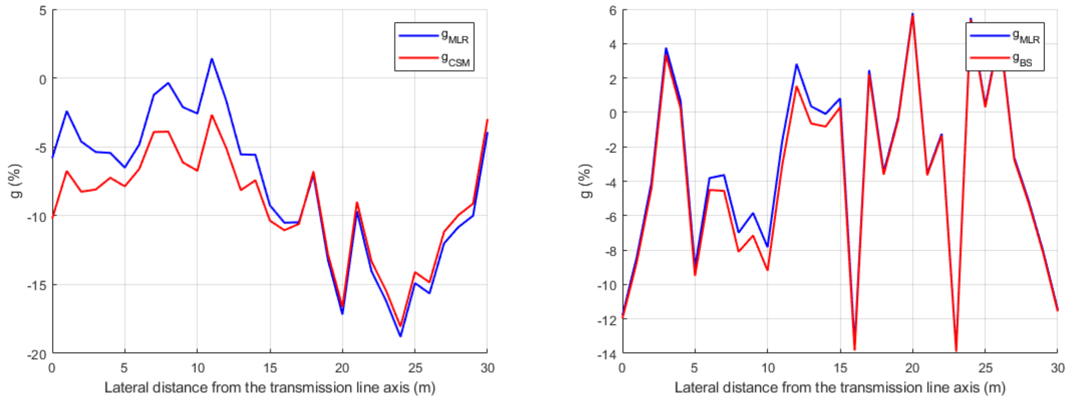
is 4.89% for the SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line, and 6.10% for the SS Tuzla 4 – SS Višegrad overhead transmission line. Similarly, the highest relative errors of the magnetic flux density estimation are 1.50% and 2.29% for the SS Sarajevo 10 - SS Sarajevo 20 and SS Tuzla 4 – SS Višegrad overhead transmission line, respectively.

It is a common practice to use field measurements to validate the results obtained by calculation methods. The proposed method can serves not only as an alternative to the application of calculation methods, but also as an alternative to field measurements. With this in mind, the proposed method is further evaluated using the relative error based on the field measurements as reference. The relative errors is calculated for all points over the considered lateral profile using equations (10)



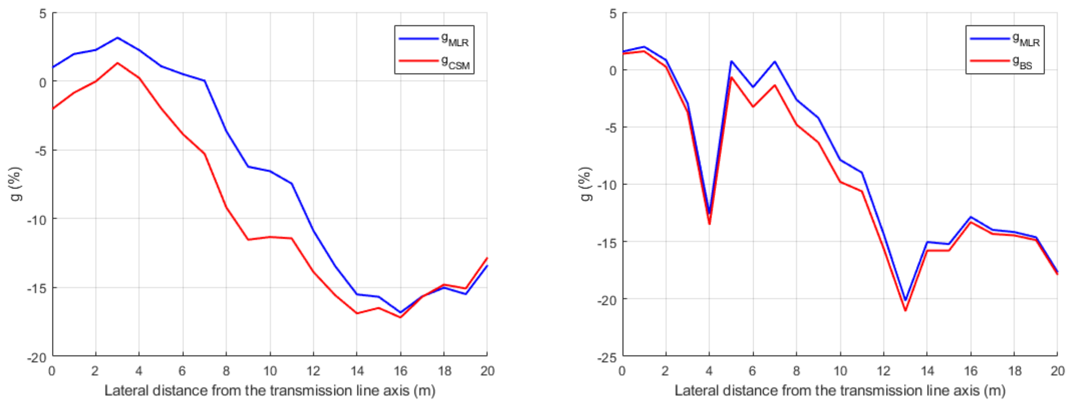
(a) (b)

Figure 11.: Distribution of the relative error: a) SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line , b) SS Tuzla 4 - SS Višegrad overhead transmission line.



(a) (b)

Figure 12.: Distribution of the relative error for the SS Sarajevo 10 - SS Sarajevo 20 overhead transmission line: a) Electric field strength, b) Magnetic flux density.



(a) (b)

Figure 13.: Distribution of the relative error for the SS Tuzla 4 - SS Višegrad overhead transmission line: a) Electric field strength, b) Magnetic flux density.

and (11). The relative error values associated with the proposed method, when field measurements are used as a reference, for the SS Sarajevo 10 - SS Sarajevo 20 transmission line are shown in Fig. 12. On the other hand, the relative error values associated with the proposed method, using the field measurements as the reference, for the SS Tuzla 4 - SS Višegrad overhead transmission line are shown in Fig. 13. Figs. 12 and 13 show also the relative error values associated with the CSM and BS law-based method calculation results, respectively. In both cases the field measurements are used as a reference.

It is interesting to observe (Figs. 12 and 13) that the proposed method and the calculation methods (CSM and BS law-based method) produce relative error distribution curves that are very similar in their shape. Also, for both investigated overhead transmission lines the relative error of the proposed method is smaller compared to the CSM and BS law-based calculation method for the greater part of the considered lateral profile. Note that the relative error curves shown in Figs. 12 and 13 are generated using the field measurement results as the reference values.

The presented results show that the proposed method produces results that well agree with measurement and calculation results, for each of the analyzed overhead transmission line. The observed discrepancies between the results obtained by the proposed and calculation methods are in part due to unequal heights of individual phase conductors. The error between the electric field strength estimates obtained by the proposed method and field measured values can be due to many factors, such as uneven terrain, proximity of the operator and the presence of bushes. The dominant causes for errors between the proposed method and the measured magnetic flux density values is the current variation during the measurements and asymmetric phase load.

4 Conclusion

The paper proposes a novel method to estimate the electric field strength and magnetic flux density in the vicinity of overhead transmission lines. The method is based on a multiple linear regression and the ordinary least squares estimator. By using the ordinary least squares estimator, the parameters of the method can be determined already in the design stage of the overhead transmission line. The parameters are determined for a particular overhead transmission line configuration. The obtained parameters can be used for any overhead transmission line of the same design during its service life. One of the main advantages of the proposed method is that the theoretical analysis of the proposed method is simple to perform. The method can be implemented, analyzed, and applied even by end-users that are not necessarily experts in the area of electromagnetic fields.

Using the proposed method, the regression parameters for the electric field strength and magnetic flux density for the investigated overhead transmission lines are determined. The electric field strength and magnetic flux density in the proximity of overhead transmission lines of a horizontal configuration of a standard and reduced dimensions are estimated. The investigated overhead transmission line configurations are typically used in 400 kV network of the electric power system of Bosnia and Herzegovina. The quality of the method is assessed by the coefficient of determination. The obtained coefficient of determination values in the analyzed cases are close to one, indicating that in each investigated case the proposed method is able to account for a high percentage of the variability of the respective dependent variables. The validation of the proposed method is performed by comparing it to the electric field strength and magnetic flux density calculation and measurement results. Based on the obtained results, it can be concluded that the proposed method gives satisfactory results and responds to the need for a simple estimation of the electric field strength and magnetic flux density.

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