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ANALYSIS OF MULTI-CIRCUIT OVERHEAD TRANSMISSION LINES ZONE OF INFLUENCE FROM THE ASPECT OF EXTREMELY LOW FREQUENCY MAGNETIC FIELDS BASED ON THE USE OF ARTIFICIAL NEURAL NETWORKS

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Abstract: Overhead transmission lines that consist of two or more circuits are frequently utilized as a solution in scenarios requiring the transmission of a higher amount of energy per unit of space, when spatial constraints exist, or to achieve cost savings in the construction and maintenance of transmission infrastructure. Despite their numerous advantages, these overhead transmission lines pose significant challenges concerning the intensity of magnetic fields in their vicinity. This paper presents an analysis of the influence zone of multi-circuit overhead transmission lines from the perspective of magnetic fields in the range of extremely low-frequencies. The zone of influence, in this context, is defined as the area surrounding the overhead transmission lines where the magnetic flux density exceeds specified reference values. To determine the magnetic flux density values, a methodology based on the application of artificial neural networks (ANNs) was employed. The paper outlines the implementation of this ANN based approach to estimate the magnetic flux density near multi-circuit overhead transmission lines. Two case studies are presented, examining double-circuit overhead transmission lines that have different configurations and rated voltages. For these cases, the zones of influence were determined with respect to extremely low-frequency magnetic field values. Additionally, a comparison was conducted between the obtained influence zones and the safety zones for overhead transmission lines defined by regulatory authorities.

Keywords: Artificial neural networks, multi-circuit overhead transmission lines, zone of influence, extremely low frequency magnetic fields

INTRODUCTION

Overhead transmission lines are the backbone of electric power systems, and they are crucial facilities for delivering energy for industrial applications, households, and vital public services. Due to their significance and irreplaceable role, numerous overhead transmission lines are built, and some new ones are planned, or already in construction. Besides the endeavours to generate electricity at the places of consumption, the most important energy sources are far away from major consumption centres. Consequently, overhead line routes occupy spaces not only in uninhabited or sparsely populated areas but also in densely populated areas [1,2].

Besides all the positive aspects of overhead transmission lines, they also have some unwanted influences on their surroundings. When considering these influences, an extremely low frequency magnetic field stands out as a major concern. Multi-circuit overhead transmission lines can be even more challenging than single-circuit considering the magnetic field that they generate in their surroundings [3,4]. Since these fields are classified as potentially carcinogenic and labelled as a source of several other health issues they attracted a lot of attention in the last decades. Consequently, expert international and national bodies prepared recommendations in order to limit the negative influences caused by the extremely low frequency magnetic field. In numerous countries, those recommendations are accepted and introduced in the legal documents that prescribe obligations for magnetic field levels to be evaluated in the vicinity of overhead transmission lines [5-7].

The regulation of electric and magnetic fields in Bosnia and Herzegovina varies across different administrative levels. At the national level, there is no established legal framework governing reference values for electric and magnetic fields. Similarly, within the entity of the Federation of Bosnia and Herzegovina, no specific regulation exists in this domain. However, in the entity of the Republic of Srpska, a legal framework has been established to regulate exposure to

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electric and magnetic fields. This is primarily governed by the Law on Protection Against Non-Ionizing Radiation of the Republic of Srpska (Official Gazette 36/19) [8], and the Rulebook on Protection Against Electromagnetic Fields up to 300 GHz (Official Gazette 99/19) [9].

When it comes to the Republic of Serbia, the issue of population protecting from non-ionizing radiation is regulated at the national level by adopting the Law on Protection from Non-ionizing Radiation and six regulations that elaborate on certain issues in more detail [10-12].

The regulations in the Republic of Serbia and the entity Republic of Srpska are harmonized with regard to the way of defining areas of increased sensitivity, electromagnetic field sources of special interest, reference values and the like. According to these documents [9-12] areas of increased sensitivity are areas of residential zones where people can stay 24 hours a day, schools, kindergartens, hospitals, accommodation tourist facilities, children's playgrounds, as well as areas of undeveloped plots which, according to valid spatial planning documents, are intended for the construction of the previously listed facilities.

Electromagnetic field sources of special interest for certain frequencies are those stationary sources whose electromagnetic fields in areas of increased sensitivity reach at least 10% of the reference level defined for that frequency. For the 50 Hz magnetic flux density the limit value is 40 μT [9-12].

The overhead transmission line zone of influence represents the zone around the overhead transmission line where the magnetic field level is above the legally prescribed level [13-16]. In this paper, the level of 10% of the prescribed limit values (4 μT), will be used as the boundary of the influence zone for overhead transmission lines.

In this paper the right-of-way (ROW) of overhead transmission lines will be compared to their zone of influence to examine which of them is more strict when it comes to actual and expected overhead transmission lines operating conditions.

The overhead transmission line ROW in Bosnia and Herzegovina is defined as horizontal-plane area corresponding to the designated safety zone, and determined by the Rulebook on safety zones of overhead power lines with a nominal voltage of 110 kV to 400 kV issued by The State Electricity Regulatory Commission (Official Gazette of Bosnia and Herzegovina No. 23/08) [17]. In the Republic of Serbia the width of safety area for overhead transmission lines is counted from the outer phase conductor on both sides of the overhead line and defined by Law on Energy, Official Gazette of the Republic of Serbia, No. 145/2014, 95/2018 and 40/2021 [18]. The widths of the safety areas for overhead transmission lines of different rated voltages in Bosnia and Herzegovina and Serbia are presented in Table I.

Table I The widths of the safety area for overhead lines in transmission networks

Rated voltage	The widths of the safety area Bosnia and Herzegovina [17]	The widths of the safety area Republic of Serbia [18]
400 kV	40 m	30 m
220 kV	30 m	30 m
110 kV	20 m	25 m

When it comes to determining the values of magnetic fields near overhead lines, they are traditionally determined by applying field measurements or by performing calculations using numerical methods. Field measurements require the possession of both personnel and material resources necessary to go to specific locations of interest, as well as conducting the measurements themselves. Also, by conducting measurements, it is possible to determine the values of magnetic fields only for overhead lines that are currently in operation and for their current operating conditions on them. That is, field measurements cannot verify all operating scenarios that may occur on overhead lines. However, the field measurements are important for validation of the calculation methods, and exposure assessments in situations when it is difficult or impractical to develop simulation models of field sources [19]. On the other hand, in order to carry out calculations using numerical methods, it is necessary to have specialized software, as well as to conduct adequate training of personnel for their use, which can be financially demanding. If, on the other hand, one is going to develop one's own calculation software, knowledge of the theory of electromagnetic fields, numerical methods, and programming skills are necessary.

It is undeniable that AI-based tools have experienced a huge boom and application in almost all areas of human activity over the last decade. This trend has not bypassed the electric power sector. Thus, numerous applications have been recognized where the application of AI-based tools can facilitate or improve processes [20,21].

In this specific case, the application of AI based methods enables simple, fast, and effective analysis of all operating scenarios that can occur during the exploitation of overhead lines without the need for specialized software, equipment, or special personnel training. Also, such tools can be easily and simply combined with other software to perform some other operations related to the design, construction, and exploitation of overhead lines.

In this paper, multi-circuit overhead transmission lines zone of influence from the extremely low frequency magnetic field point of view will be analysed. The analysis will be carried out by employing a method that uses artificial neural networks (ANNs), for different multi-circuit overhead transmission line configurations.

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1. METHODOLOGY FOR MAGNETIC FLUX DENSITY ZONE OF INFLUENCE DETERMINATION

In this paper, to determine the magnetic flux density that is generated near multi-circuit overhead transmission lines an ANN based method is employed. Multi-circuit overhead transmission lines consist of multiple independent three-phase circuits; therefore, the magnetic flux density generated by each circuit is determined individually. Then, by applying the principle of superposition, the contributions are combined to derive the resultant magnetic flux density. Thus, to determine the magnetic flux density of every single three-phase circuit separately an ANN model, shown in Figure 1, is applied.

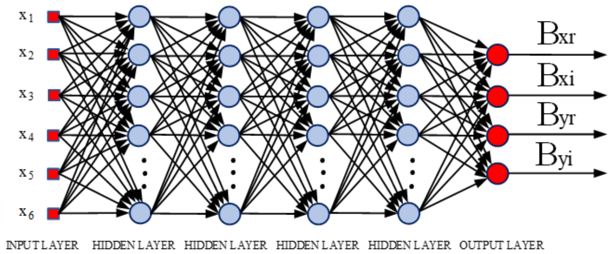

Figure 1: ANN model used for magnetic flux density determination

As it is shown in Figure 1, the applied ANN model has six inputs and four outputs. The inputs represent the positions of phase conductors in a 2D coordinate space, and the distance between the calculation point and central phase conductor of the three-phase circuit.

It is important to note that, according to standards [22,23], the values of magnetic flux density in around overhead transmission lines are determined along the lateral profile positioned at 1 meter height. Therefore, to simplify the model, this information is incorporated into the training data for the ANN model and does not need to be explicitly provided during its application. Additionally, during the training process, an assumption was made that the central phase conductor is always placed in a way in a way that x=0 m in all cases. Consequently, this information does not need to be provided when applying the ANN model. Thus, ANN model inputs are: the heights of all three phase conductors, the horizontal spacing of the outer phase conductors relative to the central phase conductor, and the horizontal spacing of the calculation point relative to the central phase conductor.

Furthermore, to enable the application of the superposition principle for combining the contributions of separate three-phase circuits, the ANN model outputs are real and imaginary parts of the magnetic flux density spatial components. These four values represent the ANN model outputs, as shown in Figure 1.

Since multi-circuit overhead transmission lines consist of multiple individual three-phase circuits, a corresponding local coordinate system is defined for all separate circuits. The local coordinate systems are established so that their vertical axis aligns with the conductor of the middle phase of the respective three-phase circuit. Besides the local coordinate systems, a global coordinate system is required to combine the contributions of separate three-phase circuits and to evaluate the total distribution of magnetic flux density for the entire multi-circuit overhead transmission line. The vertical axis of the global coordinate system can be chosen arbitrarily; however, it is most commonly aligned with the axis of the transmission tower for convenience. For all local coordinate systems, as well as in the global system, the horizontal axis is aligned with the ground–air boundary. The method for defining both the global and individual local coordinate systems is illustrated in Figure 2.

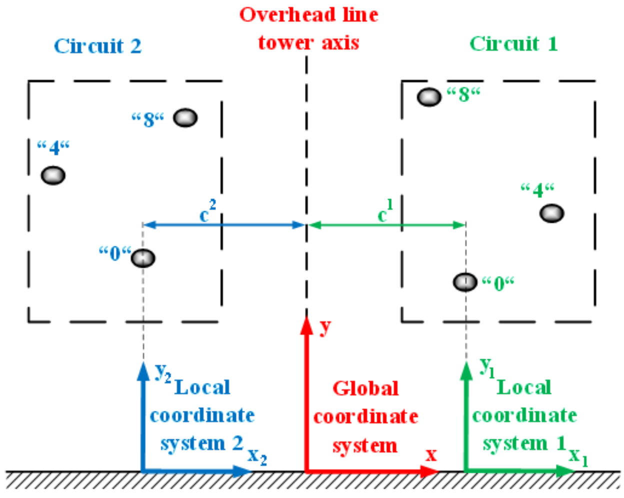

Figure 2: Coordinate systems

The flowchart of the method for determining the magnetic flux density generated by multi-circuit overhead transmission lines based on the ANN application is shown in Figure 3. The application of this method will be described in more detail in the following text.

The first step is to determine the number of individual independent three-phase circuits that constitute the multi-circuit overhead transmission line. The flowchart is presented for the case of two three-phase circuits, but the approach can be applied analogously regardless of the number of individual circuits. Once the individual three-phase circuits are identified, it is followed with the determination the magnetic flux density values generated by each circuit individually. For this purpose, ANN is utilized. Since the development of the ANN model has been carried out to enable its adaptation for application to individual three-phase circuits within local coordinate systems, it is essential to assign an appropriate local coordinate system to each of them. Next, the ANN model is applied, and results related to the real and imaginary components of the magnetic flux density's spatial components for the first

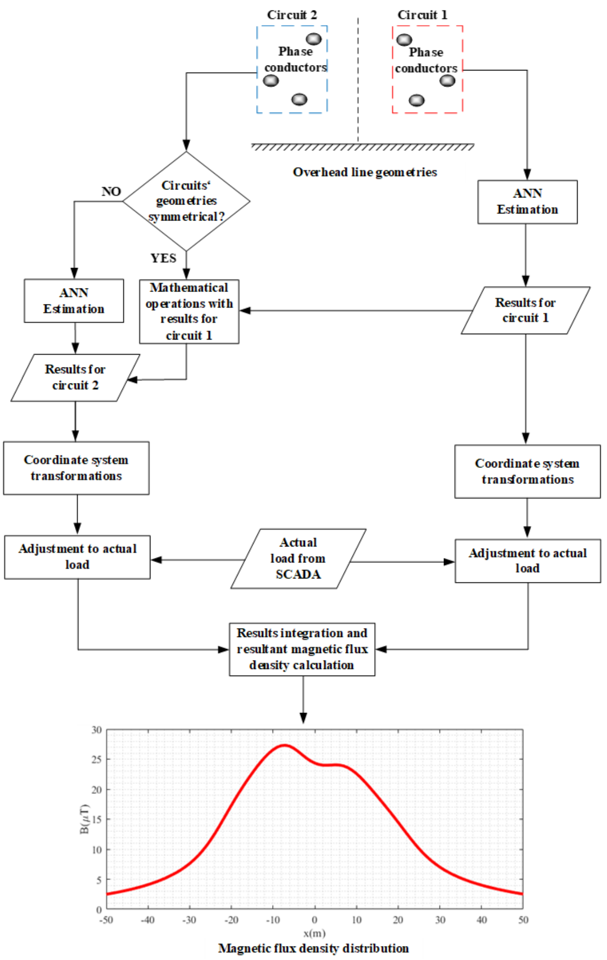

Figure 3: Flow chart of used method

circuit in the local coordinate system have been obtained.

In the next step, it is necessary to transform these results into the global coordinate system. This is performed using the appropriate mathematical operations [4,24]:

$$B^{n}_{x,r}\left(x,y\right)=B^{n'}_{x,r}\left(x\pm c^{n},y\right) \tag{1}$$

$$B^{n}_{x,y}\left(x,y\right)=B^{n'}_{x,i}\left(x\pm c^{n},y\right) \tag{2}$$

$$B^{n}_{y,r}\left(x,y\right)=B^{n'}_{y,r}\left(x\pm c^{n},y\right) \tag{3}$$

$$B^{n'}_{y,i}\left(x,y\right)=B^{n'}_{y,i}\left(x\pm c^{n},y\right) \tag{4}$$

where the marks denote the following: (x,y) - the position of the considered point expressed in the global coordinate system; $B^{n'}_{x,r}(x\pm c^n, y)$, $B^{n'}_{x,i}(x\pm c^n, y)$, $B^{n'}_{y,r}(x\pm c^n, y)$ and $B^{n'}_{y,i}(x\pm c^n,y)$ - ANN outputs for the n-th three-phase circuit in the corresponding local coordinate system; $B^{n}_{x,r}(x,y)$, $B^{n}_{x,i}(x,y)$, $B^{n}_{y,r}(x,y)$, i $B^{n}_{y,i}(x,y)$ - real and imaginary components of the of the magnetic flux density vector's spatial components produced by the n-th three-phase circuit in the global coordinate system; c^n - ordinate shift of the local coordinate system of the n-th three-phase circuit relative to the ordinate of the global coordinate system. For local coordinate systems positioned to the right in relation to the vertical axis of the global coordinate system $-c^n$ is used, while for local coordinate systems positioned to the left $+c^n$ is used. As can be seen from Figure 3, the next step is the adjustment to the applied load. Since when overhead transmission lines are designed with separate three-phase circuits, each of them can have completely different electrical loads, it is necessary to take into account the actual current intensity values for each of them. To simplify the applied ANN model, its training, and using, the results obtained at its output correspond to a reference phase current intensity value of 100 A. Therefore, once the actual phase current intensity values for each three-phase circuit are obtained, the results produced by the model need to be adjusted accordingly. This adjustment is performed using the following equations [24]:

$$B^{A,n}_{x,r}\left(x,y\right)=B^{n}_{x,r}\left(x,y\right)\cdot\frac{I^{n}_{A}}{I_{R}} \tag{5}$$

$$B^{A,n}_{x,i}\left(x,y\right)=B^{n}_{x,i}\left(x,y\right)\cdot\frac{I^{n}_{A}}{I_{R}} \tag{6}$$

$$B^{A,n}_{y,r}\left(x,y\right)=B^{n}_{y,r}\left(x,y\right)\cdot\frac{I^{n}_{A}}{I_{R}} \tag{7}$$

$$B^{A,n}_{y,i}\left(x,y\right)=B^{n}_{y,i}\left(x,y\right)\cdot\frac{I^{n}_{A}}{I_{R}} \tag{8}$$

where the marks denote the following: $B^{A,n}_{x,r}(x,y)$, $B^{A,n}_{x,i}(x,y)$, $B^{A,n}_{y,r}(x,y)$, $B^{A,n}_{y,i}(x,y)$ are real and imaginary parts of spatial components of magnetic flux density generated by the n-th circuit $B^{n}_{x,r}(x,y)$, $B^{n}_{x,i}(x,y)$, $B^{n}_{y,r}(x,y)$, $B^{n}_{y,i}(x,y)$ are magnetic flux density spatial component's real and imaginary parts associated with n-th circuit for reference phase current intensity, I^{n}_{A} denotes n-th circuit actual phase current intensity and is the reference phase current intensity.

In situations where all separate three-phase circuits have different geometry, the previously described procedure is repeated every one independently before their contributions are combined. However, multi-circuit overhead transmission lines are typically designed in a way that the individual three-phase circuits are arranged symmetrically on either side of the towers. In such cases, the results corresponding to mutually symmetric three-phase circuits can be obtained through simple mathematical operations on outputs of the ANN model, eliminating the need to apply the model separately for each circuit. If geometrically identical three-phase circuits are considered, it is sufficient to translate the ANN outputs along the horizontal axis. Furthermore, if multi-circuit overhead transmission lines have three-phase circuits that are arranged symmetrically but with opposite arrangements of phase conductors, the distribution of the real and imaginary components of the spatial components of the magnetic flux density for the symmetric circuit can be obtained by rotating all ANN outputs around the ordinate of the coordinate system and changing the sign of the real and imaginary parts of the magnetic flux density vector y spatial component.

Once the real and imaginary parts of the spatial components of the magnetic flux density vector are determined for the actual load of each three-phase system, the next step is to integrate these results. The overall distribution is obtained by summing the contributions of all three-phase circuits, according to the equations [4,24]:

$$\underline{B}_x^R(x,y)=\sum_{n=1}^{N}B_{x,r}^{A,n}(x,y)+j\cdot\sum_{n=1}^{N}B_{x,i}^{A,n}(x,y) \quad (9)$$

$$\underline{B}_y^R(x,y)=\sum_{n=1}^{N}B_{y,r}^{A,n}(x,y)+j\cdot\sum_{n=1}^{N}B_{y,i}^{A,n}(x,y) \quad (10)$$

where the marks denote the following: $\underline{B}_x^R(x,y)$, $\underline{B}_y^R(x,y)$ - the resultant values of the spatial components of the magnetic flux density vector at the point of consideration, encompassing the influences of all individual three-phase circuits; N - the total count of the examined three-phase circuits.

The resultant values of the magnetic flux density at all points of the considered lateral profile beneath the multi-circuit overhead transmission line can be determined using the following equation:

$$B(x,y)=\sqrt{\left|\underline{B}_x^R(x,y)\right|^2+\left|\underline{B}_y^R(x,y)\right|^2} \quad (11)$$

where $B(x,y)$ are magnetic flux density resultant values.

2. CASE STUDIES

In this paper two cases of multi-circuit overhead transmission lines are considered. The considered overhead lines have different rated voltage, and both of them are implemented as double-circuit, with two independent three-phase circuits on the opposite sides of the tower.

Table II Safety distances to the ground (heights) and distances for the typical areas [25]

Voltage (kV)	Safety distance to the ground (height) (m)	Safety distance between phase conductors and nearby objects (m)
Article 100. Inaccessible locations		
400	6.0	5.0
220	4.75	3.75
110	4.0	3.0
Article 101. Locations inaccessible by car		
400	7.0	6.0
220	5.75	4.75
110	5.0	4.0
Article 102. Locations accessible by car		
400	8.0	7.0
220	6.75	5.75
110	6.0	5.0
Article 105. Permanently accessible parts of buildings		
400	7.0	6.0
220	5.75	4.75
110	5.0	4.0

Safety distances to the ground for overhead transmission lines phase conductors, i.e. their heights, are for Bosnia and Herzegovina and Serbia defined by the Regulation of the technical normative for constructing overhead power lines of rated voltages from 1 kV up to 400 kV, "Official Gazette (SFRY)" No. 65/88 [25]. This document defines characteristics that overhead lines have to possess in different conditions.

For each considered case of zone of influence determination, several scenarios will be analysed. Analysis will be performed for the scenario where phase conductors have the lowest allowable heights, and for scenarios where their heights were increased by 2 meter each, up to a total increase of 10 m compared to the minimum height. In both cases, the considered phase current intensities are chosen considering expected working conditions based on the usual current measuring transformers settings. First analysed case is double-circuit 400 kV overhead line presented in Figure 4, that consists of two symmetrical three-phase circuits placed on the opposite sides of the tower.

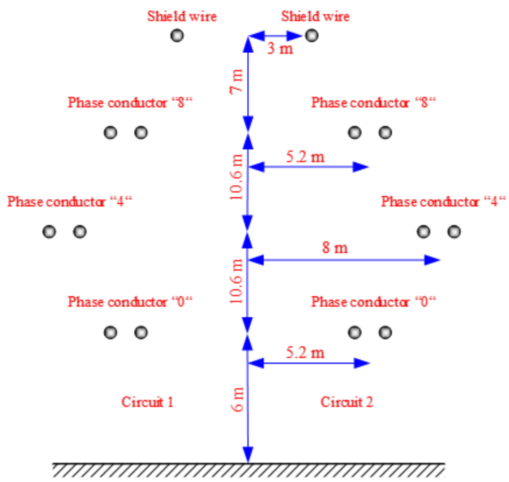

Figure 4: Double-circuit 400 kV overhead line [26]

From Table II, it can be noted that the lowest safety distance to the ground for 400 kV overhead lines, considering all possible location types amounts to 6 m. So, this phase conductor height is considered as starting value for the zone of influence analysis. The calculations are performed considering that both three-phase circuits are symmetrically loaded with a phase current intensity of 1250 A. The obtained results are presented in Figure 5, where all considered phase conductor height scenarios are indicated with different colours. Furthermore, the magnetic flux density value that is considered as the limit value for a zone of influence width is indicated with a red dotted line. The width of the transmission line safety area (ROW), as defined in Table I is indicated on Figure 5 with a black and magenta dotted lines.

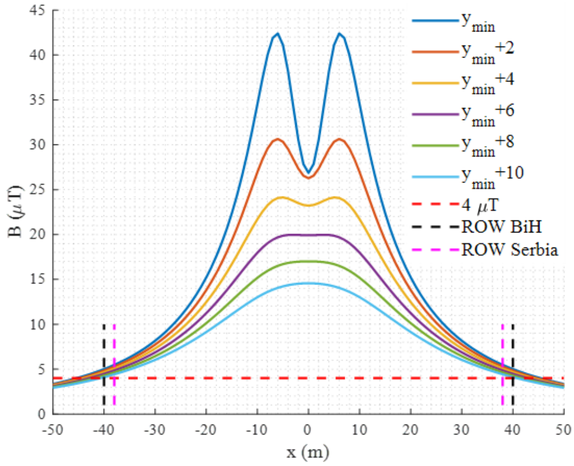

Figure 5: Results of zone of influence determination for a double-circuit 400 kV overhead line

The numerical results obtained for double-circuit 400 kV overhead transmission line are presented in Table III.

From Figure 5 and Table III it can be observed that, as expected, the highest magnetic flux density values are derived with minimum phase conductor heights, and that it decreases, as height is increased. Furthermore, it can be seen that in all considered cases zone of influence is wider than the overhead line safety area. It is the widest for minimum heights scenario and amounts to 2 x 46 m, while the safety area width for 400 kV overhead lines has width of 2 x 40 m according to [17] or 38 m, according to [18]. In the case of a scenario with maximal heights, the zone of influence is 2 x 41 m.

The second analyzed case is a typical 110 kV double-circuit overhead line, type F2 designed by Energoinvest Sarajevo, which is shown in Figure 6. This overhead line consists of two three-phase circuits that are placed symmetrically on both sides of the tower. As it can be noted from Table II, the lowest allowable phase conductor height for 110 kV overhead lines, considering all terrain types, is 4 m. Thus, in Figure 6 all phase conductors and shield wire heights are shown considering overhead line tower design and minimum phase conductors height.

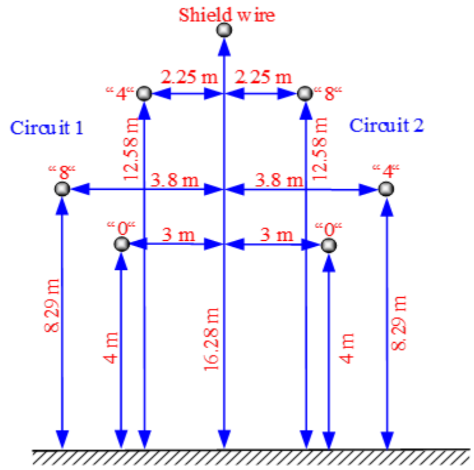

Figure 6: Double-circuit 110 kV overhead line

Similarly to the previously analysed case of the 400 kV overhead line, six scenarios of different conductor heights are also considered. Starting from 4 m, they increase in steps of 2 m up to a total of 10 m more than the initial height. The analysis is conducted for symmetrical phase current intensity in both three-phase circuits, which amounts to 525 A. The obtained results are presented in Figure 7.

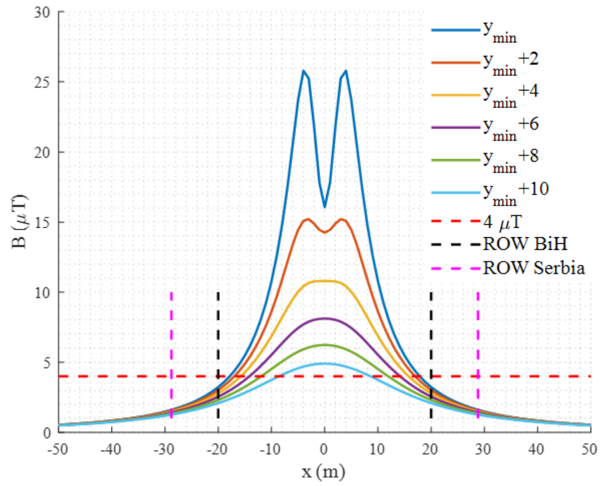

Figure 7: Zone of influence determination results for double - circuit 110 kV overhead line

Table IV presents the numerical results obtained for the case of double-circuit 110 kV overhead transmission line.

Table III Results obtained for the double-circuit 400 kV overhead transmission line

h	B_{max} (μT)	Width of the zone where B > 4 μT (rounded to 1 m)	The distance at which B drops below 4 μT (rounded to 1 m)	Safety area	
y_{min} (4 m)	42.3995	2 × 45 m	46 m	40 m according to [17]	38 m (8 m + 30 m) according to [18]
y_{min} + 2 m	30.6512	2 × 44 m	45 m		
y_{min} + 4 m	24.1399	2 × 43 m	44 m		
y_{min} + 6 m	19.9806	2 × 42 m	43 m		
y_{min} + 8 m	17.0074	2 × 41 m	42 m		
y_{min} + 10 m	14.5689	2 × 40 m	41 m		

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Table IV Results for double-circuit 110 kV overhead transmission line

h	B_{max} (μT)	Width of the zone where B > 4 μT (rounded to 1 m)	The distance at which B drops below 4 μT (rounded to 1 m)	Safety area	
y_{min} (4 m)	25.7350	2 × 17 m	18 m	20 m according to [17]	28.8 m
y_{min} + 2 m	15.3142	2 × 16 m	17 m		
y_{min} + 4 m	10.8764	2 × 15 m	16 m		
y_{min} + 6 m	8.1553	2 × 14 m	15 m		
y_{min} + 8 m	6.2530	2 × 11 m	12 m		
y_{min} + 10 m	4.9158	2 × 8 m	9 m		

From Figure 7 and Table IV it can be noted that in all considered cases, the determined zone of influence is narrower than the prescribed safety area for overhead transmission lines with 110 kV rated voltage. The highest magnetic flux density values are obtained for scenario with the lowest phase conductor heights. Furthermore, with increasing height of phase conductors, magnetic flux density values decrease, leading to narrowing of the zone of influence. In the case with the maximum considered phase conductors heights, the zone of influence in narrowest and amounts to 2 x 9 m. The widest zone of influence obtained in this case amounts to 2 x 18 m, which is close to the prescribed safety area width.

3. CONCLUSION

This paper examines the determination of the zone of influence of multi-circuit overhead transmission lines in terms of magnetic flux density values in the extremely low-frequency range. The calculation of magnetic flux density and the determination of the zone of influence were performed using a method based on the application of ANN. The case study analyses the zone of influence for two double-circuit overhead transmission lines with different rated voltage levels. The obtained results were compared with the safety zone, defined by the relevant regulatory authorities for overhead transmission lines of the considered voltage levels. The analysis revealed that in case of 400 kV overhead transmission line, the zone of influence exceeds the width of the safety zone, whereas, in case of the 110 kV line, it is slightly narrower but close to the defined safety zone width. The conducted research highlights the importance of considering the zone of influence in the process of overhead transmission line design to mitigate the potential negative impacts that multi-circuit transmission lines may have on the surrounding environment.

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