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Transmission line sag and magnetic field analysis with sag parabolic equations and Biot-Savart law

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ABSTRACT

This study presents a novel approach to enhance the precision of calculating sag and magnetic fields beneath overhead transmission lines. The Biot-Savart law is integrated with parabolic equations to assign multiple magnetic field sources to each conductor, resulting in improved prediction accuracy. Addressing oversimplifications in traditional models improves the analysis of transmission lines in real-world scenarios. An analysis was performed using MATLAB and Simulink to validate the effectiveness and broad applicability of different configurations. The results demonstrated a significant improvement in precision compared to traditional methods, indicating that this approach has the potential to establish new benchmarks in the field. This methodology makes significant contributions to electromagnetic studies, offering engineers a reliable tool for designing transmission systems that are both safer and more efficient. This advancement in electrical engineering greatly improves transmission network performance by enhancing sag and magnetic field prediction accuracy. This aids in better maintenance planning and reduces outage risks, resulting in more efficient operations and improved overall performance.

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1. INTRODUCTION

Overhead power lines transmit electrical energy from power plants to consumers. As the electric current passes through the conductors, the lines generate a magnetic field in their vicinity. The intensity of this field fluctuates depending on the load conditions. The strength of the magnetic field reduces as the distance from the power lines increases. The ground-level magnetic field is the sum of all currents flowing through the wires, operating on a three-phase system. As the current increases, so does the magnetic field [1]. The magnetic field strength decreases with the distance from the power lines. The strength of the magnetic field is measured in either tesla (T) or gauss (G). The closer one is to the power lines, the stronger the magnetic field [2]–[4].

Most overhead transmission lines are three-phase. Each phase has one or more conductors, and the ground-level magnetic field is the sum of all the magnetic fields produced by the currents in all the conductors. It is crucial to understand these electromagnetic phenomena, especially for people who are susceptible to such fields. The selection of conductor material is also significant as it directly affects the strength-to-weight ratio, ampacity, and sag, all essential parameters in the design and functioning of overhead transmission lines. It can have implications for people and animals in the vicinity of the power lines, particularly for those who are sensitive to electromagnetic fields [5]. A good conductor should perform better in strength-to-weight ratio, ampacity, and sag. The gravitational and wind force a conductor can withstand before breaking depends on its strength-to-weight ratio. Low conductor sag is the result of a high strength-to-weight ratio. A conductor with a higher ampacity is always preferred, but higher electricity transmission generates more heat. When ambient temperature and conductor elongation are combined, the sag will increase, and the best conductor should be chosen [6]. Sag is the distance measured vertically from the lowest conductor to the span length. Daily sag occurs during routine day-to-day operations of overhead transmission line (OTL) systems. The maximum electrical loading sag is a standard that should not be violated while operating the OTL. A typical 132 kV OTL system requires at least 7 m height [7], [8]. During the design process, magnetic field calculation is an essential factor that must be considered, particularly for high-voltage transmission lines. The design should ensure that the magnetic field strength does not exceed the permissible limits of relevant standards and regulations [9]. A typical OTL tower is shown in Figure 1.

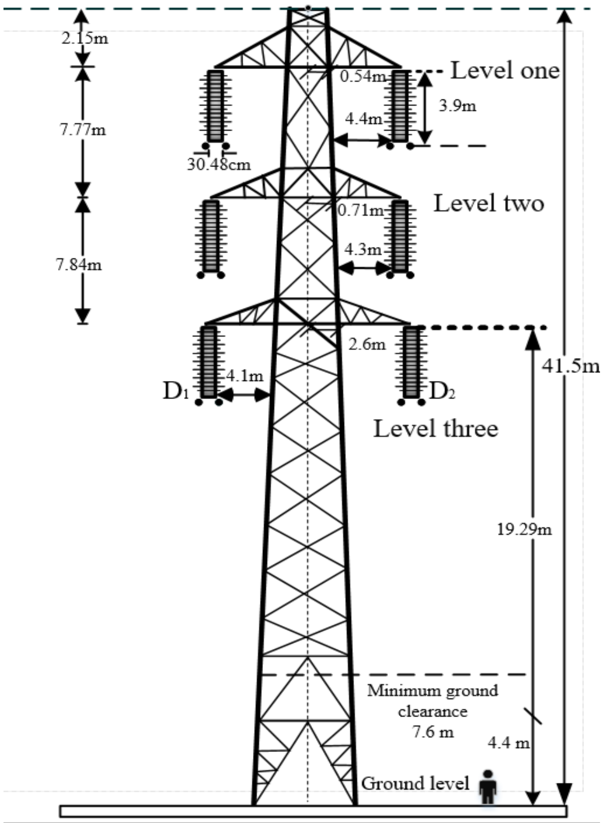

Figure 1. Typical transmission line tower

Most of the overhead transmission lines consist of a three-phase circuit. Each phase has a single or double two or more conductors where the ground level of the magnetic field is the sum of all the magnetic fields produced by the currents in all the conductors. However, the magnetic field radiation decreases as the distance from the current source to the observation point increases [9], [10]. The origin of a coordinate system is placed on the ground underneath the center phase. The conductors are at the height of *h* above the ground, and the phase separation is *s*. shown in Figure 2 [2]. The equations (1)-(3), calculate the magnetic field and flux density [3], [4].

$$|H_{ht}| = \frac{I}{2\pi}\left(K_a^2 + K_b^2 + K_c^2 - K_aK_b - K_bK_c - K_cK_a\right)^{\frac{1}{2}}(\text{Amp/meter}) \quad (1)$$

$$|H_{vt}| = \frac{I}{2\pi}\left(J_a^2 + J_b^2 + J_c^2 - J_aJ_b - J_bJ_c - J_cJ_a\right)^{\frac{1}{2}}(\text{Amp/meter}) \quad (2)$$

The corresponding flux density is as (3):

$$|B_{ht}| = \mu_o |H_{ht}| \; and \; |B_{vt}| = \mu_o |H_{vt}| \text{ (Tesla)} \quad (3)$$

The equations (1)-(3) are used to calculate the electromagnetic field for the transmission line. The conductor layout in the preceding example is horizontal and vertical.

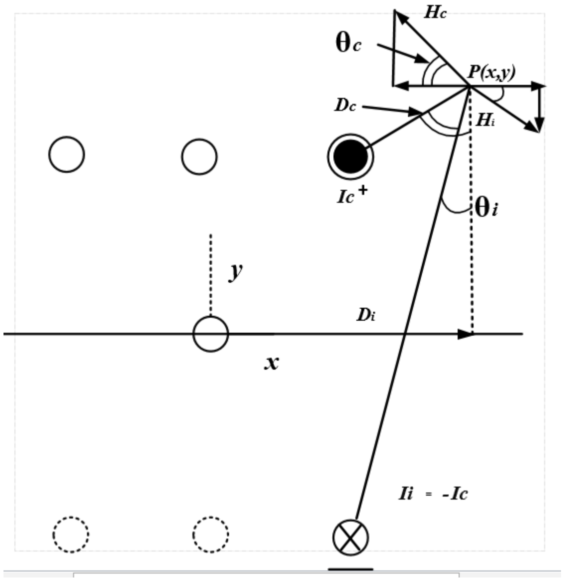

Figure 2. Vertical configuration of conductor's model [3]

The conductor sags at maximum operating temperature, which determines the tower height. During installation, the conductor's temperature ranges from 10 °C to 35 °C, with tensions ranging from 10% to 30% of their rated tensile strength. However, the conductor will be subjected to a higher temperature during high electrical loads, as shown in Figure 3. Even with high ice and wind load events, the conductors must be preserved for at least 40 years [4], [11].

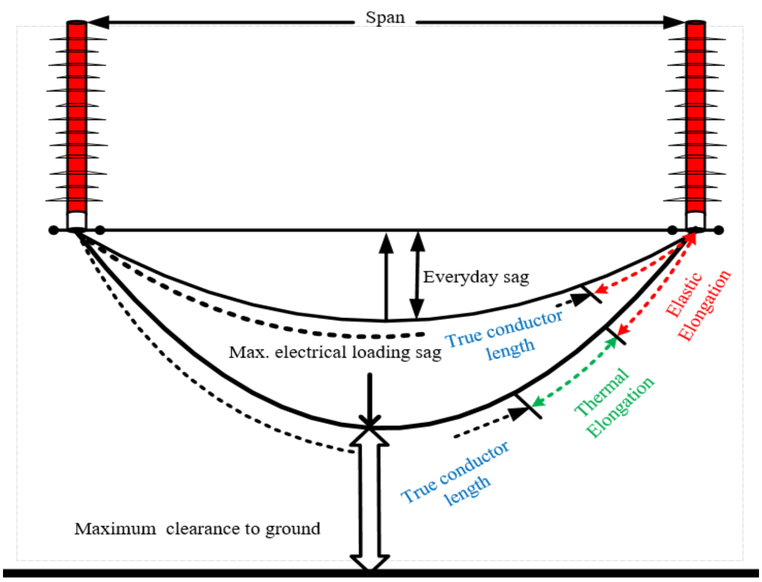

Figure 3. The sag of a conductor during typical loading [11]

The sag specification for conductors must follow the guidelines outlined in the British electricity international (BEI) modern power station practice. It provides detailed procedures for calculating sag tension in overhead lines. The tensioned conductor, with a constant mass per unit length, is suspended only at the ends and forms a catenary curve shape. In typical non-mountainous regions, the catenary curve takes on a shape resembling a parabola. The length of the conductor from the lowest point of the span to the point *x* measured horizontally along the span is given by (4)-(6) [12]–[14]:

$$l = c\ sinh\ (\frac{x}{2c}) \tag{4}$$

at any point in the span,

$$y = c[cosh(\frac{x}{c} - 1)] \tag{5}$$

for parabola,

$$y = \frac{wL^2}{2T} \tag{6}$$

where L is span (horizontal distance between supports), m; l is length of span measured along the conductor (the arc length), m; T is horizontal component tension, N; W is vertical force in the still air or resultant force per unit length N/m; X is horizontal distance from the origin or the lowest point in the span; For tower design for the type of level. The sag is measured from above by using (7) [14].

$$S = \frac{wL^2}{8T} \text{(Including sloping spans)} \tag{7}$$

The final un-tensioned conductor length equals the initial un-tensioned length plus any extension due to temperature change. The arc length is given by (8) [4]:

$$l = L + w^2L^3/24T^2 \tag{8}$$

The extension due to any change of temperature is given by $L\alpha(\theta_2 - \theta_1)$, is added, so the final (9) is [4].

$$\left[\left(\frac{2T_1}{w_1}\right)\sinh\left(\frac{w_1}{2T_1}\right)\right] - \left[\left(\frac{2T_2}{w_2}\right)\sinh\left(\frac{w_2L}{2T_2}\right)\right] + \left[\left(\frac{L}{AE}\right)(T_2 - T_1)\right] + \alpha L(\theta_2 - \theta_1) = 0 \tag{9}$$

For parabola in (10).

$$\frac{L^3}{24}\left[\left(\frac{w_1}{T_1}\right)^2 - \left(\frac{w_2}{T_2}\right)^2\right] + L/AE(T_2 - T_1) + \alpha L(\theta_2 - \theta_1) = 0 \tag{10}$$

The formula is the cubic equation, which has three positive and two negative roots. The negative roots are meaningless. For using a solution, the Raphson method is used for the new value of T_2 is shown in (11) and (12) [4].

$$T_2 \text{ (New value) } = T_2 \text{ (old value)} - \text{(correction)} \tag{11}$$

$$\text{Correction} = (\text{ LHS}/(w^2L^3/12T^2 + L/EA) \tag{12}$$

where α is effective coefficient of expansion; θ is temperature,°C; E is effective coefficient of expansion; T_1 is initial horizontal component tension, N; and T_2 is final horizontal component tension, N.

2. METHOD

This paper presents a comprehensive approach to determining the parameters of parabolic curves and magnetic fields under power transmission systems. The main objective of this technique is to improve the system's performance, ensure safety, and comply with established industry standards. It is achieved by integrating mathematical modelling, empirical data, and engineering principles. Efficient and reliable power transmission is crucial for delivering electricity from generation sources to end-users. Precise representation of system elements and strict adherence to design criteria are necessary for efficient transmission [15]–[18].

The sag calculation is determined by considering tension, temperature, and span length while considering various environmental conditions. The optimization of conductor placement aims to minimize sag while ensuring safety margins, considering the influence of thermal impacts. The flow chart of the calculation process is shown in Figure 4.

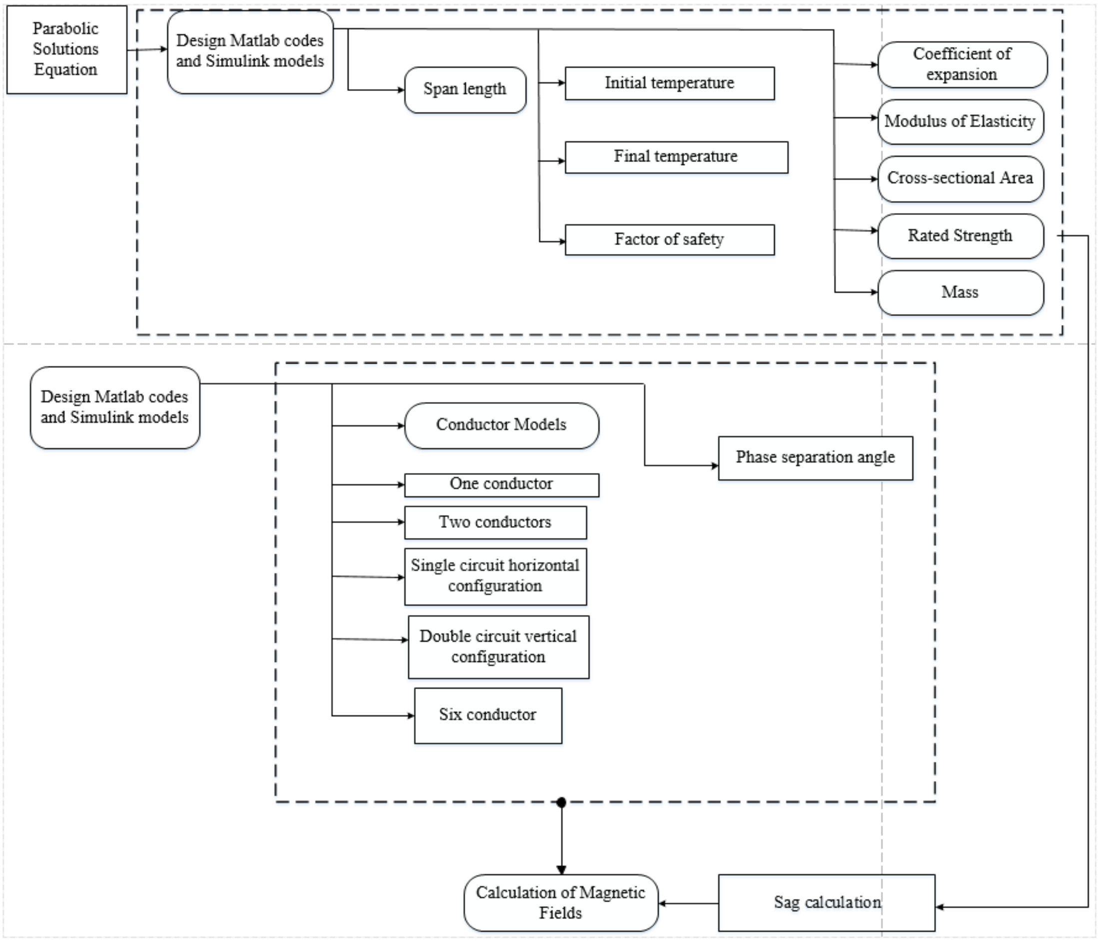

Figure 4. Flowchart of the calculation of magnetic field distribution level from overhead lines modelling procedures

2.1. MATLAB Simulink model for sag

The flowchart in Figure 5 provides a systematic approach to analyzing the physical characteristics of conductors, with a focus on their elasticity and tension. The process begins with setting parameters in Simulink, a simulation environment commonly used in engineering research. It then calculates the initial arc length excess over the span length, likely due to the conductor's droop or sag caused by its weight. The flowchart uses mathematical methods to refine the conductor's tension by solving parabolic equations related to its shape and behavior. An iterative process, possibly utilizing the Raphson-Newton method, corrects length errors until an accurate tension value is obtained. The flowchart also considers the effects of thermal expansion on the conductors, ensuring that tension calculations are precise under varying temperature conditions [18]–[22].

2.2. MATLAB Simulink models of magnetic field

The magnetic field beneath a model is accurately and efficiently determined using MATLAB calculations. Furthermore, the design of the Simulink model enabled user-friendly and interactive computations. MATLAB 2022 software creates models for calculating sag-tension and magnetic fields in traditional overhead line towers. Simulink provides various layouts for computing sag-tension and magnetic fields to accommodate diverse needs [23].

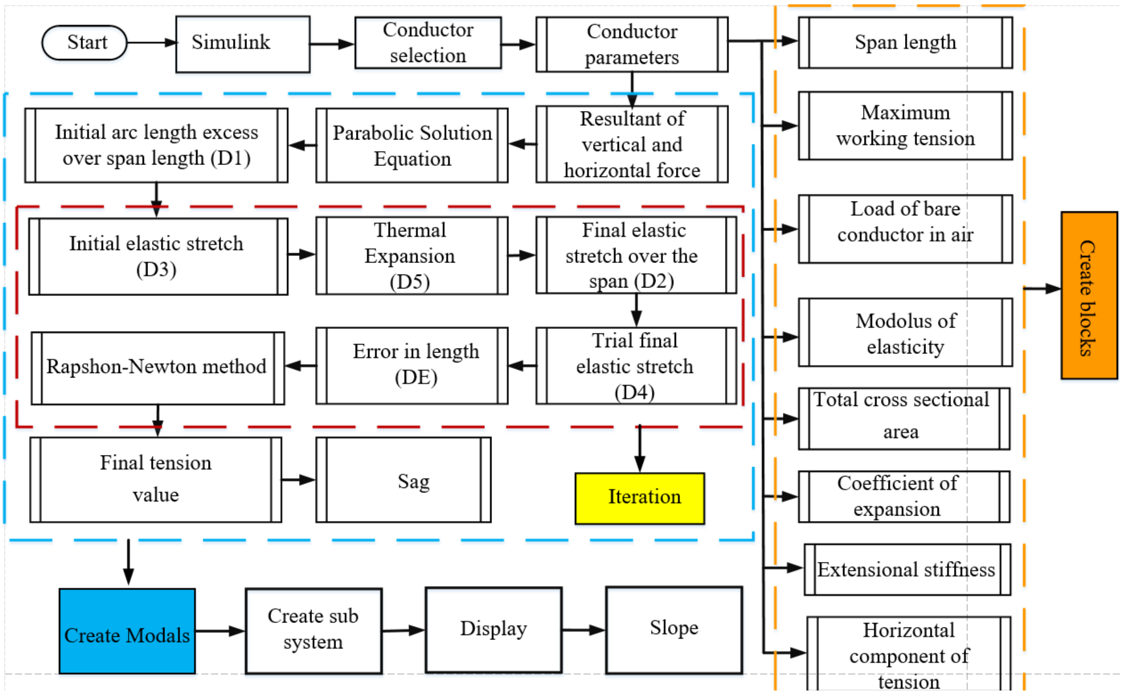

Figure 5. Procedure of sag modelling in Simulink

2.3. Magnetic field for 3-phase lines

Most of the overhead transmission lines consist of a three-phase circuit. Each phase has a single or double two or more conductors where the ground level of the magnetic field is the sum of all the magnetic fields produced by the currents in all the conductors. However, the magnetic field radiation decreases as the distance from the current source to the observation point increases [24], [25].

2.4. Single circuit 3-phase model

Figure 6 shows three overhead conductors; the image conductor below the ground surface replaces the ground surface. It assumes that the ground surface is a flux line. The origin of a coordinate system is placed on the ground underneath the center phase. The conductors are at the height of *h* above the ground, and the phase separation is *s*.

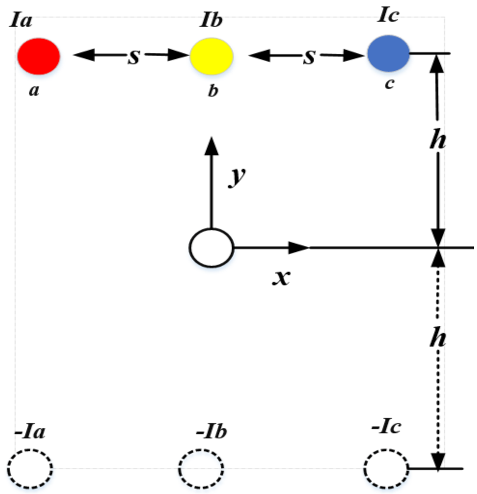

Figure 6. Horizontal configuration for single circuit 3-phase model

2.5. MATLAB Simulink model for single circuit 3-phase model

The single-circuit, horizontal, 132 kV line specifications are as follows: line-to-line voltage of 132 kV, 3-phase current of 300 Amps, a line height of 18 meters, and phase space of 15m. The model is designed in Simulink to find the accurate values of the magnetic field. The parameter data is inserted into Simulink through the MATLAB code, and the ground-level magnetic field is calculated, as shown in Figure 7.

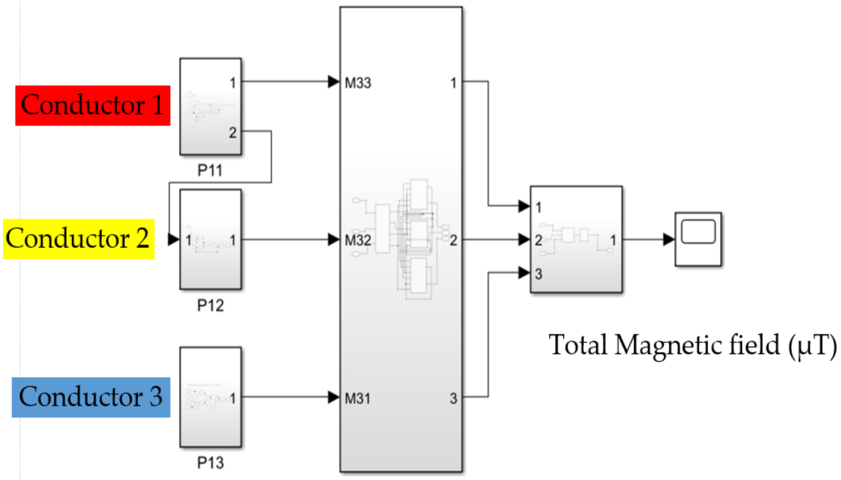

Figure 7. Simulink model diagram for single circuit 3-phase model

2.6. Double circuit 3-phase model

Figure 8 shows a double circuit 3-phase transmission line with height to the middle h. In the circuit, the six-circuit is distributed uniformly on a circle of radius *R*. The phase configurations can be in two types: “1” *abc-cba* and “2” *cba-abc*. Figure 8 shows *abc-cba* for the magnetic field.

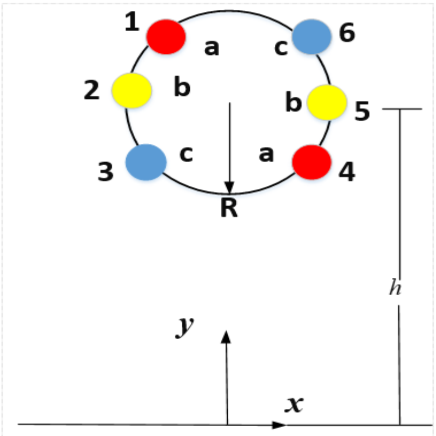

Figure 8. Vertical configuration for double circuit 3-phase model

2.7. MATLAB Simulink for double circuit 3-phase model

The double circuit vertical configuration parameters are mentioned in the MATLAB code. The double circuit vertical configuration is 275 kV, line-to-line, giving a current of 300 Amps in each conductor. The line height to the middle phases is 15m while six conductors are distributed uniformly on a circle of radius 6 m. The magnetic field is calculated at ground level within 40m from the line center to the left and 40 m to the right. The model is designed in Simulink to find the accurate values of the magnetic field. The parameter data is inserted into Simulink through the MATLAB code, and the ground-level magnetic field is calculated.

2.8. Six conductors model

Figure 9 shows six conductors 132 kV overhead transmission line towers. The tower parameters show that the top cross-arm height is 23.85 m, the middle cross-arm height is 20.15 m, and the lower cross-arm height is 16.45 m. The top, middle, and lower cross-arm length is the same and equal to 8.84 m. The current in each phase is 2,111 A, the sag is 8.36 meters, and the measurement height is 2 meters above the ground.

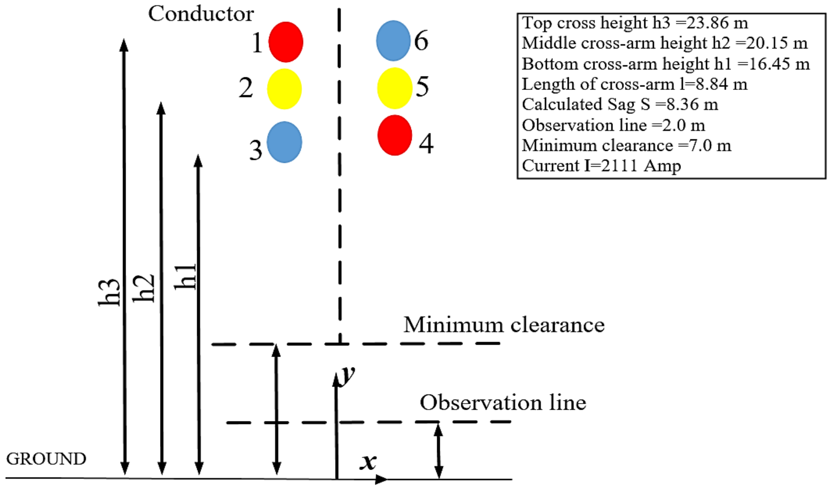

Figure 9. Vertical configuration for six conductor's model

2.9. MATLAB codes for six conductors model

The six conductors configuration parameters are mentioned in the MATLAB code. The six conductor configurations are 132 kV, line-to-line, giving a current of 2,111 A in each conductor. The magnetic field is calculated at 2 m above ground level within 40 m from the line center to the left and 40 m to the right. The parameter data is inserted through the MATLAB code into Simulink, and the magnetic field 2 m above ground level is calculated, as shown in Figure 10.

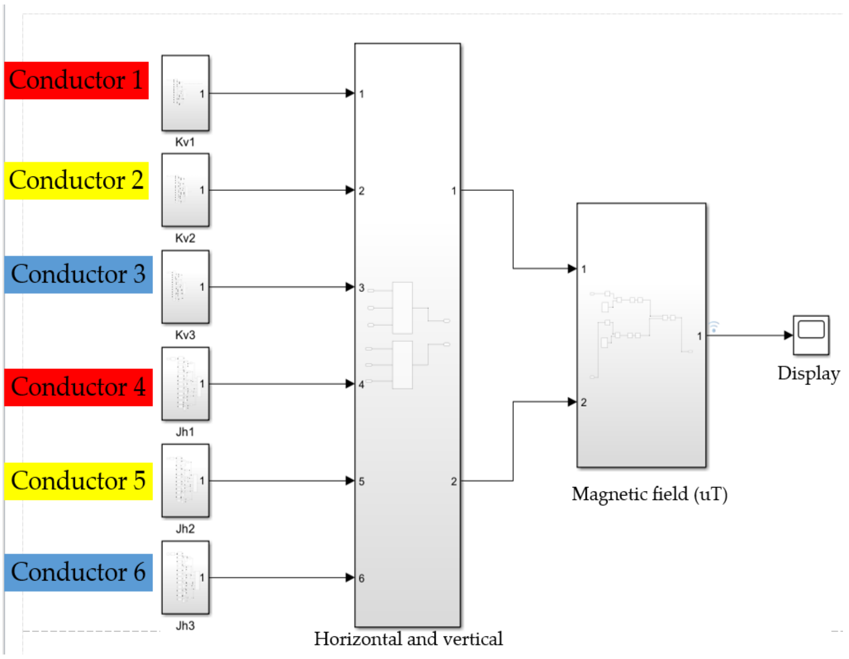

Figure 10. Simulink model diagram for six conductor's model

3. RESULTS AND DISCUSSION

3.1. Magnetic field distribution of single circuit 3-phase

At the points -17 and 17 m, the magnetic field reaches its highest value of 4.3529 µT. Measurements taken at 40 m to the right and -40 m to the left show the lowest value of 1.452 µT. This data is illustrated in Figure 11.

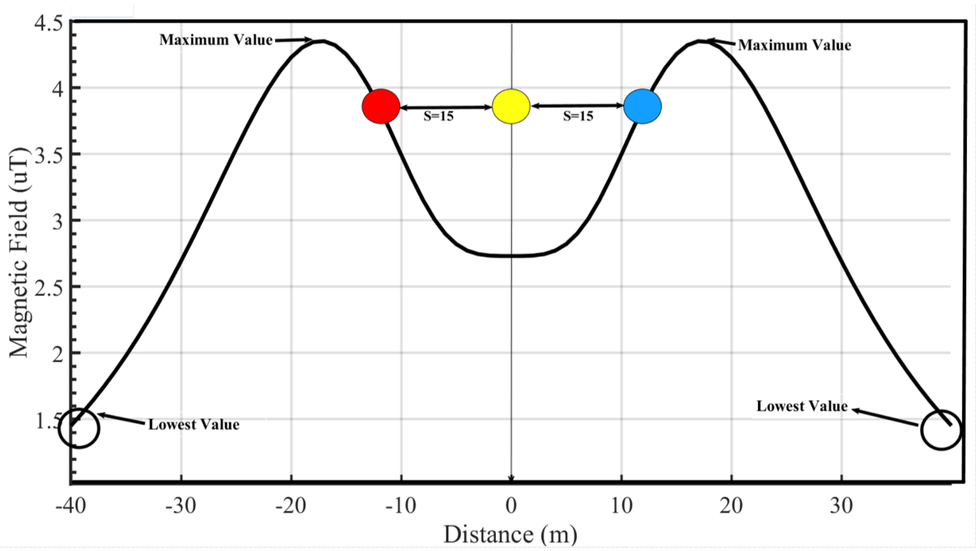

Figure 11. Magnetic field distribution level for single circuit 3-phase model

3.2. Magnetic field distribution for circuit 3-phase model

MATLAB Simulink plotted the 132 kV tower magnetic field graph shown in Figure 12. The plot of magnetic field density near the line along the ground surface only, as the distance from the line center varies from x=-40 m to x=40 m. At the point -4 m and 4 m, the magnetic field measurements show the highest value in the MATLAB Simulink is 3.7427 µT. The magnetic field measurements on the 40 m to the right and -40 m to the left show the lowest value in the MATLAB Simulink is 0.16939 µT.

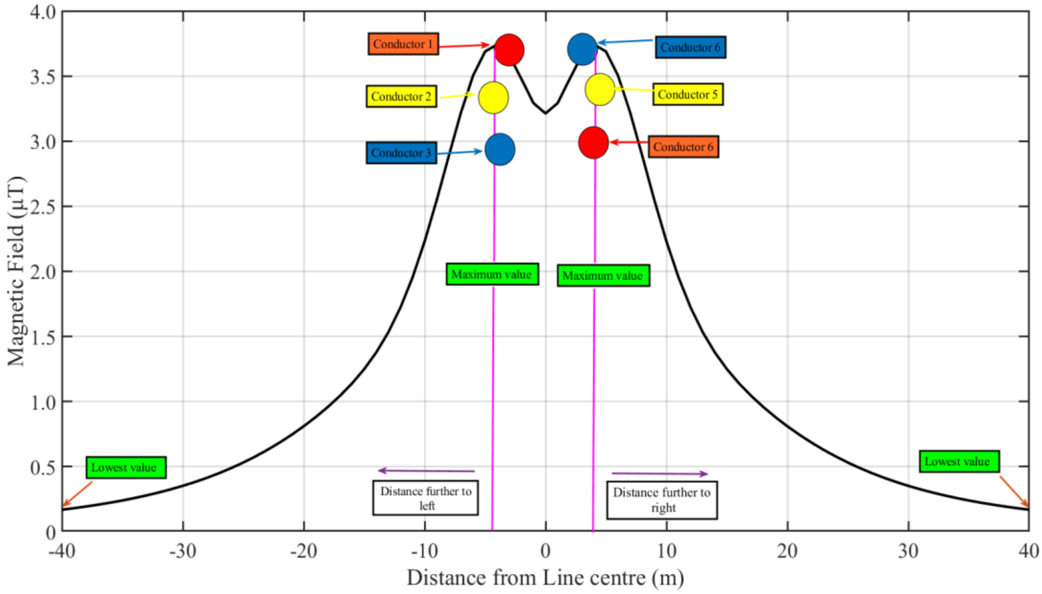

Figure 12. Magnetic field distribution level for double model

3.3. Magnetic field distribution for six conductors model

Figure 13 represents the magnetic field graph on the 132 kV tower plotted by MATLAB Simulink. The magnetic field measurement value is underneath the tower. The measurement height is above 2 m ground level, and the width is 40 m further to the right and -40 m further to the left. At points -40 m and 40 m, the magnetic field measurements show the lowest value in the MATLAB Simulink is 5.8 μT. The magnetic field measurements on the 3 m to the right and -3 m to the left show the highest value in the MATLAB Simulink is 0.25 μT.

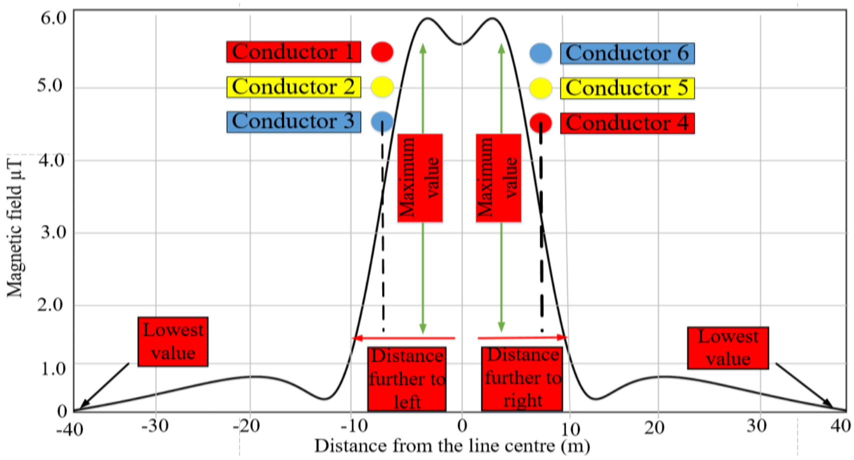

Figure 13. Magnetic field distribution level for six conductors' model

3.4. Graph for sag parabolic equation

The graph shown in Figure 14 has maximum sag values from 0 °C to 75 °C as the final temperature. As the temperature rises, the sagging value increases. The maximum values of sag at 0 °C and 75 °C are 6.244 and 9.2617 m at maximum working tension (MWT).

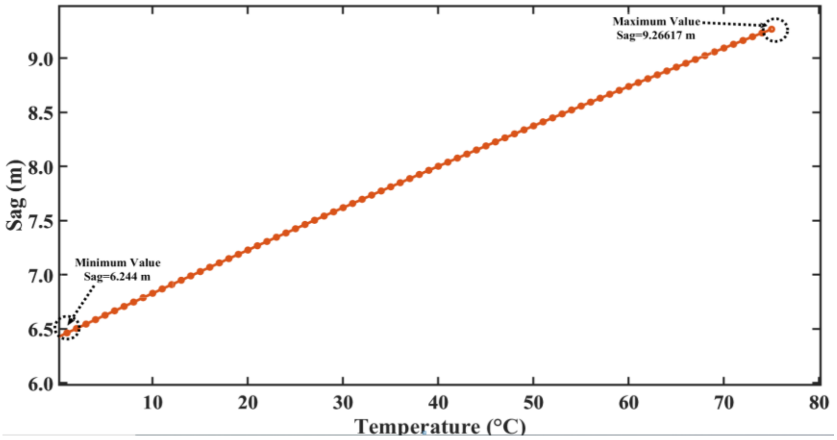

Figure 14. Sag for conductor ACSR Darke 26/7 calculated using Sag parabolic equation

4. CONCLUSION

Developing a new calculation method for accurately determining sag and magnetic fields beneath overhead transmission lines is a significant advancement. This method applies the Biot-Savart law and sags parabolic equations, providing engineers with an improved tool for evaluating line designs and their magnetic effects in practical applications. This research offers valuable insight into critical electromagnetic phenomena involved in power transmission. With the ability to efficiently model field exposures and geometry changes under varying conditions, transmission planners and designers can optimize route selection and configurations to minimize impacts. It enhances technical performance and public acceptance of vital infrastructure projects. Overall, the proposed method allows a more thorough understanding of the effects of interaction between overhead lines and their surroundings. Such understanding helps enable safer and more reliable electricity delivery now and into the future as demand increases. The method also supports the progressive improvement of industry practices informed by precise modeling capabilities. This work thus deserves recognition for its benefits toward more efficient transmission worldwide with consideration for all stakeholders.

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