Magnetic Field Calculation under Unconventional Lines with Increased Power Delivery

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2024 IEEE Texas Power and Energy Conference (TPEC) | 979-8-3503-3120-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/TPEC60005.2024.10472189

***Abstract*—To achieve net-zero emission in America by 2050, high voltage transmission capacity must expand approximately 60% by 2030 and triple by 2050 to connect further renewable(wind and solar) facilities to demand. We will fail to achieve a net-zero America through 100% renewables by 2050 unless high-capacity overhead lines are developed in conjunction with other technological advances. To tackle this problem, we developed a revolutionary and flexible design for transmission lines(TL) by changing phase configurations and sub-conductors into unconventional way, geometrically optimal arrangements within the space. To realize these unconventional high surge impedance loading (HSIL) lines, different line design aspects need to be studied. This paper calculates and studies the magnetic field under the aforementioned lines. When calculating the magnetic field from conventional lines at/or near ground level, we can assume an equivalent conductor located in the center of each bundle, however this is not the case for unconventional HSIL lines. As the distance between subconductors is comparable with their height from the ground, we have to calculate the magnetic field generated by each subconductor, so the equivalent conductor mentioned above does not work.**

Keywords—Magnetic field, unconventional high surge impedance loading (HSIL) lines, overhead line

I. INTRODUCTION

Electric power generation, transmission, and distribution businesses have been horizontally integrated over the past several decades. Supply and demand changed significantly as a result of this restructuring. Light-weight generators (such as gas turbines) and renewable resources are replacing large synchronous generators. In structure, industrial equipment, and consumer goods, distributed and variable generation resources are increasingly used along with modern converters and energy-efficient solutions. Transmission lines, however, are not subject to this rule.

Generally, underground cables cost three to ten times more than overhead lines [1], tend to higher ratios by higher voltages. As an example,estimated by Dominion Energy, underground lines to cost between $4-10 million per mile, contrary overhead lines typically cost between $1-~2 million per mile [2]. Additionally, HVAC underground cables have a transmission limit due to their charging current.

There are no reliable and commercial High Voltage DC circuit breakers (CBs) [3-6]. The converter station's cost is also high, so HVAC transmission is preferable. In addition, power system planner cannot use a point-to-point connection without HVDC CBs. Submarine projects sometime consider using HVDC submarine cables when there is no alternative technical option for long-distance transmission.

There have been studies on higher-phase order transmission lines (e.g., 6- or 12-phase lines) as alternatives to traditional 3-phase lines [7-13], but the only commercially available line (only 1.5 miles long) was operated and built by reconfiguring 115-kV double-circuit 3-phase lines. With higher phase-order lines, the same power can be transferred over smaller right-of-ways (ROWs) than with traditional 3-phase lines. A 6-phase line, however, requires 6 CBs and 6 bays, increasing the overall cost.

Therefore, 3-phase AC overhead TL will continue to dominate power transmission in the future. Transmission networks are increasingly important due to the trend towards 100% renewable energy and the focus on larger renewables, such as solar power plants and wind farms. Transmission networks are necessary for such massive resources(renewable) since most of the time they are far from load centers.

Power transmission on an AC TL is traditionally constrained by thermal, voltage-drop, and specially transient stability limitations, depending on the line's length. The line length feature addressed above is substituted by voltage limits at branches and buses(including transformers and lines) loading (thermal) limits when analyzing power flow in a power system. Short-circuit studies prefer to plann scenarios that do not increase currents(short-circuit) higher than the limits of circuit breakers(CBs) in existing substations to avoid replacing circuit breakers(CBs) or employing methods related to short-circuit reduction. As a result, more transmission lines reach lower network impedance, resulting in higher short-circuit currents. Additionally, transmission line(TL) plays a crucial charecter in maintaining dynamic stability along with transient stability. Thus, these power transmission highways are major bottlenecks that largely determine the power system's loadability.

It is possible to achieve greater line loadability and maintain near-rated voltages by using lumped reactive compensation

This work was supported in part by the National Science Foundation (NSF) under Award #2306098.

techniques. Static Var Compensators (SVC), for example, have been used as an advanced control device to increase system voltage stability and voltage control on medium- and long-length transmission lines. Series capacitors are also used on long lines to lower series impedance, reducing voltage dips and enhancing voltage stability limits. However, each option has its disadvantages, and the main one is their high costs.

In [14] by changing phase configurations and sub-conductors into unorthodox arrangements that are geometrically optimized inside the space, we created a novel and flexible transmission line design that we called it unconventional HSIL line. Different line design aspects, such as electric and magnetic fields under the line, must be studied to realize these unconventional HSIL lines. In recent years, high-voltage(HV) power lines have been mentioned intermittently in media as a potential health hazard. Therefore, the extremely low frequency (ELF) at 50 or 60 Hz of the electric field (E) distribution and especially magnetic field (B) distribution beneath the line and alsoat the vicinity at the right-of-way has to be calculated precisely. This paper deals with magnetic field calculation where we have to compute it for each subconductor in these unconventional HSIL lines instead of simplifying assumption of an equivalent located in the middle of the bundle in conventional lines, so these calculations can be challenging.

II. Method

A. Magnetic-Field Calculation under Transmission Lines

Overhead lines generate magnetic fields(B) at 50 or 60 Hz in response to the electric current flowing through them. For N_c number of horizontal conductors, a formula for magnetic flux density that also considers the induced eddy currents in a conducting earth is [15-18]:

$$B_{rms} = 0.2 \times \sum_{n=1}^{N_c} I_n \left\{ \left[\frac{(y-d_n)}{r_{cn}^2} - \frac{(y+d_n+\alpha)}{r_{in}^2} \right] \vec{a}_x - \left[\frac{(x-h_n)}{r_{cn}^2} - \frac{(x-h_n)}{r_{in}^2} \right] \vec{a}_y \right\} \quad \mu T \qquad (1)$$

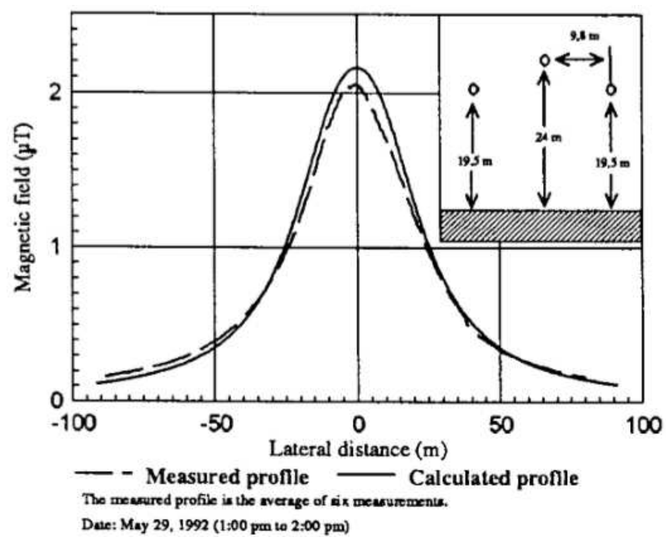
$$r_{cn} = \sqrt{(x-h_n)^2 + (y-d_n)^2}\,,$$

$$r_{in} = \sqrt{(x-h_n)^2 + (y+d_n+\alpha)^2}$$

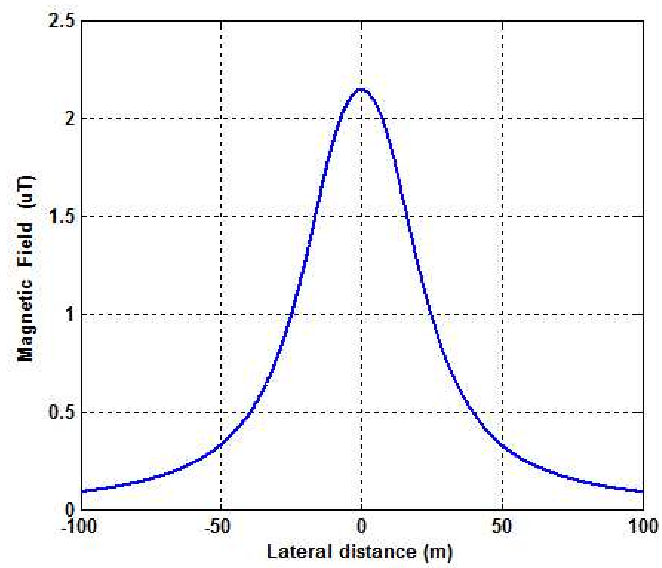
$$\alpha = \sqrt{2}\delta_g e^{-j\pi/4} \quad , \quad \delta_g = 503\sqrt{\rho_g/f}$$

where ρ_g is denoting earth resistivity (Ω.m), f is denoting the frequency in Hz, I_n is denoting the conductor current (Amps-rms), and all distances are considered in meter. The n-th conductor is positioned at $(x,y) = (h_n, d_n)$. For each conductor, its earth current equals its magnitude and runs in the opposite direction. Furthermore, each earth current is buried in the earth with a complex depth proportional to δ_g, earth's skin depth.

The lateral profile of the magnetic field can be computed using the measured currents in the conductors and the line diameters. Fig. 1a [15] shows a comparison of measurements and computations for a 735-kV transmission line arrangement. Fig. 1b shows the transmission line's lateral profile of magnetic field. Compared to Fig. 1a, the code written for magnetic field(B) calculation around the transmission line is verified. The magnetic field profiles in Fig. 1 are at a height of 1 m above the ground.



(a)



(b)

Fig. 1: (a) Distribution of magnetic field(B) and geometry of the 735 kV overhead line, (280 A) [15], (b) magnetic field profile calculated by the code written for this paper.

B. Conventional Line (Base Case)

In this paper, we have considered an actual conventional 500 kV transmission line [19] shown in Fig. 2 as the base case. Phase arrangement on the line is horizontal, with four subconductors in each phase which are placed symmetrically on circumference of a circle. In this circuit, each subconductor has a diameter of 26.82 mm, and the bundle spacing is 45 cm. Each phase is located 28 meters above ground. There is a distance of 12.3 meters between adjacent phases. The surge impedance loading (SIL) for this design is 996.0 MW.

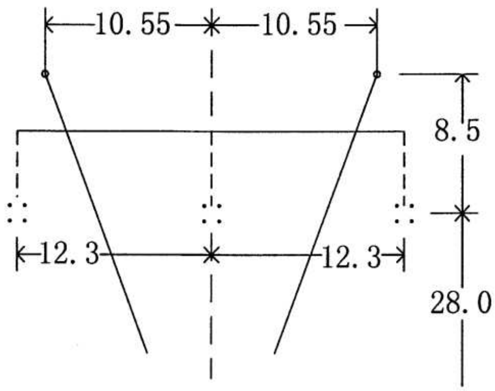


Fig. 2. Location of subconductors in the base overhead line.

C. Unconventional HSIL Line

In our previous work [14], we introduced two unconventional HSIL lines as alternatives for the traditional lines shown in Fig. 2. Shown in Figs. 3 and 4, both unconventional HSIL lines are 500 kV and have 8 sub-conductors. The diameter of the subconductors used in HSIL-1, shown in Fig. 3, is 20.93 mm. In the outer phases, the subconductor having the highest height is 32 meters, while the middle one having the lowest height of 24 meters.

To compute the magnetic field for these two unconventional HSIL lines, we must consider each subconductor separately. Because of its orientation, we cannot consider each bundle of subconductors as one equivalent conductor as done for conventional lines. That's why we must calculate the effect of 8×3=24 conductors with its image conductors.

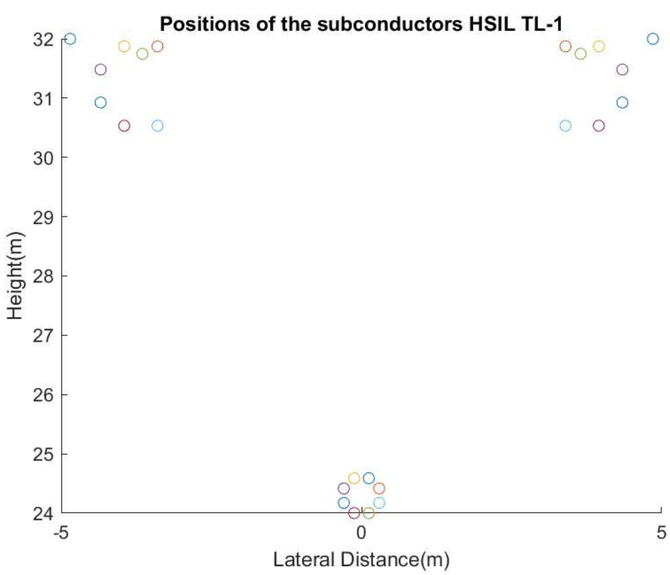


Fig. 3. Phase and bundle arrangement of the HSIL-1.

Besides the magnetic field around these unconventional lines, the electric field around them, corona loss, radio and television noises, audible noise, live line working, etc. [20-29] should also studied about these lines towards their realization.

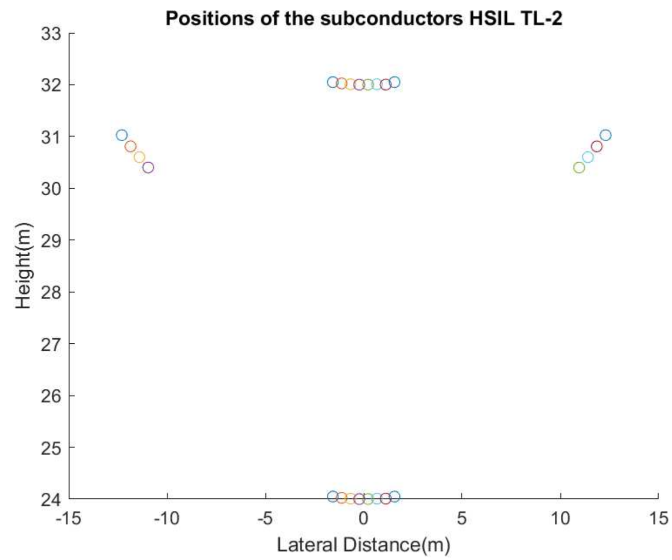


Fig. 4. Location of subconductors in HSIL-2.

III. Calculations And Results

In this paper, we have considered three transmission lines one of which is a conventional 500 kV transmission line and others are unconventional HSIL ones as alternatives introduced for the conventional line. It is assumed that all transmission lines mentioned above carry the same current to compare their magnetic field. Fig. 5 shows magnetic field for the transmission lines at ground level. As seen in Fig. 5, the newly designed HSIL(unconventional) lines possess less magnetic field than the mentioned conventional line, highlighting another merit of these lines.

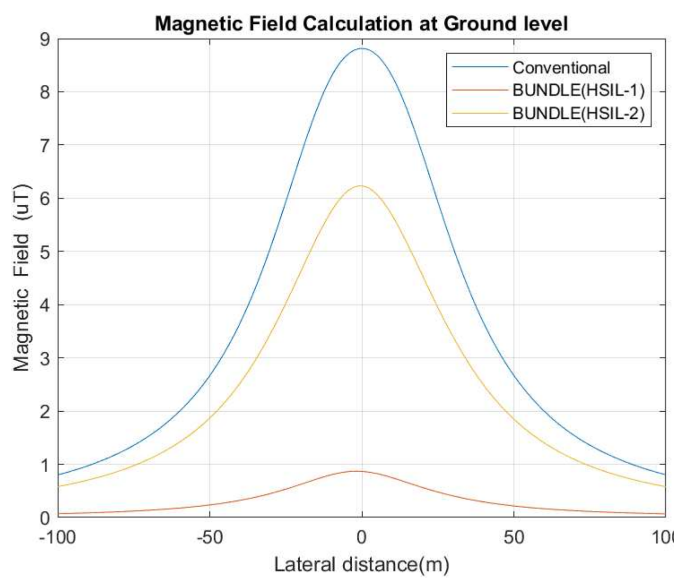


Fig. 5. Magnetic field under three transmission lines at ground level.

IV. Conclusion

In this paper first, the methods and mathematical equations for calculation of the magnetic field of transmission lines are explained in detail. The computer code written is validated by comparing results with measurements and simulations from literature and then the code is developed to able to calculate the magnetic field for two new unconventional HSIL lines designed in our previous work where the magnetic field should calculate for each subconductor instead of an equivalent conductor for each bundle in the conventional line, making computing challenging. Both unconventional HSIL lines have a lower magnetic field at the ground level than the conventional line, showing another advantage of unconventional HSIL lines.

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