A New Unusual Bundle and Phase Arrangement For Transmission Line To Achieve Higher Natural Power

Mushfiqul Abedin Khan and Mona Ghassemi
Zero Emission, Realization of Optimized Energy Systems (ZEROES) Laboratory
Department of Electrical and Computer Engineering, The University of Texas at Dallas, Richardson, TX, USA
mushfiqul.abedinkhan@utdallas.edu, mona.ghassemi@utdallas.edu

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***Abstract*—In conventional lines, subconductors are located symmetrically on an identical circle in each phase. The number of subconductors in a bundle, the radius of the bundle circle, and the radius of each subconductor, are chosen so that the maximum electric field strength on the subconductors, E_{max}, is limited to the permissible field strength on the conductor surface, E_{pr}, ($E_{max} \leq E_{pr}$), which is determined by the corona discharge limitation requirement. In this paper, we show that by shifting phase configurations and subconductors into unusual/unconventional arrangements that are geometrically optimized within the space, high power density designs can be achieved. A novel bundle and phase arrangement of a 500 kV transmission line is presented in this paper, resulting in higher natural power than conventional design.**

Keywords—High surge impedance loading (HSIL) lines, natural power, transmission lines, overhead lines.

I. Introduction

The electric power industry is constantly expanding due to the ever-growing nature of electricity demand. It is a horizontally integrated business divided into generation, transmission, and distribution sectors, where each of them operates independently. The generation and distribution sectors have gotten plenty of improvements, such as replacing large synchronous generators with much smaller and lighter ones including renewable energy for generation, introducing electronic converters for distribution, and so on. The same cannot be said for transmission lines, which are the highways for power transmission in power grids.

In a study conducted regarding achieving net-zero emission in America by 2050, high voltage transmission capacity would require an increase of ~60% by 2030 and triple by 2050. This would require a capital investment in transmission capacity of $360 billion by 2030 and $2.4 trillion by 2050 [1]. Furthermore, deregulation of the U.S. transmission network has resulted in a decreased ability to transfer power transactions in open markets. It also results in delayed investments in the transmission sector as the aim has been to see greater profits from increased utilization of the existing assets than to invest in newer ones. This is primarily due to new assets taking a long time to be commissioned and would initially provide low returns. A long lead time is also involved in obtaining the right-of-way (ROW) for new transmission lines and has several environmental and legal requirements to be met. As a result, transmission lines must be redesigned to deliver more power, which in turn reduces the number of transmission lines in a given corridor.

Due to the absence of commercial and reliable high-voltage direct current (HVDC) circuit breakers (CBs) and the high cost of converter stations, high-voltage alternating current (HVAC) transmission is often preferred. Moreover, without HVDC CBs, a point-to-point HVDC connection cannot play a role in transmission expansion planning. HVDC transmission is often considered for submarine projects, where HVDC cable is the only possible technical option for long distances. The cost of underground cables is 3-10 times the cost of overhead lines, with higher ratios for higher voltages [2]. Moreover, charging current in underground alternating current (AC) cables imposes a practical limit on the transmission length. As a result, the dominant current and future highways for power transmission continue to be 3-phase AC overhead transmission lines. Moreover, the role of transmission networks is becoming more and more important due to the trend towards 100% renewables as mentioned above, and the focus on large-scale renewables, such as wind farms and solar power plants. Since such massive renewable resources are often far from load centers, thus, they need transmission networks to transmit their power. A problem here is, however, the high cost of constructing new transmission lines. Currently, in 2023, building a new single 500 kV transmission line in different States of the U.S. would cost from $3.9M per mile to $4.8M per mile [3]. Addressing these problems would require designs that would bring about an increase in transmission power density within a given corridor.

Studies show that increasing the number of subconductors or bundle radius can increase surge impedance loading (SIL) or natural power of the line. Here subconductors in each phase are placed symmetrically on a circle; we call these arrangements conventional HSIL lines. This is what has been realized, for example, in the breakthrough overhead line design (BOLD) patented and built by American Electric Power (AEP) which has received numerous awards, including two prestigious Edison Awards [4-6]. In this paper, we show that by shifting phase configurations and subconductors into unconventional arrangements that are geometrically optimized within the space, more natural power than conventional HSIL lines can be achieved. We call these new lines unconventional HSIL lines.

II. Background, Base Case, and the Method

A. Background

The SIL of a transmission line depends on its characteristic or surge impedance, Z_c and its phase voltage, V_φ. An increase in

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the number of subconductors, subconductor radius, and bundle radius can each result in the increase of SIL, also known as its natural power, P_n. Indeed, reducing the geometric mean distance (GMD) and/or increasing the geometric mean radius (GMR) of a line can lead to an increase in its P_n. Towers in conventional lines consist of a grounded steel section between phases, resulting in an increased tower width. Those grounded steel portions between phases can be eliminated resulting in a compact design with lower rights-of-way (ROW), and thereby, a lower GMD, also causing an increase in P_n.

B. Base Case

The conventional actual 500 kV transmission line with phase and bundle arrangement shown in Fig. 1 [7] is considered our base case in this paper. It has a flat phase arrangement, each phase having 4 subconductors placed symmetrically on a circle. The conductor used has a diameter of 26.82 mm and bundle spacing is 45 cm. The phases are at a height of 28 m. The distance between adjacent phases is 12.3 m. For this design, the resulting SIL is 996.0 MW.

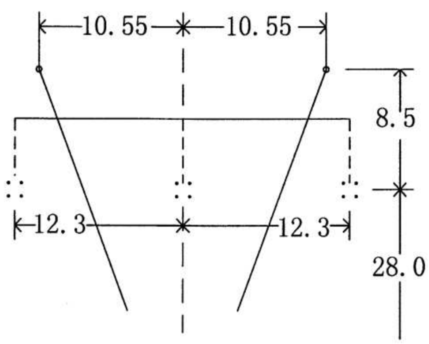

Fig. 1. Phase and bundle arrangement of the base case line.

C. The Method

We recently proposed an unconventional/unusual HSIL configuration shown in Fig. 2 consisting of 8 subconductors per phase arranged in an inverted delta phase arrangement [8]. The diameter of the conductors used is 20.93 mm. The subconductor with the maximum height from the ground is in the outer phases with a height of 32 m and the one with the minimum height is in the central phase with a height of 24 m.

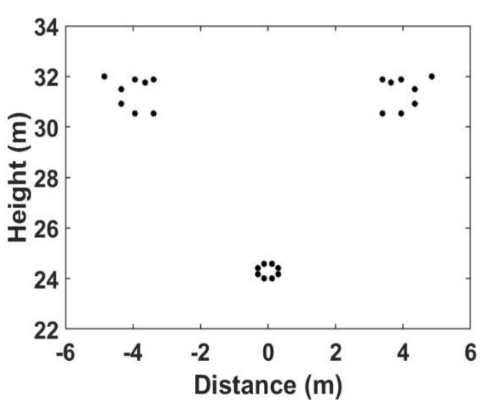

Fig. 2. The unconventional HSIL line with 8 subconductors.

Fig. 3 shows a 1.6 km, 230 kV experimental line with an unconventional HSIL design [9]. Considering such a configuration, we design our unconventional HSIL line for 500 kV and compare it with the base case shown in Fig. 1 and our other unconventional HSIL line shown in Fig. 2. As mentioned, our new design to be discussed in this paper is based on a similar structure shown in Fig. 3, where each phase is placed a horizontal arc.

Fig. 3. Structure of the 230 kV unconventional HSIL experimental line [9].

The decrease in conductor diameter when changing from the conventional design with $n = 4$ to the unconventional one having $n = 8$ allows the unconventional design not to be more expensive than the conventional one. When designing the unconventional line, the following constraints are considered.

The maximum electric field on the surface of subconductors of each phase ($i = 1, 2, 3$), E_i^{max}, has to be lower than a corona threshold value, E_{th}, as given in Eq. (1) below. In this paper, E_{th}=20 kV/cm [10].

$$E_i^{max} < E_{th}, \qquad where\ i \in \{1, 2, 3\} \tag{1}$$

As given in Eqs. (2) and (3), the distance between subconductors from different phases, D_{ij}^{ph-ph}, and the height of subconductors from the ground in each phase, H_i^{ph-gnd}, are considered to be greater than the minimum values allowed for each, $D_{min,ph-ph}$ and $H_{min,ph-gnd}$, respectively.

$$D_{ij}^{ph-ph} > D_{min,ph-ph}, \quad where\ i, j \in \{1, 2, 3\}\ and\ i \neq j \tag{2}$$

$$H_i^{ph-gnd} > H_{min,ph-gnd}, \quad where\ i \in \{1, 2, 3\} \tag{3}$$

The electric field on the surface of subconductors is calculated by replacing each subconductor having a radius of r with n_m line charges placed evenly on the surface of a hypothetical cylinder with a radius of $r/2$ and placed on the center of that subconductor. Using the described modeling, the surface potential can be found using:

$$E(P) = \sum_{i=1}^{n \times n_m} \frac{q_i}{2\pi\varepsilon_0 |\overrightarrow{r_p} - \overrightarrow{r_i}|} (\overrightarrow{r_p} - \overrightarrow{r_i}) \tag{4}$$

where $\overrightarrow{r_p}$ and $\overrightarrow{r_i}$ refer to the n_m points on circles having radii r and $r/2$, respectively, and centered on the conductor center.

A direct search algorithm is employed to find the optimized locations in space for the maximization of SIL for the unconventional HSIL line under discussion. Initially, for an assumed initial configuration, the electric field on the surface of subconductors is calculated via the method described above, and then the configuration is changed such that $E_{max} = E_{th}$ occurs, where E_{max} is the maximum of E_i^{max} for phases. Capacitance equalization is then done which helps to increase SIL further. However, this also causes an increase in E_{max}, and thus, subconductors are rearranged again to bring the maximum electric field within the threshold limit. This is repeated until the constraints are all met. Among the candidate positions found for the subconductors using this approach, the one with maximum SIL will be our optimal design. Details of this approach can be found in our previous paper [8].

III. Simulations and Results

Using the approach described above, the new, unusual line design with an initial placement of subconductors similar to that shown in Fig. 3 was obtained. Fig. 4 shows the preliminary arrangement used for this new design. It consists of 8 subconductors per phase and has the phases arranged vertically.

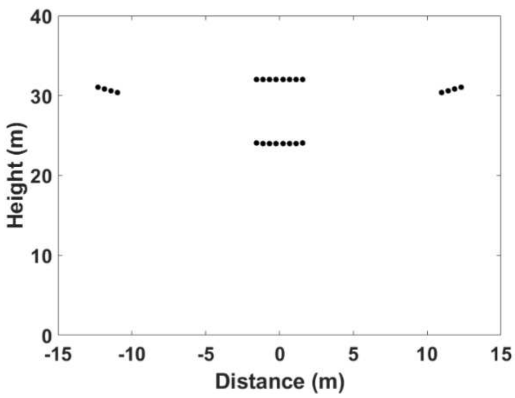

Fig. 4. Preliminary configuration for the new, unusual line.

Subconductors are initially set to have the same diameter as the conductor type, Tailorbird, used in our previous unconventional HSIL design shown in Fig. 2. The minimum height of the bottom phase is set as 24 m, and the maximum height of the top phase is set at 32 m, both in agreement with the line proposed in Fig. 2. The line width is 24.6 m, not more than the considered conventional base case, Fig. 1. The distance between subconductors from different phases meets the constraint in Eq. (2), where $D_{min,ph-ph}$=6.7 m. The minimum distance between arcs/paths where subconductors of the top and bottom phases are placed is lower than 6.7 m; however, regarding the location of subconductors as seen in Fig. 4, the distance between subconductors from adjacent/different phases is not less than 6.7 m. The bundle arrangement of the experimental line shown in Fig. 3 at 230 kV differs from this new design shown in Fig. 4 for 500 kV voltage level, where subconductors are much more evenly distributed in the former. In our new design in Fig. 4, we have subconductors closer together in sections to ensure that the second constraint, Eq. (2), is met.

The configuration shown in Fig. 4 was then simulated in COMSOL Multiphysics to find the maximum electric field on the surface of subconductors in each phase. The positions of subconductors were varied to meet Eq. (1) as well while respecting other constraints. Here using Tailorbird conductor for all subconductors would not go E_i^{max} below E_{th} for the mentioned limitations but lied very close to it. A modification was then introduced where the outermost subconductors for the top and bottom phases, and the two central subconductors for the middle phase were changed to Dove conductor. This change allows the maximum electric field to decrease further and meet the constraint in Eq. (1). However, since the other conductors are kept the same as before, the overall conductor cross section for each phase increases, thereby causing a slight increase in conductor cost. From [3], we find that for Pelican conductor, which closely resembles Tailorbird, the conductor cost per 1000 ft is \$940, whereas the cost for Dove is \$1252. A rise in installation cost is also seen from \$1353 to \$1804 per 1000 ft. However, the increase in SIL through the use of this new arrangement outweighs the increase in conductor cost, as will be shown later in this paper.

As mentioned before, COMSOL Multiphysics was used to obtain the maximum electric field on the surface of subconductors. The one finally found and described above has a maximum E value of 19.90 kV/cm thus lying within the required limit of 20 kV/cm. To calculate E precisely in COMSOL Multiphysics, an 80×80 m^2 box/square of air was considered as seen in Fig. 5 to minimize the impact of three sides while the bottom side is grounded. Each subconductor was also surrounded by a small box as seen in Fig. 6 to allow for a much more dense meshing around subconductors to ensure the accuracy of results.

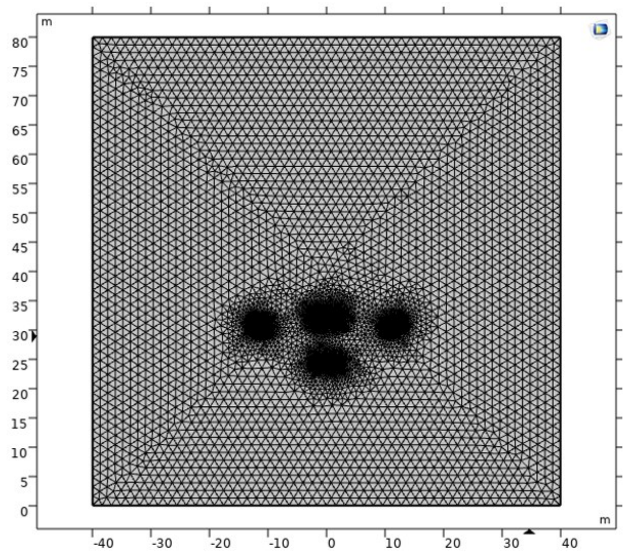

Fig. 5. A high-density meshing technique used around the subconductors.

Fig. 7 shows the situation where the maximum electric field on the surface of subconductors occurs, 19.90 kV/cm. It happens for the top phase (Phase A) and on the outermost conductors. For the central phase (Phase B), the value was found to be 19.57 kV/cm occurring on the middle conductors. For the bottom phase (Phase C), the maximum electric field occurs on the outermost conductors with a value of 19.47 kV/cm.

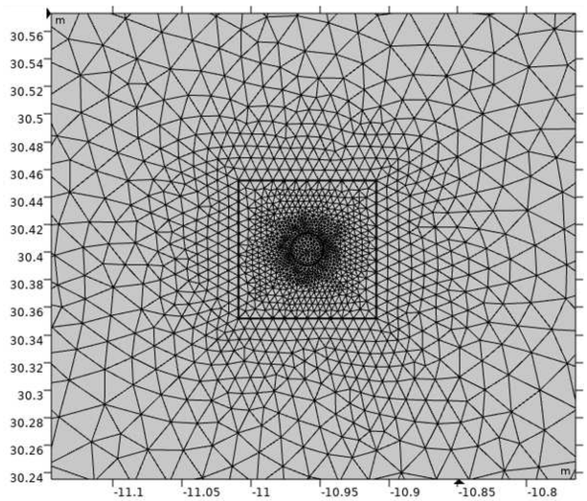

Fig. 6. A close-up of Fig. 5 showing meshing around subconductors.

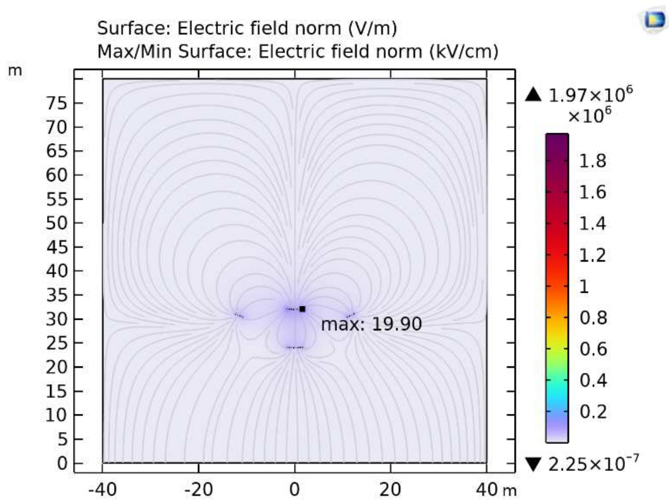

Fig. 7. Electric field distribution for the new unusual line configuration for the situation where the maximum electric field on the subconductors of the line occurs.

The SIL of this new line was then found to be 1731.3 MW which is 1.74 times the SIL of the 500 kV conventional line shown in Fig. 1. Our previously introduced unconventional line shown in Fig. 2 has a SIL of 1414.5 MW, meaning the natural power of the new unusual line designed in this paper exceeds our previously unconventional design by 1.22 times.

Further studies on unconventional HSIL lines and their combination with TEP can be found in our other papers [12-18]. Among the difficulties of designing HSIL lines, live line working may be challenging due to the interaction of maintenance personnel and those compact lines with unconventional bundle arrangements especially in freezing conditions [19-23], that has not been studied yet.

IV. Conclusion

In this paper unusual revolutionary arrangments of phase and bundle for high voltage transmission lines that can dramatically enhance power delivery were introduced. In this approach, by shifting phase configurations and subconductors into unconventional arrangements that are geometrically optimized within the space, high natural power designs of transmission lines can be achieved. The proposed design in this paper resulted in a much greater natural power, 74%, than that of the 500 kV conventional design as well as 22% more than that of our other recently proposed unconventional design.

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