Transmission Expansion Planning (TEP)-Based Unconventional High Surge Impedance Loading (HSIL) Line Design Concept

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Abstract—**This paper develops a new concept that we call *transmission expansion planning (TEP)-based unconventional high surge impedance loading (HSIL) line design*. To date, these two areas (TEP and transmission line design) have been conducted separately. For TEP, planners typically use the electrical parameters of a few standard conventional line designs to study planning scenarios, and then, the final candidate line is constructed. In such a sequence, cost-effective scenarios often do not meet the technical criteria of load flow. In this paper, we will study whether this sequence can be overturned; namely, can a transmission expansion planner get optimal line parameter values that lead to the most cost-effective scenario, and then have a transmission line with those parameters be designed? Although this cannot currently be realized through conventional designs, in this paper, we demonstrate that it is a possibility if breakthrough designs for transmission lines are used by shifting phase configurations and subconductors into unconventional HSIL arrangements, leading to the optimal line parameters determined by TEP.**

Index Terms--**Unconventional HSIL lines, transmission expansion planning (TEP), power system planning, overhead lines, power systems.**

I. Introduction

Over the last decades, the electric power industry has been restructured into horizontally integrated businesses comprised of independent generation, transmission, and distribution sectors, a restructuring that has prompted significant changes on both the supply and demand sides. On the supply side, there has been a shift from large, synchronous generators to lighter-weight generators (e.g., gas-fired turbines) and variable resources (renewables). On the demand side, there has been a growing number of distributed and variable generation resources and a shift to electronic converters and energy-saving solutions in buildings, industrial equipment, and consumer devices. However, this has not been the case for overhead lines—the highways transporting electric energy within the power systems.

Although underground cables are another way to transmit power, the cost of underground cables is three to ten times the cost of overhead lines [1], with higher ratios for higher voltages. For example, Dominion Energy estimates costs between $4 million and $10 million per mile for underground lines while overhead lines usually run between $1 million to about $2 million per mile [2]. Moreover, charging current in underground (extra) high voltage (E)HV AC cables imposes a practical limit to the transmission length.

Due to the unavailability of commercially available HVDC circuit breakers and the high cost of converters, HVAC transmission is preferred. HVDC transmission is often considered a secondary option, especially when AC transmission is not possible. For example, in underwater projects and for long distances, HVDC cable is the only possible technical scenario. As a result, the question is how to increase the transmission capability or loadability of EHV AC overhead lines.

Traditionally, the predominant limits of transferring power on an AC overhead line, in terms of its length, are thermal, voltage-drop, and transient stability limitations for short, medium, and long lines, respectively. However, when dealing with a grid/network, the line length feature mentioned above fades and is replaced by voltage limits (for example, $0.95\ p.u. \leq V_i \leq 1.05\ p.u.$ for normal conditions and $V_i \geq 0.9\ p.u.$ for single contingencies, where V_i is voltage magnitude at bus i) and the line loading limit (for example, 80% of the line's thermal limit). Today's power grids with a high number and density of lines and substations do not usually experience transient stability issues. In other words, when studying different planning scenarios, transient stability does not usually lead to a technical rejection of a scenario, but the limits mentioned above are decisive.

To date, transmission expansion planning (TEP) and line design have been considered independent processes by electric utilities worldwide. The engineering practice for power system planning is based on studying local planning cases where load flow, short circuit, and transient stability studies, under peak and light loading conditions for normal and single contingency conditions carried out by commercial software tools such as PSS®E, CYME, DIgSILENT, etc., are the usual studies to evaluate planning scenarios, and eventually, the scenarios

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meeting the technical criteria are economically compared. In this regard, planners use the per unit line parameters of a few common conventional line configurations for each voltage level for the given length of planning scenarios for the studies mentioned above, and then, the final planning scenario is constructed. In such a sequence, cost-effective scenarios often do not meet the technical criteria of the mentioned studies.

We will, for the first time, study whether the above sequence can be overturned; namely, can a transmission expansion planner get optimal line parameter values that lead to the most cost-effective/reliable/resilient scenario (or any other objective) and then have a line with those optimal parameters be designed? Although this cannot currently be realized through conventional designs, in this paper, we show that it can be realized using breakthrough line designs via shifting phase configurations and subconductors into unconventional arrangements.

In section II, a simple TEP problem is discussed where desirable line parameters are determined. Then, in section III, unconventional HSIL lines are introduced, and for the test system and the TEP problem discussed in section II, optimal locations of subconductors in space are obtained. Conclusions are presented in section IV.

II. TEP Problem

Fig. 1 shows the power flow result for the test system considered, including two 500-kV buses. Bus #1 is the slack bus and bus #2 is the load bus with a load of 390 MW with $\cos\theta$=0.85. Line 1-2 is a conventional transmission line with a length (l) of 300 km and the configuration shown in Fig. 2. Considering V_1=1.0 p.u. then V_2=0.95 p.u., as seen in Fig. 1. Thus, for $\cos\theta$=0.85 and l=300 km, 390 MW is the loadability of this conventional line given the voltage limit of $V_i \geq 0.95$ p.u. under normal conditions. In this regard, note that the phase conductor is Rail, which has an ampacity of 975 A [3]. Thus, considering 4 sub-conductors in a bundle, the thermal limit of the line is $\sqrt{3} \times 500\ kV \times (4 \times 0.975\ kA) = 3{,}777.5$ MVA while the maximum MVA power flowing through the line is only 10.5% of its capacity.

Fig. 1. The power flow result for the test system considered.

Now, consider that we want to feed a load of 538 MW with a $\cos\theta$ =0.85 load on bus 2. Using the conventional line mentioned above, either shunting capacitive compensation at bus 2, as shown in Fig. 3, or constructing two lines between buses 1 and 2 as shown in Fig. 4, can feed the load at an acceptable voltage level at bus 2, for $V_2 \geq 0.95$ p.u.

To have V_2 =0.95 p.u., a 144 MVAR shunt capacitive compensation is needed at bus 2 to reach 0.95 p.u. on bus 2. Note that 130 MVAR, shown in Fig. 3, has been obtained for 0.95 p.u. and 144 MVAR, mentioned above, is for a voltage of 1.0 p.u. Conventional shunt capacitors or static var compensators (SVC) are very expensive for high voltage levels. For example, the cost of a 350 MVAR SVC was $100 M [4]. However, this is less expensive than construction of another 300 km, 500 kV line where an additional 500 kV bay, at bus 1, is also needed compared to installing shunt capacitive compensation in bus 2.

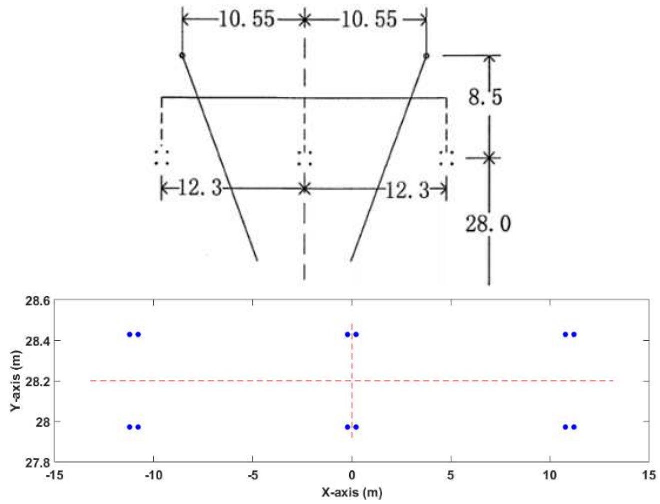

Fig. 2. The conventional line considered for the test system shown in Fig. 1.

Fig. 3. Power flow for adding a 144 MVAR shunt capacitor at bus 2 to feed 538 MW at V_2=0.95 p.u.

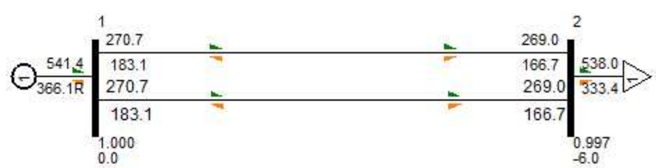

Fig. 4. Power flow for adding the second line (1-2) to feed 538 MW.

As seen in Fig. 4, installing two lines (1-2) results in feeding the load at a voltage level higher than 0.95 p.u. However, regarding the cost, mentioned in section I, for per mile of a line and considering the costs for two bays at buses 1 and 2 for this planning scenario, this scenario will be costly.

Now the interesting question is whether or not it is possible to design one line (one circuit) that can feed this load? To this end, let us first determine what the line parameters should be. In this regard, considering that line resistance (R) is usually one-tenth of its reactance, we can consider decreasing line inductance (L) and increasing line capacitance (C) to feed 538 MW with $\cos\theta$=0.85 at bus 2 under V_2=0.95 p.u. As seen in Fig. 5, this can be achieved by a 30% decrease in line inductance and an approximately 40% increase in line capacitance. Now the question is whether such a line can be designed. In section III, we show that this can be achieved through unconventional HSIL lines.

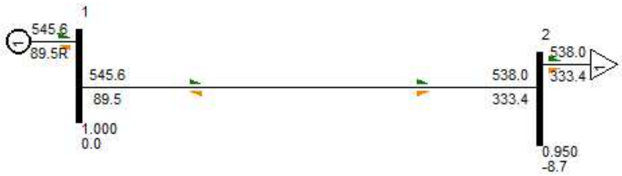

Fig. 5. Power flow for 538 MW with cos θ=0.85 at V_2=0.95 p.u. through a line with optimized parameters.

A comparison of Fig. 5 with Fig. 3 shows another merit of unconventional HSIL lines. While the voltage magnitude of buses and load in both cases are the same, the unconventional HSIL line scenario injects 55.6 MVAR more reactive power to bus 1, which can be used for solving the voltage-drop issue for the remaining grid modeled as the slack bus at bus 1.

III. Unconventional HSIL Lines

A review of HSIL lines identifying technical gaps and future research needs was presented in [5]. Experience with HSIL lines in Brazil has also recently been reported in [6]. Conventional HSIL lines, where subconductors are located symmetrically on a circle for all phases, were also recently studied in [7]. In a step forward, we introduced unconventional HSIL designs, where subconductors can be placed anywhere in space. Then, in [5, 8, 9], we developed a heuristic method to find phase arrangements and subconductors in space to maximize SIL. Moreover, it was shown in [10, 11] that there is no concern or issue about switching overvoltages for the proposed unconventional HSIL lines compared to a conventional line. In this paper, we want to introduce the feasibility of designing these new lines according to power system planning requirements.

The design of an unconventional HSIL line that would result in the line parameters (L and C) determined by the TEP problem can be formulated as

$$\text{Reach } L \text{ and } C \tag{1}$$

1. $E_i^{max} < E_{pr} \qquad i \in \{1,2,3\},$
2. $D_{ij}^{p2p} > D^{p2p,min} \qquad i,j \in \{1,2,3\}, \text{ and } i \neq j,$
3. $D_{ij}^{c2c} < D_j^{spacer} \qquad \begin{cases} i \in \{1,2,3\} \\ j \in \{1,\dots,N_{spacer}\} \end{cases},$
4. $D_i^{p2g} > D^{p2g,min} \qquad i \in \{1,2,3\},$
5. $\textit{Symmetry of configuration must be maintained.}$

The first constraint states that the maximum electric field on the surface of the subconductors cannot exceed a permissible value, E_{pr}, which is determined by the corona onset gradient. The second constraint indicates that the distance between sub-conductors in a phase and those of its adjacent phase must be greater than a minimum value, $D^{p2p,min}$. The third constraint demonstrates that in each phase, at least a couple of sub-conductors must meet the bi-conductor spacer length requirement. The fourth constraint indicates that the minimum height of subconductors from the ground must be above the minimum permissible height. The final constraint ensures symmetrical mechanical loading on the tower. More details about the algorithm can be found in [5, 8, 9].

To find an optimal solution for (1), at first, the configuration becomes compact to the degree that the maximum electric field intensity reaches its upper limit, E_{pr}. Then, the capacitance of phases is equalized so that the maximum surface electric field of the phases is equalized. This allows us to increase SIL in its trade-off with the maximum electric field intensity. The details of capacitance equalization are explained in [5]. Then, the compactness of the line is changed again to meet the surface electric field constraint. Finally, the optimal position of each subconductor is determined among its corresponding candidate positions. If all the constraints are satisfied and the SIL amount is improved, the position of the subconductor is changed to the candidate position. Note the objective function in (1) is in line with increasing SIL, which leads to HSIL lines. The whole process is described in the algorithm below.

Algorithm: Maximization of SIL

procedure Optimal conductor arrangement
Reduce $\boldsymbol{D^{p2p}}$ until reaching $\boldsymbol{E_{pr}}$
Equalize the phase capacitances
Modify $\boldsymbol{D^{p2p}}$ to satisfy $\boldsymbol{E_{pr}}$ constraint
for $\boldsymbol{1 \le j \le N_I}$ **do**
for $\boldsymbol{1 \le k \le N_{CAND}}$ **do**
Move *j*-th sub-conductor to *k*-th candidate position
Move the dependent sub-conductors to new positions
if *no constraint violation* **then**
if $SIL_{New} > SIL_{Optimal}$ **then**
$SIL_{Optimal} = SIL_{New}$
Update the subconductors arrangement
end if
end if
end for
end for
end procedure

To obtain an accurate estimation of surface electric field intensity on the subconductors, instead of using only a single line charge to model a conductor, n_m line charges are employed to set the electric potentials of n_m points at the periphery of the conductor equal to the applied voltage. The accuracy of electric field estimation is increased using this approach. The n_m line charges are uniformly distributed around a hypothetical cylinder with a radius of $r/2$, where r is the conductor radius, as shown in Fig. 6. The results obtained were validated by COMSOL Multiphysics. Then, the electric field at each point (P) on the conductor surface can be calculated by:

$$E(P) = \sum_{i=1}^{n \times n_m} \frac{q_i}{2\pi\varepsilon_0 |\vec{r}_P - \vec{r}_i|^2} (\vec{r}_P - \vec{r}_i) \tag{2}$$

where P is the point at which the electric field intensity is estimated. Vectors $\vec{r}_P$ and $\vec{r}_i$ denote the distance from the origin to P and the line charge i (q_i), respectively.

To be cost-effective, we choose Catbird, with an ampacity of 970 A, which has an aluminum cross-section a little less than

Rail for the unconventional HSIL line. Fig. 7a shows the phase arrangement and sub-conductor geometry obtained by solving Eq. (1).

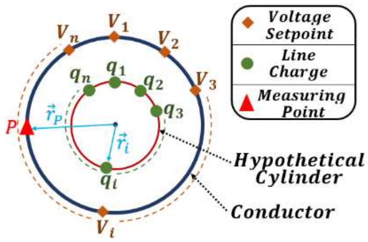

Fig. 6. The method used to obtain the surface electric field on subconductors.

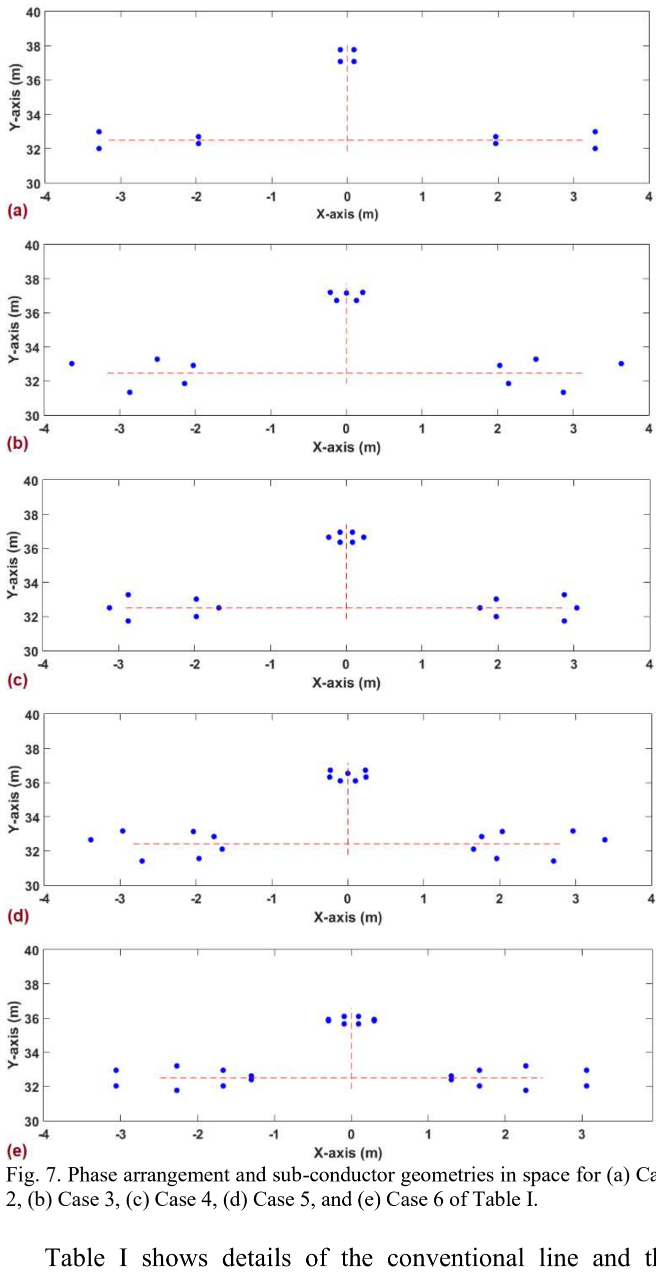

Fig. 7. Phase arrangement and sub-conductor geometries in space for (a) Case 2, (b) Case 3, (c) Case 4, (d) Case 5, and (e) Case 6 of Table I.

Table I shows details of the conventional line and the unconventional HSIL lines proposed above. Moreover, the results for larger demands are presented in Table I, where for all cases, $\cos\theta$=0.85 and l=300 km. Figs. 7a-7e show the line geometries for cases 2-6 presented in Table I. Note that in all unconventional HSIL lines, the total aluminum cross-section is less than the conventional line, meaning that all unconventional HSIL lines are less expensive than the conventional line. Fig. 8 shows the power flow result for case 6.

TABLE I. RESULTS FOR UNCONVENTIONAL HSIL LINES, $\cos\theta$=0.85, l=300 KM, AND V_1=1.0 p.u., V_2=0.95 p.u.

Case*	Subconductor type	L ($\mu H/m$)	C (pF/m)	R (Ω/km)	P_{load} (MW)
1	Rail, ∅ = 1.165 in	0.848	13.41	0.0191	390
2	Catbird ∅ = 1.140 in	0.596	19.04	0.0192	538
3	Stilt, ∅ = 1.036 in	0.533	21.26	0.0193	595
4	Eagle, ∅ = 0.953 in	0.515	21.91	0.0203	605
5	Hawk, ∅ = 0.858 in	0.471	23.96	0.0205	655
6	Tailorbird, ∅ = 0.824	0.455	24.77	0.0182	685

*Case 1: Conventional line, Fig. 2
Case 2: Unconventional HSIL line, 4 sub-conductors, Fig. 7a
Case 3: Unconventional HSIL line, 5 sub-conductors, Fig. 7b
Case 4: Unconventional HSIL line, 6 sub-conductors, Fig. 7c
Case 5: Unconventional HSIL line, 7 sub-conductors, Fig. 7d
Case 6: Unconventional HSIL line, 8 sub-conductors, Fig. 7e

Fig. 8. The power flow result for case 6.

Seen from Table I, 1) it is possible to design an unconventional HSIL line for any planned demand, 2) using unconventional HSIL lines, line loadability can be enhanced by approximately 76% (comparing case 6 with case 1), which is a remarkable improvement in transmission line loadability.

Fig. 9 shows the line loadability for the test system for l= 600 km where, due to more line charging, the line loadability for V_1=1.0 p.u. and V_2=0.95 p.u. increases. As seen in Fig. 9, the line loadability for the conventional line (461.5 MW) increases to 816 MW for case 6 (an increase of 77%).

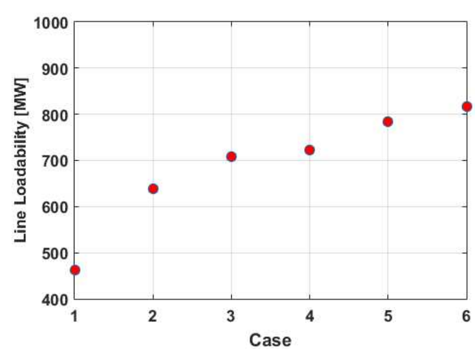

Fig. 9. Line loadability for the test system for l=600 km.

The question that is often raised about unconventional HSIL lines is that although these lines can be beneficial in peak load, much more shunt reactive compensation is needed under light load conditions. The answer to this question is that the TEP-based unconventional HSIL line design concept introduced in this article will address this issue. As mentioned before, for a TEP problem, different planning scenarios are studied. The usual studies include power flow, short circuit calculations, and transient stability. The studies are done under different load conditions including peak and light load conditions. Also, the studies are carried out under normal conditions and single contingencies.

Now, imagine that line parameters can be used as a variable (rather than a predetermined value) in a TEP case. It is clear that this will bring significant possibilities and flexibility to the TEP problem. It should be noted that the final scenario that was obtained using optimal line parameters for a TEP problem passed all mentioned studies under all mentioned conditions, including light load conditions. Today's transmission networks include several voltage levels and using unconventional HSIL lines with more generated reactive power may lead to a planning scenario with lower voltage levels compared to using conventional line design. In other words, one may solve a TEP problem by using unconventional HSIL lines of 230 kV instead of conventional lines of 500 kV, which results in remarkable savings. This topic has not been presented to date; thus, we are, for the first time, introducing this concept and idea. Further studies on unconventional HSIL lines and their combination with TEP can be found in our other papers [12-19]. 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 [20-24], that has not been studied yet.

IV. Conclusion

In this paper, the transmission expansion planning (TEP)-based unconventional high surge impedance loading (HSIL) line design concept is introduced. In this concept, line parameters are assumed as variables in the TEP problem. The optimal line parameters leading to the best planning scenario are determined where the best option can be the lowest cost, most resilient, or some other priority. We then showed that the optimal line parameters could be realized through breakthrough line design, which we call unconventional HSIL design. The simple test system and TEP problem considered in this paper showed the potential of this concept to lead to the best planning scenarios, which cannot be achieved by conventional lines.

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