Performance Analysis and Improvement of Double Circuit EHV AC Transmission Lines by Increasing Surge Impedance Loading Level

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Keywords: SIL (Surge Impedance Loading), Bundle Spacing, EHV (Extra High Voltage) AC Transmission, Expanded Hexa, Delta Configuration, Hexagon Configuration.

Abstract: The demand of Electrical Energy is continuously increasing due to the growth of society and industrialization and to fulfil this requirement, increase in power generation and its transmission at high efficiency is required. Extra high voltages are necessary to transfer large amount of power over linger distances as the power transfer limit is proportional to the square of rated voltage. Generally the power generating stations are far away from the distribution network and to connect the power surplus region to power deficit region we need long EHV AC double circuit transmission lines to carry large amount of power. But the long EHV AC transmission lines are limited by their SIL (Surge Impedance Loading) limit which is much below the thermal limit of conductor due to large inductive reactance of the line. SIL depends on various factors and geometrical arrangement of double circuit transmission lines i.e. bundle spacing, size of conductor, number of sub-conductors per phase, etc. This paper presents various methodologies to improve SIL level of EHV AC lines and also its effect on corona loss. MATLAB is used as platform for development of GUI based software to calculate and analyze the various parameters related to SIL and corona loss. The various double circuit configurations used for EHV AC transmission lines and its comparison is also presented.

1 INTRODUCTION

Extra high voltages are necessary for transfer of large amount power over longer distances. To transfer more power, higher transmission voltage is necessary. Power transfer limit is proportional to the square of rated voltage. For the same power transfer, the line losses reduce with higher rated voltage due to reduction in current. With higher Transmission Voltage, conductor size requirement is reduced. Therefore conductor cost will reduce. To transfer large amount of power from power surplus region or state to power deficit states or region requires long EHV AC transmission lines. However long EHV AC transmission lines are limited by SIL (Surge Impedance Loading) / Stability limits due to large inductance of the lines(Nayak, Sehgal, et al. , 2022), (Daconti and Daniel, 2023).

2 SURGE IMPEDANCE LOADING (SIL) AND CORONA LOSS

SIL is the MW loading of the line where natural reactive power balance occurs i.e. reactive power produced by a line is equal to reactive power consumed by a line. If we load the line above SIL the line would consume reactive power and limits the power transfer capacity to maintain stability of the system.

The surge impedance loading concept is suitable for EHV AC lines to decide the MW loading and corresponding voltage variation along the line length. To increase SIL level, line inductance is to be reduced and /or capacitance is to be increased. (Hao and Xu, 2022), (Kishore, Singal, et al. , 2021), (Siva, Rani, et al. , 2020)

Corona is formed due to ionisation of air surrounding the conductors. The formation of corona is always accompanied by Energy loss which is

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dissipated in the form of light, heat, sound and chemical action. When corona occurs, it produces loss of power. For calculation of SIL,

SIL = $\frac{kV^2}{Zs}$, where Zs is surge impedance and is given by

Zs = $\sqrt{\frac{L}{C}}$ and inductance L is given by

L = Ls–Lm

Ls = self-inductance of line=2* 10^{-7} $ln\frac{1}{GMReq}$ H/m

Lm = mutual inductance of the line=2* 10^{-7} $ln\frac{1}{GMDeq}$ H/m

Where GMD is geometric mean distance between conductors and GMR is the geometric mean radius of conductor.

For calculation of corona, the foul weather condition is selected which is worst. So the formula used to calculate corona is Project EHV, USA by Anderson, Baretsky and McCarthy Formula.

Pc = Pfw + 0.3606 k. V. r^2.ln (1+10ρ).$\sum_1^{3N} E^5$

Where,

Pc = Foul weather corona loss

Pfw = total fair weather corona loss = 1 to 5 kw/km for 500 kV and 3 to 20kw/km for 700kV,

for calculation of 400kV line Pfw is taken as 5 kw/km.

K = 7.04 * 10^{-10} for 400kV (based on Rheinau results)

V = conductor voltage in kV, l-l r.m.s

E = surface voltage gradient on the underside of the conductor, kV/cm, peak

ρ = rain rate in mm/hr, taken as 5mm/hr

r = radius of conductor in cm

N = no. of sub conductors in bundle of each phase

Voltage gradient is calculated using standard mangoldt's formula.

3 METHODOLOGIES TO INCREASE SURGE IMPEDANCE LOADING LEVEL CONSIDERING CORONA LOSS

For long transmission lines the power transfer capacity is limited by its SIL level only which is much below its thermal capacity due to large inductance. Also Decrease in line inductance and surge impedance shall increase the SIL and transmission capacity.

The surge impedance loading (SIL) depends on many factors such as (a) phase spacing (b) Bundle spacing (c) size of conductor (d) number of sub-conductors per phase and (e) conductor configurations. In this research paper, for a particular data of 400kV double circuit transmission line configurations, the effect of Bundle spacing, size of conductor, Number of sub-conductors per phase, Horizontal and vertical spacing on SIL level and corona loss is presented and hence to improve the power transmission capacity.

MATLAB is used as platform for development of GUI based software to calculate and analyze the various parameters related to SIL and corona loss. The various double circuit configurations used for EHV AC transmission lines and its comparison is also presented.

The above methods have been analyzed and discussed for 400kV Double circuit transmission line and there result tables and graphs showing its effect on SIL and Corona loss has been presented. The parameters used to obtain the results have been shown in the graph itself. (Sakhavati, Yaltagiani, et al. , 2020), (Begamudre, 2020), (Saadat, 2020), (Dritsas, Alexiou, et al. , 2022), (Gupta, Saha, et al. , 2021)

3.1 Bundle Spacing (B)

Bundle spacing is the spacing between sub-conductors, as the B increases Bundle radius R increases and GMReq of bundled conductor increases, which leads to reduction in self-inductance of the line and we can have reduction in line inductance and increase in SIL level as the B increases. However the corona loss would slightly increase with increase in bundle spacing but comparative to that there is large increment in SIL level is obtained. The Table 1 and Figure 1 show the effect of change in bundle spacing on SIL and corona loss.

Table 1: Bundle Spacing (B) in cm v/s SIL and Corona

B (cm)	L(mH/km)	C(nF/km)	SIL (MW)	Pc(kw/3phase km)
35	0.389	29.05	1382.65	11.55
40	0.379	29.84	1419.48	11.76
45	0.37	30.56	1453.63	12.04
50	0.362	31.24	1485.0	12.37
55	0.355	31.88	1515.77	13.13
60	0.349	32.48	1544.39	13.55

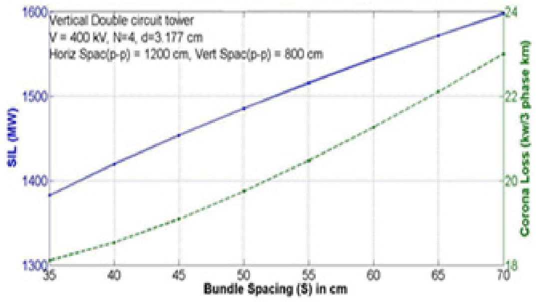

Figure 1: Bundle Spacing (B) v/s SIL and Corona

3.2 Size of Conductor (d)

The diameter of the conductor is the size of conductor, with the increase in diameter of conductor the GMReq of the conductor increases and self-inductance of the line reduces, hence there is reduction in inductance of the line and there is increase in SIL level. There would also be more reduction in the corona loss is obtained with increase in diameter of conductor. The Table 2 and Figure 2 show the effect of change in diameter of conductor on SIL and corona loss.

Table 2: Diameter of Conductor (d) in cm v/s SIL and Corona

d (cm)	L (mH/km)	C (nF/km)	SIL (MW)	Pc(kw/3phase km)
2	0.381	29.62	1409.2	11.55
2.5	0.376	30.06	1430.2	11.76
3	0.371	30.44	1447.9	12.04
3.5	0.367	30.76	1463.2	12.37
4	0.364	31.05	1476.8	13.13
4.5	0.361	31.31	1488.9	13.55

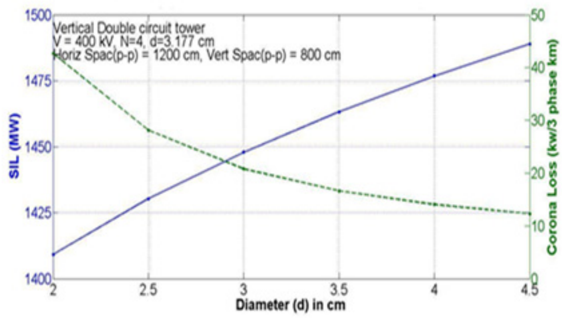

Figure 2: Diameter of conductor (d) v/s SIL and Corona

3.2.1 No. of Sub-conductors per phase (Bundle) (N)

The No. of sub-conductors in a bundle increases there would be rise in the GMReq of the conductor which would reduce self-inductance of the line, and reduction in inductance of the line, therefore there will be increment in SIL level. There is a large increment in SIL level is obtained and current carrying capacity also increases. Also corona loss would reduce drastically with increase in N. However increase in N the loading on existing transmission tower increases so to reduce the weight we can shift from twin ASCR moose conductor to quad ACSR zebra conductor having reduced diameter and weight, but still the overall weight on tower increases, so it is possible only when from the tower is designed to carry increases weight so that we can fulfil the requirement of future increase in power demand. The following Table 3,4 and Figure 3 shows the effect of change in No. of sub conductors per phase on SIL.

Table 3: N v/s SIL and Corona

N	L (mH/km)	C (nF/km)	SIL (MW)	Pc (kw/ 3phase km)
2	0.469	24.38	1153.9	55.49
4	0.37	30.56	1453.63	12.04
6	0.319	35.32	1683.33	7.16
8	0.285	39.52	1885.39	5.95

Table 4: N v/s SIL and Corona (including weight and cost)

N	ACSR Conductor diameter (cm)	Weight (kg/ km)	Approx. Cost of cond. (Rs./ m)	SIL (MW)	Difference in MW	Pc (kw/ 3phase km)
2	Moose 3.177	2004	300	1153.9	0	55.49
4	Zebra 2.862	1621	260	1443.4	289.5	13.71

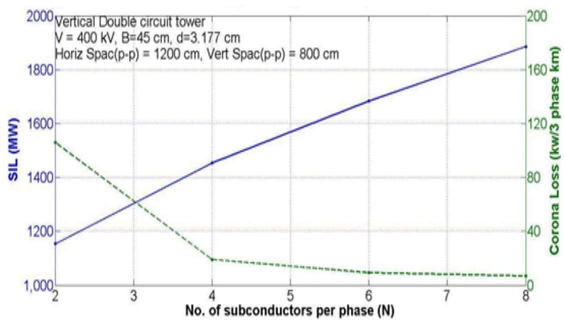

Figure 3: No. of Sub-conductors per phase (N) v/s SIL and Corona

3.2.2 Horizontal Spacing

The phase to phase spacing is a factor of GMD (Geometric Mean Distance), i.e. if the spacing between conductors is reduced GMD will decrease and there will be increase in mutual inductance of the line which leads to reduction in line inductance and increase in SIL level. However there is limit on the spacing between conductors due to sag of the conductors. This is due to the fact that more the sag more is the swing of the conductor and there are chances of p-p faults, but if we use V string insulators or conductor is replaced with HTLS (high temperature low sag conductors) eg. ACSS (Aluminium Conductor Steel Supported) either both the swinging of conductor is reduced and the spacing of conductors can be reduced. The Table 5 and Figure 4 show the effect of change in spacing between the bundles on SIL.

Table 5: P-P Spacing v/s SIL and Corona

P-P spacing (m)	L (mH/km)	C (nF/km)	SIL (MW)	Pc (kw/3phase km)
10	0.366	30.90	1469.80	12.63
11	0.368	30.72	1461.32	12.31
12	0.37	30.56	1453.63	12.04
13	0.372	30.41	1446.69	11.83
14	0.374	30.28	1440.43	11.66
15	0.375	30.16	1434.81	11.51

3.2.3 Vertical Spacing

The reduction in vertical spacing reduces GMD which leads to increases in the SIL level. But we cannot reduce this spacing much because we have to see the spacing of conductor from tower as well as the below crossarm. However we can reduce this spacing till the voltage gradient and corona loss is within limit. The Table 6 and Figure 5 show the effect of change in vertical spacing between the phases on SIL.

Table 6: Vertical Spacing v/s SIL and Corona

Vertical spacing (m)	L(mH/km)	C (nF/km)	SIL (MW)	Pc (kw/3phase km)
7	0.36	31.46	1496.14	13.06
7.5	0.365	30.99	1473.83	12.51
8	0.37	30.56	1453.63	12.04
8.5	0.375	30.17	1435.19	11.65
9	0.379	29.81	1418.23	11.30
9.5	0.384	29.48	1402.53	11.01

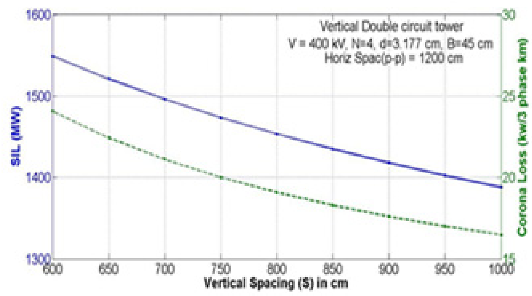

Figure 5: Vertical Spacing v/s SIL and Corona

4 DOUBLE CIRCUIT CONFIGURATIONS

The arrangement of conductors also affects the SIL. The transmission line inductance can be reduced by proper geometrical configuration of conductors. For a 400kV Double circuit tower the configurations are as shown in figure 6, 7, 8 and 9.

4.1 Vertical tower

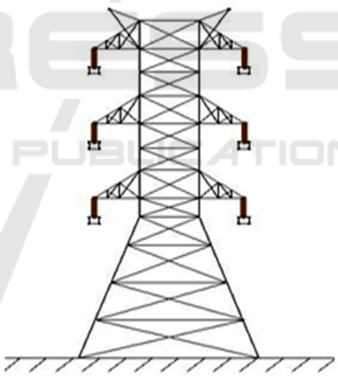

Figure 6: Vertical tower

4.2 Delta tower

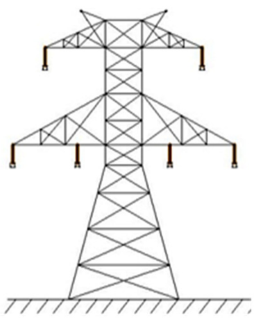

Figure 7: Delta tower

4.3 Inverted V tower

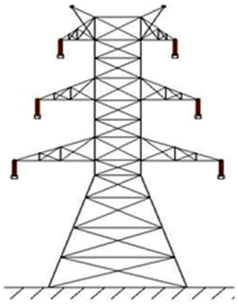

Figure 8: Inverted V tower

4.4 Hexagon tower

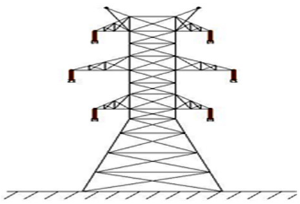

Figure 9: Hexagon tower

5 COMPARISON OF DOUBLE CIRUCIT CONFIGURATIONS

Comparing Horizontal, Delta and L configuration Towers in terms of SIL level for a specific given data

V = 400kV, N = 4, B = 45 cm, d = 3.177 cm (moose conductor)

- For vertical configuration S = 1200 cm (horizontal p-p spacing), S = 800 cm (Vertical p-p spacing)
- For delta configuration Dhb = Dhy1 = 600 cm, Dhy = Dhr1 = 1400 cm, Dhr = Dhb1 = 1000 cm, Dvry = Dvbr = Dvy1b1 = Dvr1b1 = 692.82 cm, Dvyb = Dvr1y1 = 0 cm, Dry = Dyb = Dbr = Dr1y1 = Dy1b1 = Db1r1 = 800 cm
- For Inverted V Configuration Dhr = Dhb1 = 600cm, Dhb = Dhr1 = 800 cm, Dhy = Dhy1 = 700 cm, Dvry = Dvyb = Dvr1y1 = Dvy1b1 = 800 cm, Dvbr = Dvr1b1 = 1600 cm
- For Hexagon configuration Dhr = Dhb1 = Dhb = Dhr1 = 600cm, Dhy = Dhy1 = 800 cm, Dvry = Dvyb = Dvr1y1 = Dvy1b1 = 800 cm, Dvbr = Dvr1b1 = 1600 cm

Where, Dhr = Horizontal distance of R phase from centre of tower, Dvry = Vertical distance between R and Y phase.

Table 7: Comparison of various Double circuit line configurations

Double Circuit Configurations	L(mH/km)	C(nF/km)	Fair corona loss (kw/3phase km)	SIL (MW)
Vertical	0.37	30.56	0.65	1453.6
Delta	0.365	31.04	0.65	1476.2
Inverted V	0.374	30.25	0.64	1439.0
Hexagon	0.369	30.63	0.64	1456.9

5.1 Advantages of using Delta configuration and Hexagon Configuration over Vertical

- There is an increase of approx. 23 MW in SIL for delta compared to Vertical.
- The advantage of using Delta configuration is reduction in no. of cross arm requirement. Also height of the tower can be reduced using Delta tower compared to vertical.
- There is no need for transposition of lines as the spacing between the lines is symmetrical, hence the voltage drop would be equal among the lines.
- There is an increase of approx. 3.3 MW in SIL for Hexagon compared to Vertical.

6 CONCLUSIONS

The power transmission capacity of long EHV AC lines is limited by SIL/Stability limits due to the presence of large inductance of the line. So by reducing the inductance and hence inductive reactance and surge impedance, the power transfer capacity can be enhanced. The decrease in inductance and surge impedance would increase SIL level. The Various techniques to increase SIL level close to thermal limit can be done by

- Reduction in spacing between conductors (p-p),
- Increase in bundle spacing
- Increase in diameter of conductor
- Increase in no. of sub-conductors per phase

The comparison for EHV AC 400 kV double circuit tower configurations have been done. The double circuit configurations considered for comparisons are Vertical, Hexagon, Inverted V, and delta tower configuration. The delta and Hexagon Configuration shows increment in SIL compared to vertical tower, as well as it is possible to reduce height of tower. Hence it is possible to enhance the power transfer capability by above different techniques.

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