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Power Transmission Capacity Enhancement of EHV AC Double Circuit Transmission lines by Increasing Surge Impedance Loading Level Considering Corona Loss Effect

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ABSTRACT

Increase in the power demand requires the development of EHV AC double circuit and high power carrying capacity lines. 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, diameter of conductor, no. of sub-conductors per phase, etc. In this paper an attempt is made to present various techniques implemented on EHV AC double circuit transmission lines to improve SIL level and also its effect on corona loss is shown with the help of mathematical programming in Matlab software. In this paper various double circuit configuration and its comparison is also presented.

Key words: *SIL (Surge Impedance Loading), Bundle Spacing, Expanded Hexa, Delta Configuration, Hexagon Configuration*

INTRODUCTION

It is economical to transmit large amount of power over longer distances by using EHV lines (above 300kV). An increase in line voltage increases the transmission efficiency. To transfer more power, higher transmission voltage is necessary as the power transfer limit is proportional to the square of rated voltage [3, 4]. For the same power transfer, the line losses reduce with higher transmission voltage due to reduction in current. Transmission voltages between 300kV and 765kV are termed as extra high voltages (EHV).

Also according to load-generation balance report of India [1] and annual report of SLDC Gujarat [2], it seems that the power generation and load demand in India is not uniform in various regions. Some regions are in power surplus state whereas some regions are in power deficit state. So to connect the power surplus regions and power deficit regions, long EHV AC transmission lines are needed. However long EHV AC transmission lines are limited by SIL (Surge Impedance Loading) / Stability limits due to large inductance of the lines. For a long EHV AC line the power capacity of transmission is limited by Surge Impedance Loading due to the presence of large inductance of line. Decrease in inductance and surge impedance increases SIL (Surge Impedance Loading) level [5, 6, 7].

SIL AND CORONA DEFINITION

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 consumes reactive power and limits the power transfer capacity to maintain stability of the system [11]. Corona is ionisation of insulating material at the surface of conductor is called corona or the complete disruption of dielectric strength of insulating materials at the surface of power conductor is treated as corona in transmission line.
For calculation of SIL,

$$SIL = \frac{kV^2}{Zc}$$

Where Zc is surge impedance and is given by

$Zc = \sqrt{\frac{L}{C}}$ 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.

The corona is formed due to ionization of air surrounding the conductors. The phenomenon of corona is accompanied by a hissing sound, production of ozone gas, power loss and radio interference. Bundled conductors are the best solution for reducing the corona loss in transmission of power over the high voltage lines.

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 [3].

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

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].

TECHNIQUES TO INCREASE SIL LEVEL CONSIDERING CORONA

Following methods are discussed for 400kV Double circuit transmission line and the result tables and graphs showing its effect on SIL and Foul Weather Corona loss are presented. The parameters used to obtain the results are shown in the graph itself.

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 increases slightly with increase in bundle spacing but comparative to that there is a large increment in SIL level 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

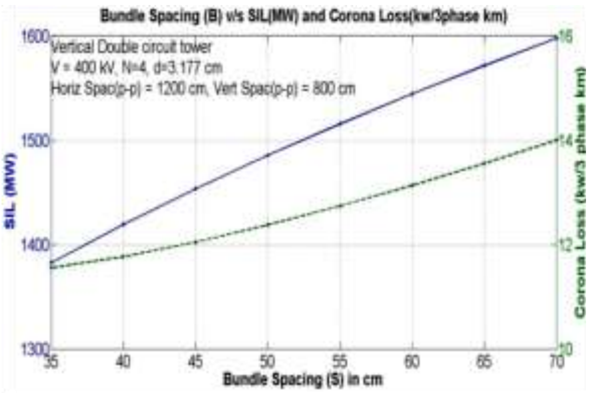

Fig.1 Bundle Spacing (B) v/s SIL and Corona

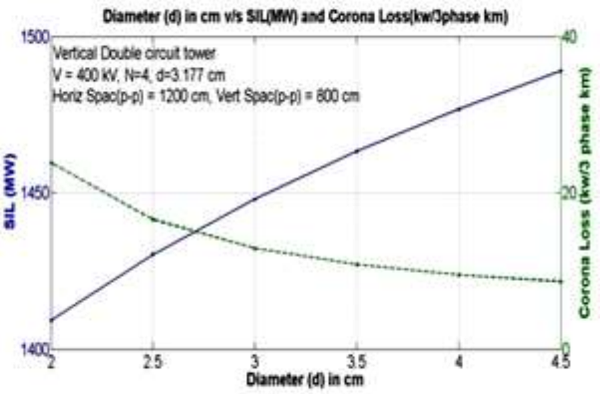

Fig.2 Diameter of conductor (d) v/s SIL and Corona

Diameter 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 [6, 7]. Additionally, 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.

Number of Sub-conductors per phase (N)

If the No. of sub-conductors in a bundle increases, there is a rise in the GMReq of the conductor which reduces self-inductance of the line. This reduces the inductance of the line leading to increment in SIL level. There is a large increment in SIL level obtained and the current carrying capacity also increases. Also corona loss would reduce drastically with increase in N. However on increasing 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. Still the overall weight on tower increases. Thus it is possible only when the tower is designed to carry increased weight so that we can fulfill 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-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

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

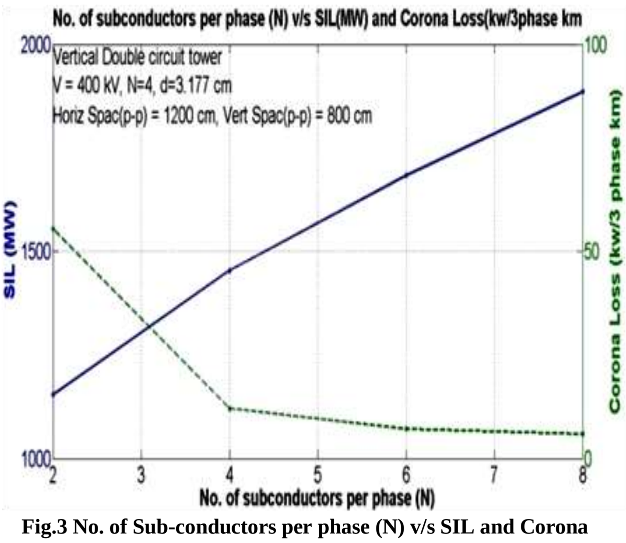

Fig.3 No. of Sub-conductors per phase (N) v/s SIL and Corona

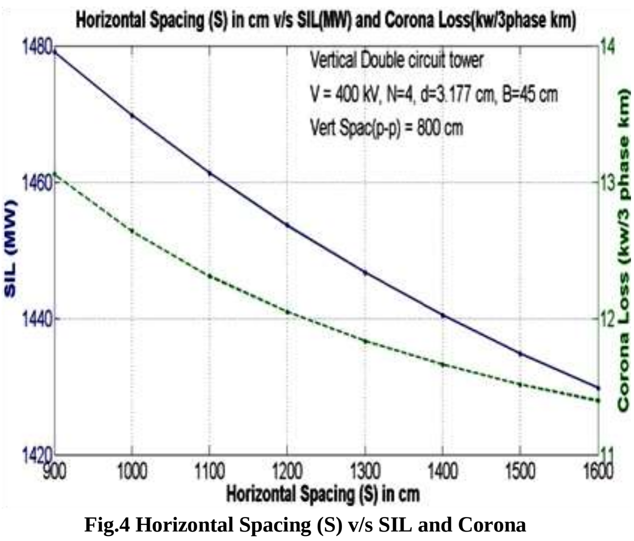

Fig.4 Horizontal Spacing (S) v/s SIL and Corona

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. If we use V string insulators or conductor is replaced with HTLS (high temperature low sag conductors) e.g. ACSS (Aluminium Conductor Steel Supported), 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.

Vertical Spacing

The reduction in vertical spacing reduces GMD which leads to increase 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 cross arm. 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 -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

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

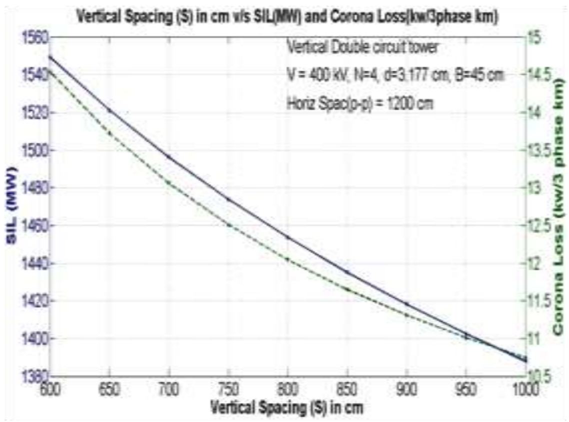

Fig.5 Vertical Spacing v/s SIL and Corona

DOUBLE CIRCUIT CONFIGURATIONS

The arrangement of conductors also affects the SIL [8-10]. The transmission line inductance can be reduced by proper geometrical configuration of conductors. For a 400kV Double circuit tower the configurations [11] are as shown in figure 6-10.

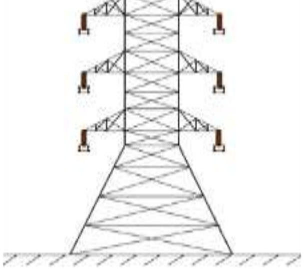

Fig.6 Vertical tower

Fig. 7 Delta tower

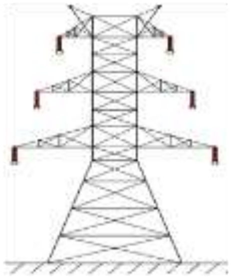

Fig.8 Inverted V tower

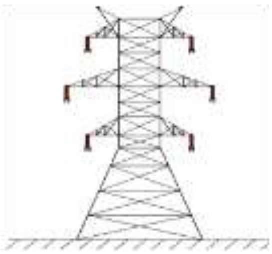

Fig.9 Hexagon tower

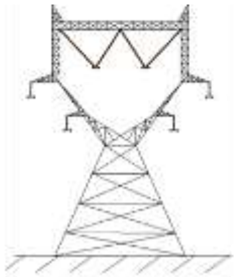

Fig.10 Expanded Hexa tower

Table-7 Comparison of various Double Circuit Configurations

Double Circuit Configurations	L(mH/km)	C(nF/km)	Fair corona loss (kw/3phasekm)	SIL (MW)
Delta	0.365	31.04	0.65	1476.2
Expanded Hexagon	0.368	30.72	0.69	1461.3
Hexagon	0.369	30.63	0.64	1456.9
Vertical	0.37	30.56	0.65	1453.6
Inverted V	0.374	30.25	0.64	1439.0

COMPARISON OF DOUBLE CIRCUIT CONFIGURATIONS

Comparing Horizontal, Delta and L Configuration Towers in terms of SIL level for a specific given data [3,4]:

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 Hexagon configuration Dhr = Dhb1 = Dhb = Dhr1 = 600cm, Dhy = Dhy1 = 800 cm, Dvry = Dvyb = Dvr1y1 = Dvy1b1 = 800 cm, Dvbr = Dvr1b1 = 1600 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 Expanded Hexa Configuration Dhr = Dhb1 = 350 cm, Dhy = Dhy1 = 1250 cm, Dhb = Dhr1 =750 cm, Dvry = Dvyb = Dvr1y1 = Dvy1b1 = 500 cm, Dvbr = Dvb1r1 = 1000 cm

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

Advantages of using Delta 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.

Advantages of using Expanded Hexa Configuration Over Vertical

- There is an increase of approx. 8 MW in SIL level compared to Vertical.
- The advantage of using Expanded Hexa configuration is that we can have reduction in no. of cross arm requirement compared to all above configuration except delta.
- The added advantage of using Expanded Hexa configuration is reduction in vertical spacing between conductors so we can reduce height of tower.

CONCLUSIONS

The major generation capacities of India are lying in northern part which is a power surplus state and most of our load requirement is in central and southern regions, also to transfer power to our neighboring states we need long EHV AC transmission lines.

In case of long EHV AC lines the transmission capacity is limited to Surge Impedance Loading (SIL) level to maintain stability of system. The power transfer capability of EHV AC lines can be improved by increasing the SIL level.

The SIL level can be increased by reduction in transmission line inductance. This is possible by increase in Bundle spacing, diameter of conductor and converting twin moose tower to quad zebra or using any other conductor which has reduced diameter and weight of conductor which results in large increment in SIL level as well as large reduction in corona loss is obtained.

However, the existing transmission tower could be transformed from twin to quad if the tower is designed to carry increased weight. Also by different geometrical arrangements of double circuit tower increment in SIL level has been achieved which has been analyzed and results are obtained. The delta and Expanded Hexa 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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