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Selection of Best Conductor Configuration in Double Circuit Extra High Voltage Transmission Lines Considering Electromagnetic Field Effects

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Abstract: A significant rise in the nation's power demand necessitates the utilization of extra and ultra high voltages in the transmission of power. In order to increase the reliability of power transmission, it is desirable to use a multi-circuit line instead of a single circuit line, until and unless the ground field situations don't allow it. This research work describes in detail the methodology for selecting the best configuration for double circuit transmission lines, considering the effects of electromagnetic fields. Three phase double circuit transmission lines have various possibilities of arranging the conductors of two circuits, and based on the placement of different phases in two circuits, their performance changes. In this paper, alternative conductor arrangement configurations are evaluated on the basis of the inductance value offered by each individual possible configuration. Minimum electromagnetic interference is desirable while designing the transmission lines. This is to avoid complications with communication lines in proximity and also to avoid corona losses and the harmful effects of radio interference and audible noise. All computations are facilitated by an indigenous tool developed with the help of MATLAB coding, and the results are validated with field measurements.

Keywords: *Electric fields, Magnetic fields, Extra High Voltage AC Transmission, conductor arrangements, double circuit lines*

1. Introduction

The Indian power sector has been largely insulated from global competition because most of its assets are domestically owned or government-controlled. Power generation has been dominated by publicly owned firms mainly because it has traditionally been viewed as highly capital-intensive, risky, and lacking in financially viable returns for a competitive and vibrant private sector. Given that India has slid from being a power-surplus country in the 1980s to a balanced country in the mid-1990s and finally to a power deficit country in the early 21st century, the structure of the power sector deserves significant attention. About 85% of India's CO2 emissions from electricity generation are from coal-fuelled thermal power generation: coal is the mainstay of power production and accounts for 60 percent of the installed capacity [1]. At the project level, investment in high voltage transmission lines is a prerequisite for investment in the next generation of generating capacity. The nation being on the fast track development stage, and due to exponential growth of industrialization, the ongoing demand for power is likely to be ramped up day by day. Electricity consumption is also constantly increasing due to steady population growth, and in order to meet this demand, an increase in electricity generation and effective transmission is mandatory. Since power producing facilities are typically situated distant from end customers, it is necessary to build an integrated transmission and distribution network to make it easier for end users to receive electricity. Electrical energy is transmitted at extremely high voltages to ensure its efficient usage. This creates a network of high-voltage transmission lines that is always present. Higher transmission voltages have the following benefits: less space needed, fewer circuits needed for the same amount of transmitted power, better voltage regulation, smaller conductor size, lower line costs per MW and km. At present, 765 kV lines cover a distance of 54,797 km throughout India [2]. Most of these lines are commissioned in the form of double circuit transmission lines in order to increase reliability of power supply. These double circuit transmission lines can be installed in various arrangements. Following section discusses in detail the different possible arrangements of conductors based on the fashion in which they are placed.

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2. Double circuit transmission line arrangements

A double circuit transmission line is the one where six conductors run through the single tower construction and that carries two circuits of a three-phase transmission line. Following are comparative advantages of double circuit transmission lines over single circuit arrangements [3].

2.1. Importance of double circuit arrangement for transmission of power at high voltages

- **Enhanced Reliability and Redundancy**

The overall reliability of the power supply is increased when two circuits are housed on a single transmission tower, acting as a backup in case one circuit fails. Continuous service can be ensured by doing maintenance on one circuit without affecting the other's power flow.

- **Increased power transfer capability**

Large volumes of electricity can be sent over lengthy distances with the use of double circuit lines, which can accommodate expanding demand and transport more power than a single circuit line. By dividing the power between the two circuits, the power system's stability and efficiency can be increased.

- **Economic and environmental benefits**

When compared to establishing separate lines, using a single set of towers for two circuits lowers construction and land acquisition costs. Double circuit lines minimize the impact on the environment and the requirement for additional right-of-way (ROW) because they occupy less land than two independent single circuit lines [4].

- **Flexibility in network configuration**

Double circuit lines offer more grid management options because they can be set up to run independently or in parallel. They facilitate the integration of various power generation sources by serving as links between various grid segments or renewable energy sources.

- **Improved system stability**

By offering two channels for electricity flow and lowering the possibility of outages and blackouts, having two circuits contributes to system stability. Better voltage regulation and control can be achieved with the use of double circuits, which would enhance the power system's overall performance.

- **Mitigation of transmission congestion**

Double circuit lines provide more electricity-flowing channels, which reduces transmission network congestion and promotes more dependable and efficient power supply. Long-distance transmission, which is necessary to move power from distant generating locations (such wind farms or hydroelectric plants) to urban areas, is best served by double circuit lines [5].

2.2. Various arrangements of double circuit structure

- **Simple vertical arrangement:**

Following figure 1shows simple vertical arrangement of transmission line conductors of two circuits placed side by side. This is one of the simplest and most commonly used configurations.

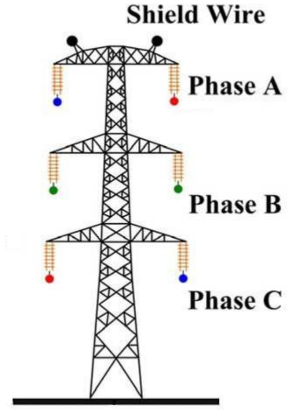

Fig. 1. Simple vertical arrangement in double circuit line

- **Hexagonal arrangement:**

This arrangement houses all the six conductors in the fashion of a hexagon with all the distances kept balanced. The same is shown in figure 2.

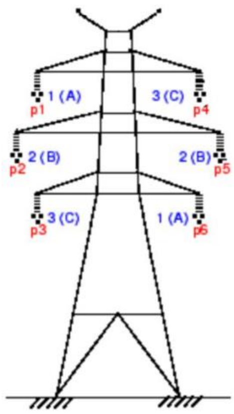

Fig. 2. Hexagonal arrangement in double circuit line

- **Inverted V arrangement:**

This configuration houses the conductors of two phases on the tower such that their arrangements result into a structure shaped Inverted V. Distance of the phases from the center line of tower keep on increasing as we move from top conductor to the bottom one. This arrangement is shown in figure 3 below. This arrangement is more popular nowadays due to its superior technical performance compared to simple vertical arrangement.

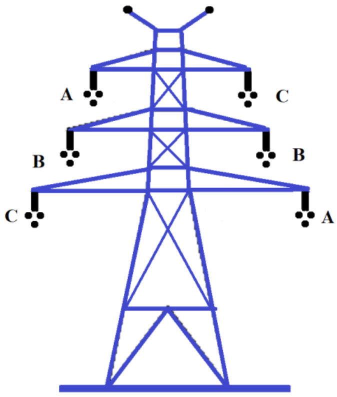

Fig. 3. Inverted V arrangement in double circuit line

3. Computation of inductance

The flux linkage per ampere, or inductance, of a transmission line is calculated differently depending on the design of the conductors. The following formula can be used to calculate inductance generally. This calculated value is in terms of Henry per phase per meter length of transmission line [6].

$$L = 2 * 10^{-7} \ln\left(\frac{G_m}{G_s}\right) \quad (1)$$

G_m represents equivalent aerial distance between conductor of different phases and is known as Geometric Mean Distance or more popularly GMD.

G_s represents self GMD or geometric mean radius of conductor itself.

3.1. Calculation of GMD

For double circuit transmission lines under discussion, Geometric mean of separation between conductors of different phases is calculated by following equation.

$$G_m = \sqrt[3]{D_{ab} D_{bc} D_{ca}} \quad (2)$$

D_{ab}, D_{bc} and D_{ca} are aerial distances between conductors of three phases of two circuits of transmission lines. They are further calculated by following equation and figure 4 helps in understanding the nomenclature.

$$D_{ab} = \sqrt[4]{D_{ab} D_{a\prime b} D_{ab\prime} D_{a\prime b\prime}} \quad (3)$$

$$D_{bc} = \sqrt[4]{D_{bc} D_{b\prime c} D_{bc\prime} D_{b\prime c\prime}} \quad (4)$$

$$D_{ca} = \sqrt[4]{D_{ca} D_{c\prime a} D_{ca\prime} D_{c\prime a\prime}} \quad (5)$$

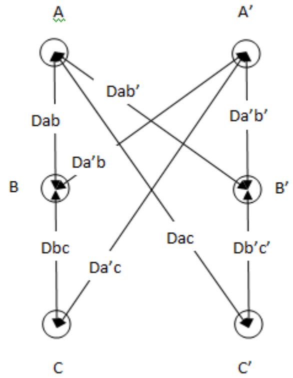

Fig. 4. GMD calculation in double circuit line

3.2. Calculation of GMR

As such GMR is nothing but the radius of the conductor only, however due to skin effect and need to use bundled conductors in case of transmission voltage above 132 kV lines; it is required to use formula for calculating effective radius of the conductors for inductance calculations.

Following are equations for single conductors and bundled conductors respectively.

$$G_s = r' = 0.7788*r \quad (6)$$

Where r is actual radius of conductor and 0.7788 factor is introduced to take into affect the phenomena of skin effect resulting in reduction of actual overall effective radius of the conductor.

For bundled conductors the equation becomes

$$r_{eq} = R\left(\frac{N*r}{R}\right)^{\frac{1}{N}} \quad (7)$$

Where

R is bundle radius

N is no. of sub conductors in the bundle

r is radius of each sub conductor alone

This equation is applicable for twin, trio, quad, hexa or octa configurations of bundled conductors ranging from 220 kV to 1200 kV voltage levels.

4. Selection of best conductor arrangement in double circuit line

As discussed previously, rearranging the phases in two circuits allows for 6 different conductor layouts. These possible 6 arrangements of conductors are shown in figure 5 below. Here conductors of the circuit on the left hand side are kept as constant and conductors of circuit on the right side are varied to get different combination of conductors' arrangements [7].

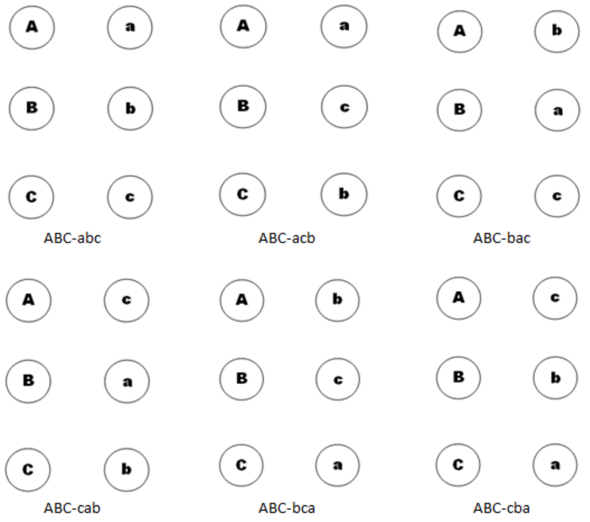

Fig. 5. Conductor arrangements in double circuit lines

The comparative performance study and optimal conductor arrangement choices for transmission lines are covered in the discussion that follows. Three-phase conductors in two circuits might be organized differently as described before in three arrangements viz. simple vertical, hexagonal and with an inverted V configuration. Out of these three the configuration with an inverted V structure is found to be top performing that can be referred from [8].

The best configuration of conductor arrangements among all of these choices is dictated by the inductance values that a particular combination produces. A lower inductance value optimizes the performance of the line arrangement. The inductance computation, relative comparison of multiple configurations, and selection of the best arrangement are all demonstrated in the explanation that follows.

Sample data of a double circuit transmission line with inverted V configuration is tabulated below in the tale 1. This data is taken from a consultancy project done by Dr. J. G. Jamnani [9]. This arrangement is inverted V structure and for this all combinations as shown in figure 5 are considered for computation of inductance.

Table 1. Data of double circuit transmission line

Description	Unit	Value
Voltage	kV	765
Sub conductors		6
The separation between the tower's center and Phase A	m	7.8
The separation between the tower's center and Phase B	m	8.3
The separation between the tower's center and Phase C	m	8.8
The elevation of Phase A above the earth surface	m	49.4
The elevation of Phase A above the earth surface	m	39.1
The elevation of Phase A above the earth surface	m	28.8
Sub conductor radius	cm	1.43
Spacing between sub conductors within the bundle	m	0.45

All potential double circuit line combinations have their inductance determined, and the results are summarized as seen below in table 2.

Table 2. Inductance calculation for different conductor arrangements

Combination of conductors	***Inductance in mH/km***
ABC-abc	0.547
ABC-acb	0.54
ABC-bac	0.535
ABC-bca	0.534
ABC-cab	0.533
ABC-cba	0.527

Above results are also represented in form of a chart as shown in the figure 6 below.

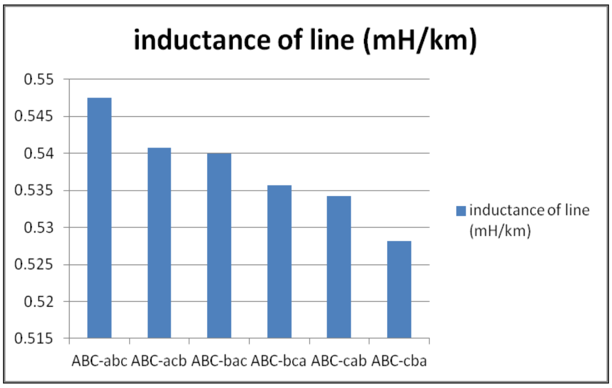

Fig. 6. Inductance values of different conductor arrangements

Above results show that ABC-cba arrangement of conductors is the one which offers lowest inductance along the transmission line. The reason is increased GMR due to father spacing of conductors. This altogether reduces inductive reactance and increases capacitive reactance.

Results of this are lower surge impedance and improved power flow.

5. Impact of conductor arrangement on other performance parameters

Although the best conductor configuration selected above results in the minimum inductance value and associated benefits in power transfer capability, it is essential to check its impact of the electromagnetic fields produced by the transmission line and feasibility looking to national and international standards also for erecting the transmission line from environmental perspective.

Mathematical modeling for computation of electric and magnetic fields has been discussed at stretch in [10]. Considering those formulae and using data of table 1, calculations have been made for electric and magnetic fields for the inverted V configuration of double circuit transmission line under consideration. Following tables 3 and 4 along with figures 7 and 8 depict the results obtained for different arrangements of conductors of two circuits. Maximum electric and magnetic fields also have impact on selecting right of way for transmission lines which is a crucial parameter.

Table 3. Electric field calculation for different conductor arrangements

Combination of conductors	*Electric field in kV/m*
ABC-abc	5.62
ABC-acb	3.67
ABC-bac	5.6
ABC-bca	2.97
ABC-cab	2.99
ABC-cba	2.43

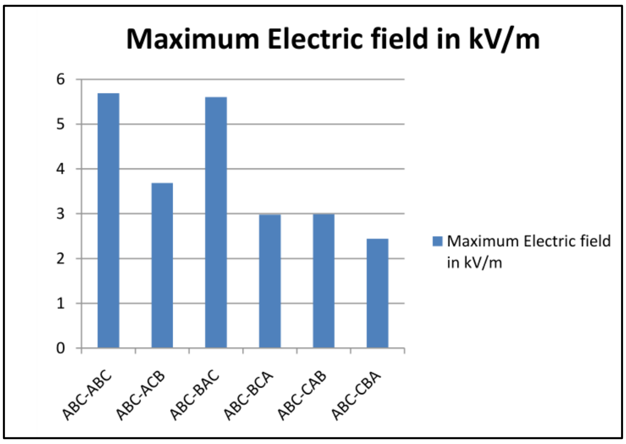

Fig. 7. Electric field values of different conductor arrangements

Table 4. Magnetic field calculation for different conductor arrangements

Combination of conductors	*Magnetic field in uT*
ABC-abc	12.85
ABC-acb	10.25
ABC-bac	11.95
ABC-bca	7.05
ABC-cab	8.2
ABC-cba	4.83

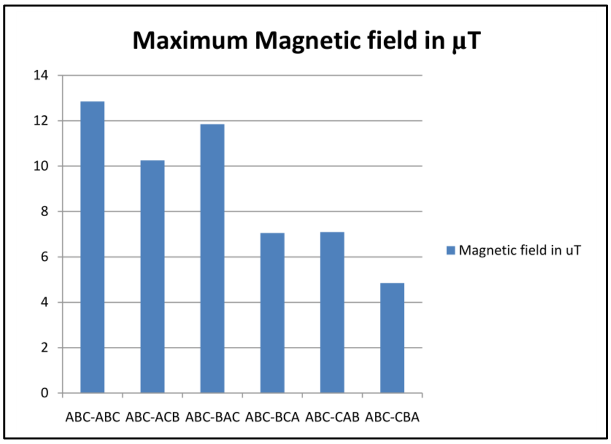

Fig. 8. Magnetic field values of different conductor arrangements

6. Results Validation with field testing data

Each of the mathematical formula found in the literature [11-13] has been transformed into a code, which MATLAB has then been used to turn into software. Following figure 9 shows front end of the software module developed with the help of MATLAB.

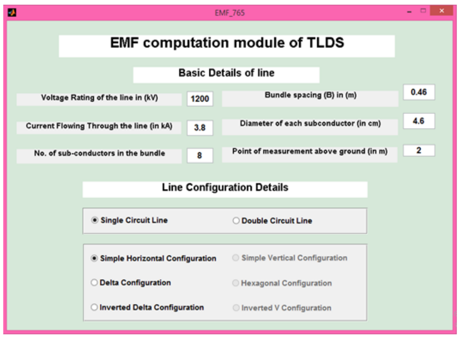

Fig. 9. Front end of transmission line designer software

In order to validate the performance of model developed here, the results are validated in comparison with the field data. The reference data is received from a research work carried out in Gujarat, India [14]. Field testing is carried out for 400 kV double circuit transmission line, model of which is shown in the figure 10 below. Data for the same is tabulated in table 5 below it.

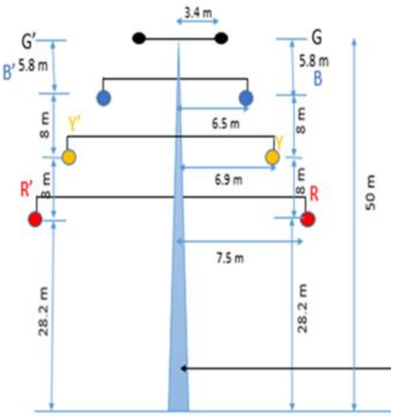

Fig. 10. 400 kV double circuit transmission line under study

Table 5. Data of 400 kV double circuit line

Description	Unit	Value
Sub conductors		4
The separation between the tower's center and Phase A	m	28.1
The separation between the tower's center and Phase B	m	36.1
The separation between the tower's center and Phase C	m	44.1
The elevation of Phase A above the earth surface	m	7.45
The elevation of Phase A above the earth surface	m	6.85
The elevation of Phase A above the earth surface	m	6.45
Sub conductor diameter	cm	3.18
Spacing between sub conductors within the bundle	m	0.45
Sag	M	13.1

6.1. Objective function development for optimization

Here, field effects for this line are computed analytically and compared to those reported in the literature for verification. Results from freshly built software are validated as there is a good level of agreement between analytical and real-time field measurement values. Figure 11 shows computed and field tested values of electric field for the above configuration of transmission line.

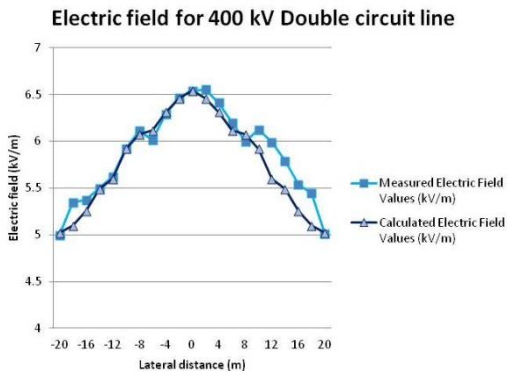

Fig. 11. Electric field effects for 400 kV transmission line

Significant cost savings are possible if the transmission lines' right of way is kept to a minimum. Transmission line optimization aims to maintain all field effects under the maximum allowable exposure values while also lowering the line's ROW need. The maximum values of allowable exposure are displayed in table 4 below. These values are derived from several national guidelines and standards [19–22]. Every field needs to have a maximum value and a ROW value that is less than what is listed in this table. Therefore, it is now necessary to keep tower design safe while also making it compact [23].

Table 6. Comparison of measured and calculated values of electric field

Distance from centre of tower	*Measured electric field (kV/m)*	*Computed electric field (kV/m)*
20	4.99	5.01
18	5.34	5.1
16	5.37	5.26
14	5.49	5.48
12	5.62	5.59
10	5.93	5.92
8	6.11	6.09
6	6.01	6.1
4	6.28	6.3
2	6.47	6.46
0	6.54	6.54

Also magnetic field for the same configuration have been calculated, measured and plotted as shown in figure 12 below. Also results are shown in tabular form in table 7 below.

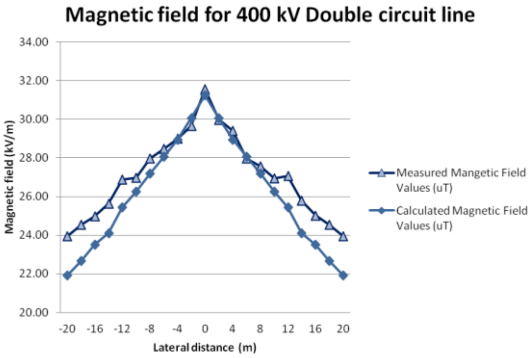

Fig. 12. Magnetic field effects for 400 kV transmission line

Table 6. Comparison of measured and calculated values of Magnetic field

Distance from centre of tower	*Measured magnetic field (uT)*	*Computed magnetic field (uT)*
20	23.93	21.93
18	24.53	22.65
16	24.98	23.5
14	25.64	24.1
12	26.89	25.45
10	26.98	26.25
8	27.96	27.2
6	28.46	28.1
4	29.01	28.95
2	29.65	30.01
0	31.56	31.25

7. Conclusion

Looking to results obtained in section 4 and 5, it is apparent that best configuration available for the double circuit transmission line is ABC – cba and inverted V structure gives the best performance. This arrangement not only reduces inductance value thereby enhancing power transmission capabilities, but also reduces the effects of electric and magnetic fields confirming to standards [15-18] and results in optimal solution for design of overall transmission line network. Also as verified from section 6, the results obtained by the software developed here are closely matching with the actual readings taken on the field. This also validates the worthiness of the computation methodology adopted here. Actually this research article is part of a major research project that attempts to optimize the design of transmission lines operating at the EHV and UHV levels in India. Such research has gained momentum in India due to the potential it provides to reduce land acquisition costs and, at the same time, alleviate the transmission congestion problem.

Author contributions

Dr. Kaustubh Vyas has undertaken the research project and developed core technical concepts and written as well as guided co-authors in developing the research article; **Prof. Hitendra B. Vaghela** has contributed in research article development, **Prof. Nitinkumar R. Prajapati** has looked after organization of the paper and drafting part, **Prof. Roopal R. Kapadia** has helped in research work and completed the proof reading and finalization of research article writing. **Prof. Nilesh J. Patel** has supported in drafting the research article.

Conflicts of interest

The authors declare that this work is purely research work carried out by them and there are no conflicts of interest.

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