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Design considerations and performance evaluation of EHVtransmission lines in India

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Increasing energy demand worldwide needs the development and strengthening of high voltage and high power intensity power transmission lines for meeting the energy requirements. Extra and ultra high voltage transmission lines have been developed and being operated successfully in the developed nations. Recent trends in Indian transmission scenario are progressing towards establishing extra and ultra high voltage lines to strengthen its transmission infrastructure. In the present study, an attempt has been made to discuss broad design aspects of extra high voltage lines. Performance analysis for evaluation of the benefits and costs resulting from these lines in power transmission has also been presented.

Keywords: EHV transmission lines, design, performance evaluation, benefits, costs.

Introduction

Electricity sector of India is growing at a rapid pace. According to Central Electricity Authority (CEA) annual report 2014[1], installed capacity in India is 2,49,488 MW with a generation mix of 63% from thermal, 25% from hydro, 3% from nuclear power plants and 9% from renewable energy sources. The country's peak energy demand is 1, 35,918 MW and the peak demand met is 1, 29,815 MW with a demand shortfall of about 10%. The peak demand in 2017 and 2021 has been projected as 200 GW and 284 GW, with corresponding energy requirements of 13, 54,874 and 19, 04,861 MU respectively. One of the major reasons for not meeting the peak demand is the lack of proper transmission infrastructure. India is a vast country having varied geography, terrain and weather conditions due to which generation resources are wide spread. The generating stations are mostly located near the generation resources due to economics of operation and environmental constraints and are far away from the load centres. This triggered the need for developing extra and ultra high voltage transmission systems for evacuation of bulk power with minimum transmission losses[2-4]. Presently, 400 kV transmission lines form the backbone of India's power network. Even though 765 kV line technology is available, the numbers of these lines constructed and operational are few as compared to 400 kV lines; even some of these lines are under operated at 400 kV. In the present study, an attempt has been made to present the design aspects of Extra High Voltage (EHV) transmission lines with due emphasis on economics along with performance evaluation of EHV lines.

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Design Considerations

Electrical Parameters

The major electrical design parameters for a single circuit, delta conductor and narrow based tower configuration of 765 kV transmission lines is available in literature[5,6.] The electrical parameter specifications are, conductor - 42/7 ACSR Bersimis, Quad configuration, current carrying capacity - 772 A (708 A), cross section in view of short circuit - 724.4mm^2(380 mm^2), GMD - 18 m, GMR - 0.207 m for inductance calculations, GMR - 0.2204 m for capacitance calculations, L - 0.8930 µH/m, C - 0.012 nF/m, Voltage regulation - 4.19%, Corona Loss - 291.42 kW/km/ph, RoW - 64 m and Transmission efficiency - 45 MW/m. The values shown in braces for current carrying capacity and cross section are the minimum values required for transmitting the power. The power to be transmitted is estimated to be 3000MW at a power factor of 0.8 lagging for a distance of 300 km basing on SIL value (2250MW) of a 765 kV transmission line[7-9]. Fig.1 shows the conductor geometry of the considered 765 kV line.

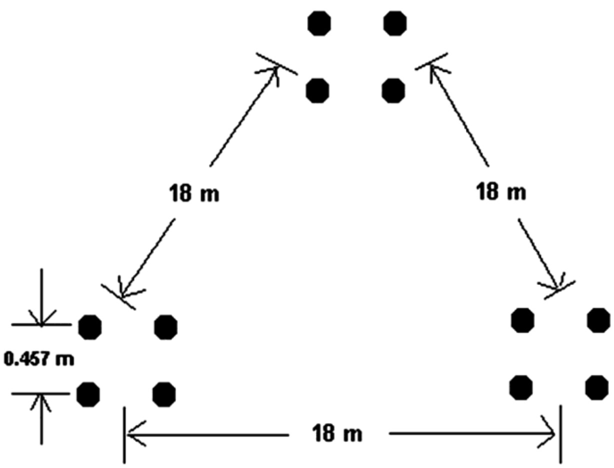

Fig. 1—Conductor geometry of a 765 KV line

Insulators

The design of insulator strings for EHV power lines depends on the level of pollution in which the line operates. IEC 60815 and IS 3188:1980 provides the guidelines for selection of insulator strings. The line under consideration employs "IVI" and "VVV" configurations for insulator assembly and specifications for suspension and tension towers are for 0^O IVI - 2×40 double suspension 120 kN insulators (I string) and 2×35 single suspension 210 kN insulator (V string), for 5^O IVI - 2×40 double suspension 120 kN insulators (I string) and 2×2×35 single suspension 160/210 kN insulator (V string), for 15^O VVV: 4×35 double suspension 210 kN and for Tension Towers: 4×35 Quad suspension 210 kN. These configurations are highly variable and depend on the pollution level in the line operating area[10].

The insulators generally have a creepage distance of 330mm and failure load and no-load deformation strengths of 210 kN and 140 kN respectively.

Loadings

The values of various loadings computed according to IS 802: Part 1: Sec. 1, 1995, for a typical 765 kV single circuit delta line with two ground wire points operating in wind zone 3, terrain category 2 and with a reliability level of 2 are presented. These loadings (kg) are computed for reliability requirement (Normal Condition - NC) under 32^OC and full wind conditions on a suspension tower with 0-2^O angle deviation. The wind span is considered to be 400m and maximum and minimum weight spans to be 600m and 200m respectively. Based on the input data, wind load on conductor, ground wire and insulator is computed to be 10764, 1012 and 585 respectively. The line deviation loads due to conductor and ground wire are found to be 950 and 108 respectively. The equivalent wind load on tower can be computed by transferring the total wind load acting on tower to all conductor and ground wire points which are already subjected to other loadings. For obtaining the exact value for this parameter, complex calculations involving computer analysis is required and hence, a value of W_T is considered for equivalent wind load on tower for calculation purpose[11]. The total traverse loading on the tower due to conductor and ground wire are computed as 12300+W_T and 1120+W_T respectively. Longitudinal load is nil under the present conditions. Considering the weight of conductor and ground wire per weight span as 5249 and 350, weight of insulator string as 400, the total vertical load at one conductor and ground wire point are found to be 5649 and 350 respectively.

Performance Evaluation

Power Transfer Capability

In modern day power systems there exists a need for huge amount of power transfers between generation sources and load centres within the available transmission capacity. SIL is a good measure of power transfer capability of a transmission line. SIL is a loading condition on the line, where the amount of inductive reactive power required by the line is offset by the amount of capacitive reactive power generated by the line or the line attains the state of self sufficiency for reactive power. According to St. Clair, SIL value is approximately equal to 2.5 times the square of the transmission voltage for a single conductor configuration at 60 cycles[12]. A more versatile formula used for calculation of SIL is given by equation (1)[15],

$$P = V^2/Z_C = V^2/\sqrt{(Z/Y)} \qquad \ldots (1)$$

where, P is the SIL loading, V is the receiving end voltage, Z_c is the characteristic impedance or surge impedance, Z and Y are the series impedance and shunt admittance values per km respectively. The value of surge impedance for overhead line starts at around 400Ω at lower voltages and decreases with bundling to 225Ω at 1500 kV. Table 1 presents the line loading limits for different voltages and lengths of transmission lines based on St. Clairs Curve[8, 13]. From Table 1, it is observed that the power transfer capacity of a 765 kV line is 4 times the capacity of a 400 kV line and 12 times that of 220 kV line for any given length.

Transmission Losses

A comparison of the transmission losses for the EHV lines under study as a function of the power to be transferred and line length is presented in this section. The calculations are based on the number of lines required for specific combinations of power transfer requirements and line lengths based on the SIL values as presented in Table 1. The number of lines required and transmission losses for different voltage classes are shown in Table 2. From Table 2, it is seen that three 220 kV lines are required for transferring 500 MW to a distance of 480 km and numbers increase drastically for higher amount of power transfers. Hence single circuit 220 kV lines are highly uneconomical even for power transfer ranges of 400-500 MW over long distances and hence, neglected in further sections for analysis purposes. From Table 2, it is also observed that the number of lines required for 2500 MW of power transfer to a distance of 480 km at 400 kV is five. A 765 kV line requires two lines only in two cases and hence economical to transfer bulk power over long distances. The transmission losses are determined based on resistance at 20°C in Ω/km and the number of lines required for transmitting the power over a specific distance. The values of resistances in Ω/km are 0.069, 0.056 and 0.0424 for Zebra, Moose and Bersimis conductors respectively. The ratio of transmission losses for 400/765 kV lines can be computed from Table 2. The 765 kV line losses are found to be lower for all cases of power flows and distance combinations. An average loss ratio of 2.5-4.5 is considered best for 765 kV installations and value above 5 is considered uneconomical or not cost-effective. The increase in loss ratio value for 2500 MW at distances of 400 and 480 km indicate the need for a second 765 kV line.

Table 1—Line loading limits for different voltages and lengths

Voltage (kV)		220	400	765
Conductor		Twin Zebra	Twin Moose	Quad Bersimis
SIL (MW)		175	515	2250
Line Length (km)	Line Loading in SIL (MW)	Line Loading Limits (MW)		
80	3.0	525	1545	6750
160	2.0	350	1030	4500
240	1.6	280	824	3600
320	1.3	228	670	2925
400	1.1	193	567	2475
480	1.0	175	515	2250

Right of Way

RoW widths vary based on the voltage of the transmission line to be installed within the corridor and is directly related to the installation cost. This depends on many safety and environmental factors. The typical values of RoW widths for a single circuit 400 kV and 765 kV lines are 52m and 64m respectively. Based on these values, the RoW widths required by a single circuit 400 kV and 765 kV lines and ratio of 400/765 kV RoW widths for various combinations of line lengths and power transfers are given in Table 3. The value of RoW is increased proportionally where ever the use of multiple towers is essential. From Table 3, it can be observed that RoW requirement for a 765 KV line is almost constant for a wide range of power transfer capacities

Table 2—Number of lines and transmission losses

Power Flow (MW)	500			1000			1500			2000			2500		
Voltage (kV)	220	400	765	220	400	765	220	400	765	220	400	765	220	400	765
Line Length (Km)	Number of Lines Required														
80	1	1	1	2	1	1	3	1	1	4	2	1	5	2	1
160	2	1	1	3	1	1	5	2	1	6	2	1	8	3	1
240	2	1	1	4	2	1	6	2	1	8	3	1	9	4	1
320	3	1	1	5	2	1	7	3	1	9	3	1	11	4	1
400	3	1	1	6	2	1	8	3	1	11	4	1	13	5	2
480	3	1	1	6	2	1	9	3	1	12	4	1	15	5	2
Line Length (km)	Transmission Losses (MW)														
80	15	3	0.4	29	14	2	43	31	4	57	28	6	72	44	9
160	15	7	0.8	39	28	3	52	32	7	76	56	12	89	59	18
240	24	10	1.1	43	21	5	64	47	10	86	56	18	119	66	27
320	19	14	1.5	46	28	6	74	42	13	102	75	24	130	88	36
400	24	17	1.9	48	35	8	80	53	17	104	70	29	138	88	23
480	28	21	2.2	57	42	9	86	63	20	114	84	35	143	105	27

Table 3—RoW width required and ratios of 400/765 kV row widths

Power Flow (MW)	500		1000		1500		2000		2500	
Voltage (kV)	400	765	400	765	400	765	400	765	400	765
Line Length (km)	RoW required in Acres									
80	1028	1266	1028	1266	1028	1266	2056	1266	2056	1266
160	2056	2532	2056	2532	4112	2532	4112	2532	6168	2532
240	3084	3798	6168	3798	6168	3798	9252	3798	12336	3798
320	4112	5064	8224	5064	12336	5064	12336	5064	16448	5064
400	5140	6330	10240	6330	15420	6330	20560	6330	25700	12660
480	6168	7596	12336	7596	18504	7596	24672	7596	30840	15192
Line Length (km)	Ratio of 400 / 765 kV RoW									
80	0.8		0.8		0.8		1.6		1.6	
160	0.8		0.8		1.6		1.6		2.4	
240	0.8		1.6		1.6		2.4		3.2	
320	0.8		1.6		2.4		2.4		3.2	
400	0.8		1.6		2.4		3.2		2	
480	0.8		1.6		2.4		3.2		2	

over long distances while in case of 400 KV line, RoW increases exponentially with increase in power transfer capacity and/or distance. A value less than 1 for ratio of 400/765 kV RoW indicates that the RoW requirement for 400 kV line is less than that of 765 KV and a value more than 1 indicates the vice-versa. Hence the breakaway point favouring 765 kV line installations is at 1000 MW, 240 km. The ratio for 765 kV line reduces at 2500 MW power transfer requirement for a distance of 400 and 480 km due to a second line requirement.

Cost

The estimation of installation cost of an EHV transmission line is a complex aspect as the line design varies from project to project and depends on many technical and environmental factors. The average benchmarked installed cost excluding RoW costs is estimated at INR 5 million/km and INR 11.8 million/km for 400 kV and 765 kV lines respectively considering plain area terrain and wind conditions as per IS 802 (Part-1/Sec-1). The standard classification for number of towers includes 75%, 15%, 7% and 3% for suspension, small angle, large angle and dead end towers respectively[14]. It is inferred that the installation cost of one 765 kV line is 60% less than four 400 kV lines for carrying the same amount of power.

Other Issues

Aesthetics

In developed nations, aesthetics is of major concern. The visual impact created by transmission lines should be as minimum as possible. One 765 kV line can carry as much power that can be carried by four 400 kV lines. This means 400 kV multiple lines are required in the same path for carrying the same amount of power requiring increased RoW as well as produce more visual impact due to more number of lines. As both these lines are of single circuit and comparable height, 765 kV line is preferred in view of aesthetics.

Reliability

A comparison between 765 kV line and 400 kV line shows that momentary and normal circuit outages are 40% and 30% less respectively, on a 765 kV line. The average time taken to repair a sustained outage is about 27% less than that required for a 400 kV line. The single circuit 765 kV delta configuration line design has a phase to phase spacing of 18m. This physical separation reduces the occurrence of phase to phase faults and phase to phase faults which sustain on the line and emerge as three phase faults[15]. The line design also allows single phase tripping operation which increases transient stability, reduce switching over voltages, reduce torsional oscillations on shaft and improve availability. Studies conducted on 765 kV lines show that these lines are highly reliable and cost effective.

Statutory Clearances

In general, transmission projects are time consuming due to the regulatory and development clearances that are to be acquired by State and Central Governments and its constituent bodies. Transmission projects are executed after getting various clearances viz. techno economical clearance (TEC), RoW clearance, financial clearance and forest clearance etc.

Of all clearances, forest clearance is considered vital for timely execution of transmission lines. Transmission lines are planned along with generation projects for evacuation of power and any delay in construction of lines results in generation loss. The line routes are planned in such a way so as to avoid forests, national parks, wildlife sanctuaries etc. but are not possible to the complete extent. In such cases, a mandatory clearance from the forest department for the restricted area is essential.

Mitigation of Hazards

The common hazards for transmission line projects are overinvestment and underinvestment. In overinvestment, a significant amount of capital investment will be stranded as the full capacity of the 765 kV transmission line will not be utilized in most of the situations. On the other hand the risk of underinvestment leads to reduced system reliability and may not exploit the available generation resources completely. In underinvestment, the newly constructed lines are operated without margins for future load growth, posing the need for additional lines for satisfying energy requirements and hence, do not justify the capital investment for a particular project.

Market development

The Electricity Act 2003 (EA-2003) has introduced many new features for empowering the power sector. Transmission system open access, minimum renewable purchase obligation (RPO), specification of grid code, connectivity to grid, electricity trading and fixing trade margins etc. are some of the instrumental factors aiding the development of the sector. Many independent power producers (IPP) emerged as a consequence of open access and other facilities. Power trading has achieved significance. A major impact of constructing 765 kV EHV lines can be seen in the enormous growth of inter-regional power flows to fully exploit the generation diversity.

Conclusion

In order to meet the continuous demand of electrical energy, it is inevitable for transmission utilities to strengthen their infrastructure by augmenting and constructing EHV lines. Based on the analysis presented in this study following conclusions are drawn which favour the establishment of EHV lines.

(1) The transmission efficiency ratio of a 765 kV line is three times more than a 400 kV line.
(2) Power transfer capacity of a 765 kV line is four times the capacity of a 400 kV line and twelve times the capacity of a 220 kV line.
(3) The 765 kV line losses are lower than 400 kV line losses for all combinations of power transfers and distances.
(4) A range of 2.5 to 4.5 for average loss ratio has been found best suitable for 765 kV line installations.
(5) A value of 1.6 for the ratio of 400/765 kV RoW width requirement indicates the breakaway point for 765 kV line installations.
(6) For transferring the same amount of power, the installation cost of a 765 kV line is 60% less as compared to 400 kV lines.
(7) Voltage level, SIL and RoW are the major design parameters affecting the reliability and cost of EHV power transmission lines.

The design and establishment of EHV lines must aim to reducing the RoW widths, losses and other environmental hazards and limitations. In this paper, the design considerations of EHV lines has been presented through the design of major parameters for 765 kV delta configuration single circuit line in compliance with the existing standards. The performance evaluation of benefits by adopting high voltage transmission lines was carried out by comparing the essential parameters with lower voltage lines and the results were analyzed.

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