Chapter-4

DESIGN APPROACH TO H.V. TRANSMISSION LINE

4.1 Introduction

A transmission line must be capable transmitting bulk power over relatively long distance (as compared to distribution lines) economically, satisfying the electrical and mechanical requirements [104,117]. The amount of power to be transmitted, the power factor, and the distance from the sending to the receiving ends are generally specified. The transmission has to be made within the limits imposed on voltage regulation, and efficiency. The lines must be capable of withstanding the weather conditions of the locality through which it passes e.g. temperature cycles, deposition of ice in the winter, wind pressure on the conductors (along with ice) etc. [87]. There must not be any mechanical failure of the conductors or the transmission towers. The dielectric strength must be enough to withstand the high voltage under all extreme conditions e.g. travelling waves due to lightning stroke or switching phenomena. The leakage current must be small. Corona formation and corresponding losses are other considerations [87]. The charging current of the line should be within limits. If it be very high, inductive compensation has to be provided. The designer must take into account all these points before making the design. For underground cable transmission, the particular consideration is the charging current, which may cause large scale Ferranti effect.

To easily maneuver the design, to avoid long hand computations, and to make the design flexible, a properly written computer program is essential [126]. Those who are engaged in design, design modification and subsequently in fabrication of high voltage transmission lines face difficulty as there is no properly constructed computer programme for the task. In the following sections of the chapter, the principle of design of EHV transmission lines has been vividly discussed and algorithm developed for computer-aided design [131]. The programme includes both electrical and mechanical design and effects like corona losses. Steps for analysis of the transmission line before erection has also been given. A no. of case studies has been made by running this programme and has been given at the end of this chapter. Design of underground transmission lines has not been taken up.

4.2 General description of long EHV transmission lines

Long transmission lines are particularly required for transmitting power from Hydroelectric Power Stations (HPS) to the load centers. Hydroelectric power stations are generally situated at remote hilly areas, thinly populated and having very low load density. The generated power has to be transmitted to densely populated localities. For example, hydroelectric power is generated at Chukha of Bhutan (84x4 MW). Most of the power is transmitted to Birpara of Coochbehar wherefrom it is evacuated through NHPC. Similarly, power stations at Teesta valley, Ramam etc. are far away from the load centers. The power generated at these stations has to be evacuated through transmission lines[138].

Transmission lines are also used to transmit thermal power. Thermal power stations should be sited near to the coal mines to reduce the transportation cost. Also, they should not be sited in densely populated cities in consideration of the pollution to be caused by them and the high price of the land. Therefore, thermal power is to be generated at a place near the coal mines, in rocky and arid areas, and then it is to be transmitted in bulk to the city centers. Exceptions to this general consideration may sometimes be noted e.g. Kolaghat TPS is situated amidst fertile lands, far away from coal mines. There may be reasons behind such choice but the reasons are not known.

Transmission, generally speaking, is taken as overhead transmission. However, at places, cable transmission must be opted. For example, it is neither convenient nor secure to run H.T. transmission lines through the metropolitan city of Kolkata (An exception is the bulk power transmission to Salt Lake substation). In such areas, cable transmission may have to be used, though it is more expensive. Cable transmission is also used to connect lands separated by straits e.g. English channel. HVDC transmission is best-suited for cable transmission to avoid Ferranti effect arising out of relatively high value of capacitance of the underground cables[104].

4.3 The design considerations and procedure

Various considerations are to be made beforehand for the design of a transmission line. Such considerations are enumerated below [87,104,131]:

The selection of voltage: It is made from within a set of standard voltages – the choice is basically made on an economic basis. The most economic voltage depends on the length of the line and the bulk of power to be carried by the line. An expression was advanced by

Westinghouse Electric Corporation in the past for the most economic voltage, but now-a-days the choice is made from the table of standard voltages against Kw-Km product. Some people also uses a table of voltages against the line length in Km. There are also other considerations such as voltage of the near-by transmission line with a look to making interconnections, the line losses, the probable voltage regulation and the spacing of the conductors. The best way to treat this problem is to compute the cost and the performance variables against a no of standard voltages and choose the best one by making comparisons [131].

Choice of conductors- ACSR (Aluminium Conductors Steel Reinforced) conductors are used for high voltage application. It combines the cheapness of Aluminium, also high conductivity, with the strength of steel. The size of the conductor to be chosen depends on the length of the line, operating voltage and the load. The basis is permissible current density and the annual ohmic losses. As per Kelvin's law, the most economical size of the conductor is one for which the sum total of the cost of energy units lost per annum and the capital cost on investments made for the erection/commissioning of the line is minimum. For high voltage lines, the corona losses should also be accounted for. Besides economic considerations, the voltage drop and the permissible temperature rise (particularly important for cable transmission) are also taken into considerations while choosing the conductor size. The size of the conductor is generally chosen from the standard sizes [22].

Spacing of conductors: It depends on the line voltage and the span between the transmission towers. The conductors must not touch with each other under conditions of sag, taking wind pressure (and also ice-load, if the case may be) and variations of temperature into consideration. It should be reliable against lightning surges. Larger spacing gives rise to larger inductance: $L = 0.2 \ln (D_{eq} / (0.7788\, r)$ mH/Km, D_{eq} is equivalent spacing. It gives rise to more voltage drop and reactive power loss. The spacing may assume many types of geometrical configurations but the equivalent spacing is guided by standard tables against operating voltage. For voltages above 220 Kv, bundle conductors are more suitable. Double and multi-circuit lines also give advantages[104].

Corona- Corona arises due to ionizing effect in the air surrounding the high voltage lines. Above a threshold, a pale violet glow appears at the surface of the conductor along with a hissing sound. The minimum voltage required between conductors to start corona is called the disruptive critical voltage. At this point, corona starts but there is no visual glow. The visual glow is noticed as the voltage crosses the visual critical voltage. The potential gradient at which a dielectric disrupts is called its dielectric strength. For air at normal pressure and 25^{o}C, the peak value for disruption is 30 Kv/cm.The dielectric strength is proportional to the density of air over a wide range. It is given as:

$$\delta = \frac{3.92b}{273+t} \qquad 4.1$$

For parallel wires, the disruptive critical voltage is given as:

$$E_d = 21.1 mr\delta \ln\frac{d}{r} \text{ Kv (rms) line-to-neutral,} \qquad 4.2$$

Where, d = distance between the conductors; r = radius of the conductor; m = surface factor

The service factor is 1 for polished wires, for rough surfaces it ranges between 0.92 to 0.94; for stranded conductors, the value is taken as 0.82.

The visual critical voltage is given as:

$$E_v = 21.1 m_v r\delta(1+\frac{0.3}{\sqrt{\delta r}})\ln\frac{d}{r} \text{ line-to-neutral (rms)} \qquad 4.3$$

m_v is 0.72 for local corona in stranded conductors and 0.82 for decisive corona.

The visual critical voltage is higher for bundle conductors. The expressions are omitted as no work has been done on bundle conductors.

When corona occurs, it causes power loss. The following expression for corona loss has been given by Peek:

$$P_c = \frac{2.44}{\delta}(f+25)\sqrt{\frac{r}{D}}(E-E_d)^2 \text{ W/phase/Km} \qquad 4.4$$

where, E = Voltage in Kv between phase and neutral, f = frequency in Hz, δ=air-density factor, r =radius of the conductor and D = spacing between conductors, E_d =disruptive voltage in Kv. The following are the limitations of the formula:

- frequency range: 25-120 Hz.
- r >0.25 m
- E / E_d >1.8
- weather conditions are fair.

Under stormy conditions, the value of E_d should be taken as 0.8-times of its value under fair weather.

While the ratio $E/E_d < 1.8$, Peterson's formula is more appropriate. It is given as:

$$P_c = \frac{21e-6.f.E^2}{[\log(D/r)]^2}.F \quad \text{Kw/Km/conductor} \qquad 4.5$$

The factor F varies with the ratio E/E_d. The variation is shown below in table 4.1:

Table 4.1 E/E_d vs. F

E/E_d	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2
F	0.012	0.018	0.05	0.08	0.3	1.0	3.5	6.0	8.0

The corona effects are to be seriously considered while designing a high voltage transmission line. The h.f. harmonics produced by corona may interfere with the near-by communication lines and cause serious distortion of the signals. If transmission lines are designed with disruptive voltage at least 10% higher than the rated, then the corona effects do not become large. The conductors should be chosen from the point of view of corona.

*Insulators:*The insulators used for h.v. transmission lines are of the suspension type. The no of disks is determined by the voltage. The voltage distribution among the disks is not uniform due to capacitive effect. Due to this effect the peak voltage that the suspension can withstand is somewhat less than the sum of the peak voltages that the individual disks can withstand. In this context, a ratio called string efficiency is defined as:

String efficiency = $E/(ne)$ 4.6

where, E = the peak voltage that the line can withstand, e = the peak voltage a disk can withstand and n = no of disks. The no of disks to be used against line-to-line voltage is given in table4.2:

Table 4.2 No of disks against line voltage in Kv

Line voltage in Kv	66	110	132	166	230
No of disks	5	8	10	12	16

4.3.1 Transmission line specifications:

The following specifications of transmission lines are given to the designer beforehand:

No of phases, frequency, power to be transmitted, p.f. at the receiving end, length of the line, permissible voltage drop, minimum efficiency, corona loss limit, temperature variation to which the line will be subject to, the wind pressure and pressure due to ice load, if any.

The designer is to choose the line voltage, the no of circuits, the conductor type and size, spacing of the conductors, the type of towers and the span, no of insulators per string, size of the ground wire etc. Finally, he has to work out the ABCD parameters of the line and the performance variables and check whether the given specifications have been satisfied[131].

4.3.2 The algorithm

The algorithm for design is given below in a compact form. The detailed algorithm is given in the annexure.

1. Enter data for the transmission line, standard transmission voltages
2. Make performance evaluation at full load
3 Find out the appropriate voltage: using formula: $V = 5.5 * \sqrt{(L / 1.6 + S * 10)}$
   where, L = Length of the line in Km and S = transmitted power in MVA
4. Compare this value with the chart for standard voltages and choose the nearest one.
5. Find out the base quantities and the rated current.
6. Make data entry for ACSR conductors
7. Find dimensions of ACSR conductors (no. of strands and diameter of each stand) for this current
8. Find over-all diameter of the conductor, resistance/Km at operating temperature
9 Find out the resistance in p.u, and the line loss at rated current.
10. Find out the ultimate strength and the weight of the conductors.
11. Choose between single circuit and double circuit line from ratings.
12. Find out the span between transmission towers from standard chart
13. Find out the spacing between conductors consulting standard table
14. Find out the equivalent spacing.
15. Choose the type of insulator to be used for the chosen voltage level. If it be disk type, find the no. of disks required for the chosen voltage.

16. Find out self-GMD and the line inductance in pu.
17. Find out the required clearance from the ground for the specified voltage level.
18. Find out capacitance of the line in p.u.
19. Find out ABCD-parameters of the line.
20. Find out receiving and sending end quantities at continuous maximum rating (CMR)
21. Find out the voltage regulation at CMR
22. Find out the disruptive and the visual critical voltage w.r.t corona formation and the ratio with line voltage.
23. Find out the corona loss using the appropriate formula- Peek's or Peterson,s

24 Find out the charging MVAR

25 Find out the transmission line efficiency

26. Find out the Surge Impedance Loading (SIL) and the charging MVAR/SIL

27 Find out the mechanical stress taking the effect of wind

28. Find out the sag and the length of the stretched conductors.
29. Find out the tower configurations- position and length of the cross-arms etc.
30. Check whether spacing is adequate in consideration of the horizontal sag produced by the wind. If inadequate, increase spacing between conductors and redesign
31. Stop
32. End

4.4 Performance analysis

Step for making performance analysis has also been included in the program. It computes the efficiency and the voltage regulation at rated power. Performance analysis for other conditions of operation can be easily made by using the ABCD-parameters of the transmission line computed by the program. For the short line the effect of shunt capacitance is generally negligible. For medium transmission lines, the effect is accounted for using lumped parameters, the use of π-representation being commonly made. The analysis must take care of the distributed parameters in case of long lines[104].

4.5 Case studies

Two different case-studieshave been made- one for the design of a short transmission line of length 30 Km carrying a power of 20 MVA at 66Kv and another for the design of long transmission line of length 250 Km carrying a power of 500 MVA at 220Kv. The computer print outs for the case-studies, converted to word-format are given below:

4.6.1 Design of a short transmission line operating at 66 Kv

Length of the line in Km = 30

MVA rating = 20

The chosen transmission voltage = 66 KV

The line current = 174.95 A

The nominal power factor = 0.85 LAG

ACSR conductors are being used.

No. of Aluminium conductors = 30

Diameter of Aluminium conductors in mm = 2.36

No. of Steel conductors = 7

Diameter of Steel conductors = 2.36 mm

Cross-section.ofAluminium conductors = 128.1 mm^2

Resistance/Km at 20 ^{o} C = 0.222 Ω

Ultimate strength = 56.5 KN

Weight of conductor = 5.917Kg/m

The conductor resistance/phase at 20 ^{o} C= 6.66 Ω

The conductor resistance/phase at operating temperature = 7.353Ω

The total ohmic loss = 0.6752 MW

The % ohmic loss = 3.9716

Single circuit line with horizontal spacing is being used.

Distance between adjacent conductors = 2.1 m

The equivalent spacing = 2.6 m

The span = 200 m

The insulators chosen are of the suspension type.

The no. of insulators should be = 5

Clearance from the ground in m = 6

Resistance = 0.0397 p.u.

Leakage reactance = 0.05207p.u.

Capacitive susceptance on either side = 0.01775 p.u.

Surge impedance = 295.85 Ω

ABCD parameters of the transmission line are given below:

A = D = 0.9989989 +j 7.050467E-04

B = 0.039691 +j 0.0520632

C = -8.340476E-06 +j 3.548193E-02

Performance evaluation:

Receiving and sending end quantities at Continuous Maximum Rating (CMR)

V_R = 1 +j 0 ;p.f. = 0.85 lag

I_R = 0.85 -j 0.52678 = 1 $\angle$-31.784^o

V_S = 1.060 + j 2.4050E-02 = 1.0604$\angle$1.2994 ^{o}

Percent voltage regulation = 6.0435

I_S = 0.8495 -j 0.4902 = 0.9808$\angle$-29.98 ^{o}

The disruptive critical voltage= 74.65Kv

The visual critical voltage = 100.5 Kv

The ratio of disruptive critical voltage to line voltage = 0.5104

The ratio is less than 1.8. So Peterson's formula is applied.

Corona loss in KW = 0.2442

Charging MVAR drawn = 0.7313

Transmission line efficiency = 0.9553

Surge impedance loading = 14.724MW

% Charging MVAR/SIL = 4.967

The working tensile force = 14125 N

The vertical load due to self-weight= 5.917 N/m

Sag without wind load in m = 2.0946

There is no possibility of ice. The wind pressure in N/m^2 = 380

The load due to wind = 4.8212N/m

The total load = 7.633N/m

Sag with wind load = 2.702 m at 39.17^o with horizontal.

Length of stretched conductor = 200.1 m

Single circuit towers with horizontal spacing is used

Distance between lines in m = 2.1

The height at which conductors are placed in m = 8.1 m

The height at which cross-arms are placed = 9.05 m

The height at which earth wires are placed in m = 12.96 m

Two earth wires of GI are run throughout.

Adequate spacing = 2.084 m

The spacing used is more than adequate.

4.6.2 Design of a long transmission line operating at 220Kv

Now, a transmission line operating at relatively high voltage is being designed. In this case the design considerations and the design variables to be chosen are somewhat different. The results obtained by running the program converted to word-format are given below[87,131]:

Length of the line= 100 Km

MVA rating= 125

The chosen transmission voltage= 220 KV

The line current= 328.04 A

The nominal power factor= 0.85 Lagging

ACSR conductors are being used: Code no ELK is chosen from the table

Its current-carrying capacity is 860 A, which is much more than the line current 328.04 A

The diameter of each conductor= 4.5 mm

The no of Al/Steel strands: 30 / 7

The total no of strands = 37

Total diameter of the line conductor = 31.5 mm

C.S. of Aluminium conductors = 588.4mm^2

Resistance/Km at 20^{o}C =0.0611 Ω

Ultimate strength = 20240Kg

Weight of conductor = 2196 Kg/Km

The conductor resistance/phase at 20^o C= 6.11 Ω

The conductor resistance/phase at operating temperature of 50^o C= 6.855 Ω

The total ohmic loss in MW= 2.213

The % ohmic loss= 1.7704

Single circuit line with horizontal spacing is being used.

Distance between adjascent conductors = 4 m

The equivalent spacing= 5 m

The chosen span= 225 m

The insulators chosen are of the suspension type.

The no. of insulators should be 16

Clearance from the ground in m = 7.54 m

Resistance in p.u. = 0.0177

Leakage reactance = 0.09754 p.u.

Capacitive susceptanceon either side= 0.11343 p.u.

Surge impedance= 255.96 Ω

ABCD parameters of the transmission line are given below:

A=D= 0.988 +j 0.00202; B= 0.0176 +j 0.0972 ; C= -0.000152 +j 0.226;

Receiving and sending end quantities at Continuous Maximum Rating (CMR)

V_R= 1+ j. 0

V_S= 0.9518 +j 0.0939 = 0.9564 $\angle$ 5.632^o

Percent voltage regulation= -4.363

I_R= 0.85- j 0.5268 = 1 $\angle$ - 31.78^o

I_S= 0.8386 +j 0.7482 = 1.1238 $\angle$ 41.73^o

Corona effects:

The surface factor has been taken as 0.82 for stranded conductors

The disruptive critical voltage = 144.78Kv

The visual critical voltage for decisive corona = 180.82Kv

The ratio of disruptive critical to line voltage= 0.8773

The ratio is less than 1.8. So Peterson's formula is being applied.

Corona loss = 24.66 Kw

Charging MVAR drawn= 27.738

Transmission line efficiency= 0.9794

Surge impedance loading in MW= 189.09

% Charging MVAR/SIL= 14.67

The working tensile force =10120 Kg

The vertical load due to self-weight = 2.196 Kg/m

Sag without wind load = 1.3732 m

There is no possibility of ice. The wind pressure in Kg = 38

The load due to wind in Kg/m = 1.197

The total load = 2.501Kg/m

Sag with wind load = 1.5639m at 28.6^o with horizontal.

Length of stretched conductor in m = 225.03

Single circuit towers with horizontal spacing is used

Distance between lines in m = 4

The height at which conductors are placed = 8.9 m

The height at which cross-arms are placed = 11.5 m

The height at which earth wires are placed = 14.24 m

Two earth wires of GI are being run

Minimum allowable spacing in m = 2.717

The spacing used is adequate.

It may be noted that the capacitive effect is highly dominant in this case. Even for full load condition at rated power factor, the voltage regulation is negative. So it is advisable to add inductive compensation at the terminals to resist VAR-IN phenomenon.

4.7 Conclusion

Text-books for the design of electrical machines are readily available. But such books for the design of transmission lines are rarely found. M.V. Deshpande, former CE, Maharastra SEB has indicated the design procedure in one of his famous books [131]. However, he has not written anything on computer-aided design of transmission lines.

Much calculation and many steps are involved in the design of transmission lines. It becomes a tedious task if one has to go through these steps many times to find out a feasible solution or to find out the optimal solution. The problem becomes more complicated, if the optimization has to be made in the presence of design constraints.

The analytical design just gives a feasible solution in one, two or multiple trials. The synthetic design keeps certain performance variables at or very near to specified values. The optimal design seeks and finds out the best possible solution from many feasible solutions with reference to a specified objective function, generally in presence of constraints. The standard design keeps the design in a framework of accepted and readily available standards. In the design of a transmission line the use of optimal as well as standard design procedure is recommended, as a non-standard design is not acceptable. However, for simplicity,the analytic and the synthetic procedure have been used.

The programme developed for the purpose of design runs through many steps, starting from the choice of voltage through choice of conductors, insulators, transmission towers etc. It finds out all the dimensions and computes all the performance variables e.g. voltage regulation, efficiency etc. inclusive of corona loss.

There is scope for further improvement of the programme to cover optimal design.

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