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765 kV Transmission Line Design (Electrical Section)

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Article Info	ABSTRACT
	Nowadays, due to the ever increasing energy consumption and power supply optimization, it is required to construct new power plants, substations and transmission lines. In Iran, also, because of increasing demand for electrical energy, for a significant power loss reduction in power transmission over long distances, and to construct high transmission lines that lead to reduction in the economic costs of transmission lines, the transmission lines must be considered at extra high voltage (EHV) levels. These EHV levels should be compared with the low voltage levels in order to extract the benefits. Therefore, in this paper, a review has been conducted on the types of 765 kV transmission lines used in different countries and a comparison between them and the low voltage levels have been performed. Accordingly, the advantages of EHV transmission lines are summarized. Finally, designing a line of 765 kV single-circuit with 6 conductors per bundle based on existing standards is presented.

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1.   INTRODUCTION

Nowadays, power systems are extensively interconnected requiring the huge transfer of electric power. Considering that a typical transmission line with a certain voltage level, can only carry a limited capacity, to carry an enormous power it is required to construct extra high voltage (EHV) transmission lines [1]. Due to the vastness of Iran and energy demand increase, using 765kV EHV transmission lines can be a good choice to meet the needs.

765 kV transmission lines have been established in some countries including South Korea, India and the United States of America [1, 2] and different standards are provided for these transmission lines by IEEE, BS and ANSI [3]. However, to make in parameters these standards with respect to Iran's current conditions, such as for weather conditions, require the combination and analysis of international standards and national standards which are available for other voltage levels.

In this paper, using IEEE and ANSI standards related to 765kV transmission lines, and 230kV and 400kV standards, electrical design of all parts of a 765kV transmission line is presented.

2.   DETERMINING THE TYPE AND NUMBER OF CONDUCTORS PER PHASE

Reviews on a variety of transmission lines in United States of America, South Korea and some other countries shows that the type of conductors in EHV transmission lines are of Rail or Curlew. Further, from Table (1) it can be understood that Curlew conductors has lower resistance and higher minimum tear compared to the Rail conductors which shows a better characteristics. However, in high power transmission, to reduce losses and limit the corona phenomenon, it is needed to increase the number of conductors per

bundle. Therefore, Curlew conductor can not be used due to excessive weight. Rail conductors, hence, have a low electrical resistance; high mechanical strength and low weight are selected.

Table 1. Rail and Curlew conductors' characteristics

| Conductor | Conductor structure | | | Conductor diameter (mm) | Approximate weight of conductor | | Maximum electrical resistance in 20 ^{0}C (Ω/km) | Minimum tear strength (kN) | Packing Areas (m) |
	Cross section (mm^2)	AL. (No-mm)	St. (No-mm)		AL. (No-mm)	St. (No-mm)			
Martine	684.84	54*4.02	7*2.41	36.17	1906	679	0.04259	205.8	1000
Rail	483.42	45*3.70	7*2.47	29.61	1339	260	0.05994	115.6	1000
Curlew	523.68	54*3.52	7*3.52	31.68	1451	530	0.05531	162.7	1000

Considering the issues related to high power transmission and corona phenomenon in EHV lines the use of several conductors in a bundle is essential [4]. Studies on a variety of existing 765kV transmission lines show that these lines are designed to transfer a power of 4000 MVA (or even more), for which line current is calculated using Eq. (1).

$$I = \frac{S}{\sqrt{3}.V} \tag{1}$$

According to the analysis of 765 kV transmission lines, the transferred power of S=5000MVA is considered for a single circuit line has six conductors per phase [4]. And by considering the voltage V = 765 kV, rated current value is equal to a 3773 A. Therefore, regarding the following cases, the mentioned transmission line is chosen to have six conductors per phase [5]:

- To balance the weight, the number of conductor bundles must be even (four or six).
- The four-wire bundled Rail Conductor has a tolerable current equal to 3940A when compared with the rated current of 765kV transmission line, it is inferred that the former will has a lower loading margin.
- An example of six-wire transmission line is shown in Figure 1.

Figure 1. Six-wire transmission line

3. APPROPRIATE CROSS SECTION FROM THE VIEWPOINT OF SHORT CIRCUIT

Besides the numerous factors that are involved in determining the cross-section of conductors, short circuit current is another key aspect in proper selection of the conductors. Conductor cross section is determined according to the rated current, and then based on the level of short circuit test. Eqs. (2) and (3) assess the minimum cross section required to withstand the heat generated due to the short circuit [6].

$$S = \frac{I_{SC} \cdot \sqrt{t}}{K} \tag{2}$$

$$K = \sqrt{\frac{W.C.\Delta\theta}{0.24\rho}} \tag{3}$$

Where:

S: Cross section of conductor (mm)

I_{SC}: Standard short circuit current (A)

t: The persistence time of short circuit current (s)

k: Constant coefficient related to the conductor material which is dependent to the following parameters:

w: Specific weight of the conductor (gr/cm^3)

C: Specific heat of conductor metal (Calory/g-o$_c$)

$\Delta\theta$: The conductor temperature rise (0c)

ρ: Specific resistance of the conductor (ohm.m/mm2).

K value for ACSR conductors is 85, Isc value for 765kV line is 70kA, and the t is 0.5s. Inserting these values in Eq. (2), the required cross section is obtained to be 582.32 mm^2 which is able to withstand short circuit level compared to the six-wire bundled Rail conductor.

4. DETERMINING THE APPROPRIATE DISTANCE FROM THE BUNDLE, GMD AND GMR

The studied transmission line is a horizontal single-circuit line with six conductors per bundle. According to the standards, maximum distance between conductors in bundled lines is 457mm.

By studying various transmission lines, phase distance from the next phase is about 18m while this distance in lateral phases is about 36m [7].

Then geometric mean radius (GMR) and the geometric mean distance (GMD) are calculated using Eqs. (4) and (5) [8]:

$$GMR = \sqrt[6]{6D.d^5} \tag{4}$$

$$GMD = \sqrt[3]{D_{12} \times D_{13} \times D_{23}} \tag{5}$$

Where:

GMR : Geometric mean radius (m)

GMD: Geometric mean distance (m)

d: Distance between the conductors in the bundle (m)

D: Distance between the phases (m).

Inserting d = 0.430 m and D = 18 m, GMR and GMD values are obtained as follows:

GMD=22.678 m

GMR=0.371 m

By calculating the GMR and GMD, the inductance and the capacitance values of transmission line are obtained using Eqs. (6) and (7).

$$C = \frac{2\pi\varepsilon_0}{ln(\, GMD/GMR\,)} \tag{6}$$

$$L = 2 \times 10^{-7} ln \frac{GMD}{e^{-1/4} GMR} \tag{7}$$

Where:

C : The line capacitance (F/ m)

ε_0 : The dielectric coefficient of vacuum which is 8.85*10^{-12} (F/m)

GMD : Geometric mean distance (m)

GMR : Geometric mean radius (m).

By placing GMR and GMD values, inductance and capacitance values are obtained as follows:

$$L = 0.8725 \quad H\!/\!m$$
$$C = 0.01351 \quad nF\!/\!m$$

Thus, regarding network frequency f=50Hz, reactance and susceptance values of the transmission line are obtained using Eqs. (8) and (9).

$$X_L = 2\pi.f.L \tag{8}$$
$$B = 2\pi.f.C \tag{9}$$

By inserting L, C and f values,

$$X_L = 0.274 \quad \Omega\!/\!km$$
$$B = 4.24241 \times 10^{-6} \quad 1\!/\!\Omega.km$$

Rail conductors' permitted current value is equal to 985A. Also, regarding the line characteristic for which the transmitted power is considered about 5000 MW, it can be claimed that the amount of current passing through each phase with respect to line voltage 765kV is 3770A. And given that there are six wires for each phase, therefore for each bundled conductors' current passing is 630A in steady state.

As a result, Rail conductors can easily pass constant current through transmission line.

5. DETERMINING THE PROPER CROSS SECTION FOR FITTINGS

One of the problems occurred in fittings due to short circuit current is in welded joint corrosion, such as connecting two parts together or celebrating with a hole between the bolts and nuts. Considering the amount and time of current passing through lines, a cross section can be obtained using Eqs. (2) and (3) for existing connections in the line which are of steel and aluminum type such that short circuit current and in turn the generated heat do not deform them.

According to the standard for metal alloys, the values of W, C, $\Delta\theta$, ρ, t and Isc for steel are 7.8, 0.11, 0.096, 0.5 and 70, respectively, while the mentioned values for aluminum are 2.7, 0.215, 0.028, 0.5 and 70. Inserting these values in Eqs. (2) and (3) results in proper cross sections of 580 mm^2 and 330 mm^2 for aluminum and steel, respectively.

6. DETERMINING THE NUMBER OF INSULATORS

Insulators used in designed transmission line are 160kN insulators with tolerable voltage of 10kV. To calculate the number of insulators in insulator string, voltage distribution should be checked along insulator string and finally obtain the required number of insulators.

In practice, due to the capacitance between metal parts of insulator string, towers and earth, voltage distribution on insulators is not uniform. The maximum and minimum voltages on insulator strings are on the insulator connected to the conductor and the insulator connected to the tower, respectively.

To calculate the voltage distribution along the insulator string, the capacitance between insulators themselves and the tower should be determined. Although the capacitance of all insulators is not same, however, considering the short length of insulator string respect to the tower height and its uniformity, capacitance of whole insulators is same to be C_1, and the capacitance between insulators and tower is to be C_2. Accordingly, by calculating α using Eq.(7), voltage on to ends of insulator string is obtained by Eq.(8).

$$\alpha = (\frac{C_2}{C_1})^{0.5} \tag{7}$$

$$V_{kg} = V_{ng} \cdot \frac{Sinh(\alpha.K)}{Sinh(\alpha.n)} \tag{8}$$

Where, C_1 and C_2 values given in [9] are the capacitance between the metal part and earth, and insulator capacitance, respectively. Consequently, having the value of α, distributed voltage in two ends of insulators is obtained. If the voltage distribution curve is considered to be linear along insulators, in this case, $C_1/C_2=12$ and α=0.2887. In addition, K, n, V_{ng} and V_{kg} are insulator numbers we can calculate the voltage across it, the total number of insulators, phase voltage of transmission line, and *K*th insulator voltage, respectively. Inserting all of these parameters in Eq. (8), the number of insulators is obtained to be 35.

7. CALCULATING THE VOLTAGE GRADIENT

Voltage gradient around the conductor and fittings can play an important role in the phenomenon of corona and the resulted losses. According to Ref. [7] the voltage gradient for Six-bundled Rail conductors in each phase is obtained using Eqs. (9) to (11).

$$g_{max} = \frac{18.C.V}{nr}[1 + \frac{2(n-1)r\sin(\pi/n)}{GMR}] \tag{9}$$

$$C = \frac{0.02413}{Log(\frac{GMD}{GMR})} \tag{10}$$

$$GMR = [\,r.n[\frac{B_S}{2\sin(180/n)}]^{n-1}\,]^{1/n} \tag{11}$$

Where:
g_{max}: The maximum voltage gradient at the surface of conductors (kV/cm)
V: Line phase voltage (KV)
n: The number of bundled conductors per phase
r: Radius of conductor (cm)
C: Line capacitance (F/ km)
GMR: Geometric mean radius of the bundled conductors (cm)
B_s: Distance from the bundle conductors (cm).
According to the Standard of Power Ministry [7], g_{max} value should not exceed the critical voltage gradient $g_0=15.9$ kV/cm, which the performed calculations also are in the desired range. However to limit the amount of voltage gradient in the surrounding insulator strings and fittings, corona rings can be used [10].

8. CALCULATING CRITICAL VOLTAGE

In a transmission line, if the applied voltage reaches to the critical value, the surrounding air begins to be ionized. Corona losses and communication disturbances to be in a certain level, it is required that according to Ref. [7] the applied voltage to the conductor does not exceed 1.8 times of the critical voltage.
Critical voltage value is a function of the line physical features and environmental conditions which is calculated using Eqs. (12) to (14).

$$g_v = g_0.(1 + \frac{0.3}{\sqrt{\delta.r}}) \tag{12}$$

$$\delta = \frac{298P}{T} \tag{13}$$

$$V_C = g_v.m.\delta.r.ln(GMD/r) \tag{14}$$

Where:
g_v : Critical voltage gradient (kV/cm)
g_0 : The threshold breakdown voltage (KV / cm)
r : Radius of conductor (cm)
δ : Relative density
P : Air pressure (At.)
T : Air temperature (K°)
m : Coefficient of conductor surface roughness
GMD : Geometric mean distance between conductors (cm).

Due to different climatic conditions existing in Iran, the temperature of 40^0C and height of 1000m is considered which can be a good condition in summer in most parts of the country. The value of m for ACSR conductors is 0.85. It is noteworthy that the values of g_0 and GMD are mentioned formerly.

By inserting the mentioned parameters in Eqs. (12) to (14), the critical voltage is V_C=267.843 kV.

$$\frac{V_{ph}}{V_C} = \frac{441.686}{267.843} = 1.65 \prec 1.8$$

9. THE AMOUNT OF CORONA LOSSES

The main disadvantage of corona phenomenon is the resulted losses which may be increased to ten times on rainy or snowy days. In a typical EHV transmission line, the losses can be of a significant amount. Therefore, in designing transmission line the corona losses should be also calculated [11].

There are two methods for calculating corona losses. One of these methods is presented by Pik which is formulated according to Eq. (15).

$$P_C = 0.00314.F.(\frac{V}{log(\ GMD\ /\ r\ )}) \tag{15}$$

Where:
P_C : Corona losses (kW / km)
V : Effective-phase voltage (kV)
GMD : Geometric mean distance between conductors (cm).
r : Radius of conductor (cm)
F: Constant coefficient and the critical voltage

Studies show that when corona losses are low, the mentioned equation has no good accuracy, and at this situation using Peterson method would has good accuracy as shown in Eq. (16).

$$P_C = \frac{0.545}{\delta}(V - V_C) \cdot \sqrt{r/GMD} \tag{16}$$

In which;
Pc: Corona losses (kW / km)
V : Effective-phase voltage (kV)
V_c : A critical voltage (KV)
GMD : Geometric mean distance between conductors (cm).
r : Radius of conductor (cm)

Given that the amount of V_{ph}/V_C is less than 1.8, therefore, to calculate corona losses Peterson equation is used as follows:

P_c=1.44 kW/km

Corona losses in a 1000km transmission line are almost 1.5MW/km which is a good value.

10. CORONA RING DESIGN

Figure 2 shows an example of the 765 kV insulator strings with 35 insulators divided into four branches (to withstand tensile forces), in which to limit the voltage gradient along the insulator string ring located in proper position and with appropriate dimensions. In addition to reduction of the voltage gradient around insulator string causes to reduction of losses.

In corona ring design, three main parameters should be determined [12],
1) Diameter profiles
2) Radius of the ring
3) Position of ring along the insulator strings
For this purpose, an insulator strings along with a corona ring are simulated in Quick Field simulation software. Ring radius and profile diameter are changed in the range of different to obtain optimal dimensions for corona ring. The corona ring diameter of 7cm and radius of 150cm are the best optimized to reduce the size of the voltage gradient around insulators.
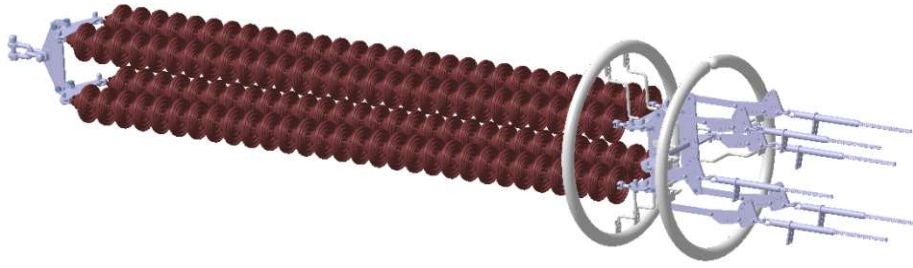
Figure 2. A typical corona ring

After determining the corona ring dimensions, the height of the corona ring is also examined along insulator strings. Finally, with the simulation software and changing the height respect to the first insulator, it was determined that the height of 4cm above the first insulator to corona rings that is placed along with insulators, and the second corona ring on the connections of end clamp create the best position to decrease the voltage gradient [10, 12].

11. VOLTAGE REGULATION PERCENTAGE

Voltage regulation percentage is the change of voltage from zero to the rated voltage divided to the nominal value which is expressed by Eq. (17).

$$VR\% = \frac{V_s - V_r}{V_r} \times 100 \tag{17}$$

Where:
VR%: Line voltage regulation percentage
Vs : Sending end voltage (kV)
Vr : Receiving end voltage (kV)
Vr is the line rated voltage. And Vs is obtained in long transmission lines as follows:

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \tag{18}$$

Where:
Is : The sending end current (A)
Ir : The receiving end current (A). Values of A, B, C and D are obtained from Eq. (19) to (22).

$$A = cosh(\gamma l) \tag{19}$$
$$B = Z_c \, sinh(\gamma l.) \tag{20}$$
$$C = \frac{1}{Z_C} \sinh(\gamma l) \tag{21}$$
$$D = cosh(\gamma l) \tag{22}$$

In which:

$$\gamma = \sqrt{z.y} \tag{23}$$

$$Z_C = \sqrt{\frac{z}{y}} \tag{24}$$

Where:
y: Parallel Admittance of transmission line (Ψ/ Km)

z: Series impedance of transmission line (Ω/ Km).
Inserting the parameters obtained from section three, voltage regulation percentage will be:

VR%= 0.042

Given that the voltage changes from ±10% in line is allowed, the amount of voltage regulation percentage is appropriate.

12. SIGNIFICANTLY REDUCING INSTALLATION PERMITTED DISTANCE AND COST OF TRANSMISSION LINES

One of the most striking features of the transmission lines are the permitted distance which is directly related to the cost of transmission lines installations [2]. Permitted distances requirements depend on several transmission line factors which are considered during calculations. These factors include: electric and magnetic fields, and the safety distance required for each voltage level, considering the distance required between conductors in the line to prevent the effects of wind and storm, planning and future development of lines due to the increase in consumer demand, and mechanical considerations and considering the permitted distance between the line conductors to prevent the occurrence of galloping in two circuits transmission line [5]. In most cases, the allocation of extra line distances in designing and constructing the line leads to better control of the line and thereby increase network reliability. However, it is impossible in many cases due to lack of space, expensive lands, and/or a favorable ground for the construction of this line. So the best solution to solve the permitted distance problem is the use of high voltage lines, which in this case by replacing high voltage lines instead of low voltage lines will lead to a significant reduction in the size and permitted distance.

As it is depicted in Figs. (3) and (4), for construction of a 765 kV single circuit transmission line with 6 conductors per phase about 200 feet permitted distance is required, while for a 400kV two circuits transmission this value is about 150 feet. Thus, for transmitting the equal electric power by 400 kV power transmission line, it is required to have three 400 kV transmission lines of two circuits or six single-circuit transmission line. In this case, the permitted distance is increased 450 feet (2.5 times) for two-circuit line and 900 feet (4.5 times) for single-circuit line. Also, as it can be seen from Figs. (3) and (4), by the voltage reduction the problem of permitted distance is resolved. Given the importance of construction of high voltage lines, it is clear that this will result in lower costs [13, 4].

Six 345 kV single lines
900 ft

One 765 kV single line
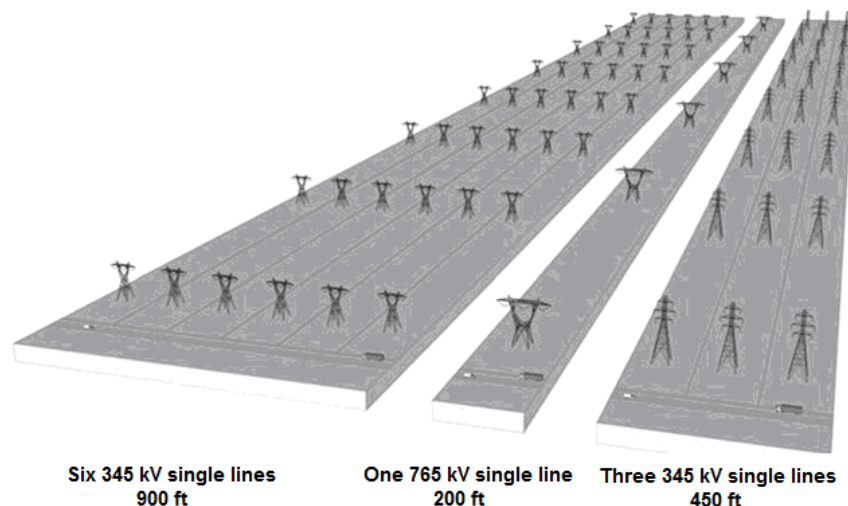200 ft

Three 345 kV single lines
450 ft

Figure 3. Comparison between 345kV and 765 kV permitted distance with equal transmission capacity
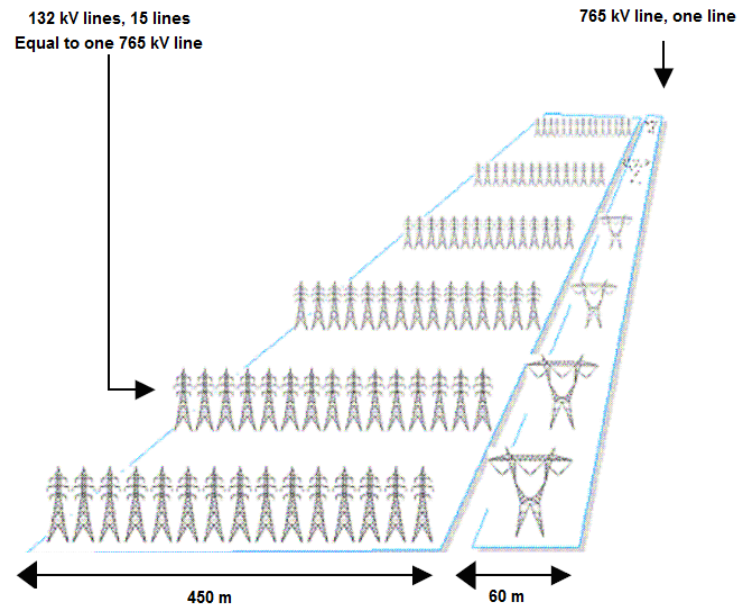
Figure 4. Comparison between 132kV and 765 kV permitted distance with equal transmission capacity

13. 765 kV NETWORK RELIABILITY RESPECT TO THE LOWER VOLTAGE LEVELS

In studies conducted in various types of transmission lines of different voltage levels and the comparison with 765 kV voltage reveals that the transmission lines of 765kV level are inherently more reliable than the other lower voltage levels lines. When 765 kV transmission lines with six conductors in each phase is utilized, due to the increase in geometric mean radius, and the uniform distribution field, the level of corona effects and noises are acceptable [13, 4].

According to statistics results obtained in [3], 765 kV transmission lines have one outage in every 100 miles per year, while for 500kV transmission lines the outage is 1.4. Further, because these lines are of single-circuit type, the faults are single phase to the tower and the two-phase as well as three-phase faults are rare resulting in less outage. Also, using single circuit line causes no Galloping phenomenon, also due to the far distance between phases the fault occurrences by phases are reduced [14].

14. CONCLUSION

Given the growing need for electrical energy, appropriate measures are essential to overcome the problems of electric power transmission lines, reducing permitted distances, increasing network reliability from the view point of less outage, power loss reduction especially corona losses, communication disturbances reduction and many other issues. In this paper, the importance of increasing voltage of transmission lines and the benefits that resolve many of the problems are studied, and finally, a single circuit 765kV transmission line with six conductors per phase were compared with lower voltage levels transmission lines and the results were analyzed.

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