Design and Technical Analysis of 500-600 kV HVDC Transmission System for Turkey

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Abstract

Design and technical analysis of an overhead 500 - 600 kV HVDC transmission system for Turkish Power Transmission System is presented in this paper. Based on the design, resistive losses and corona losses are calculated using analytical formulations. Maximum electric field stress on the conductors is determined by using Comsol Multiphysics Software. Several bundle geometries, conductor types and voltage levels were taken into consideration. A simplified 2D model of the transmission lines, and tower were considered in the electrostatic simulations.

1. Introduction

The concept of high voltage direct current (HVDC) power transmission emerged in the mid-1920s for reliable and economic transmission of bulk power to longer distances as well as for undersea applications. HVDC transmission went to a second phase with the development of the silicon semi-conductor thyristor in 1970s. HVDC is an effective technology to transmit vast amounts of electric power over very long distances with lower electrical losses in comparison with AC systems. Moreover, it is the best alternative for subsea electrical transmission and for the interconnection of asynchronous AC grids, providing efficient and stable transmission and control capabilities. Nowadays, there are a considerable number of HVDC applications all over the world [1]. With the dawn of a new smart energy era, and the need to build a smarter grid, it is expected that the HVDC systems will grow far beyond its traditional position as a supplement to AC transmission.

HVDC links have several technical, economical and environmental advantages over AC ones. Technically, these systems can transmit bulk power over very long distances, with higher efficiency and lower electrical losses. HVDC enables secure, and stable asynchronous interconnection of power networks that operate on different frequencies. In addition, HVDC transmission provides instant and precise control of the power flow. They show smaller short circuit currents as well as smaller switching overvoltages than AC systems. In addition, they show smaller corona losses and better radio interference (RI) performance [2-3]. On the other hand, the most important disadvantages of HVDC systems (in fact AC grid connected by DC links) are the elevated cost of converter stations, the reactive power requirements of the grid, the presence of harmonics, and the difficulties of switching actions [4].

The HVDC transmission system design depends on the amount of energy to be transferred as well as on some side-specific characteristics of the countries. In this paper, an overhead HVDC transmission system was designed for Turkey. Depending on the selected design, resistive losses and voltage drops were estimated. In order to obtain corona losses, the surface gradients of the conductors were determined by using Comsol, which uses Finite Element Method.

2. HVDC Transmission System Design

The designing process of an HVDC system starts with the estimation of the power intended to be transmitted. The amount of power to be transmitted is the dominant factor affecting the selection of operation type of the HVDC transmission line (monopolar or bipolar), which include the conductor size and conductor configuration. The second important parameter is the locations of the sending and receiving converter stations of the system. It is clear that the sending end should be located close to the generation stations. However, there are several different receiving end alternatives which are mainly determined according to economic considerations. Once the power level and the terminal locations of the system are determined, several HVDC system alternatives can be compared in terms of power losses, voltage drops or corona losses.

Because of the high terminal costs, and HVDC transmission systems can be more economic than AC transmission only over certain transmission distances. Although this distance depends on the amount of power, a threshold level of 500 km is generally assigned as the lowest transmission distance for economic HVDC applications. The South-east part of Turkey has a big hydro generation capacity, which is transferred to the western part of the country by means of several 400 kV AC transmission systems. Therefore, the sending end of the HVDC link is selected as KEBAN. The selection of KARAKAYA or ATATURK DAM as the sending points will not change the results. On the other hand, Marmara Region (Istanbul, Kocaeli, Adapazari, Bursa) is the most power consuming part of Turkey. Among them, Adapazari seemed the best location for the receiving end of the system, since the power can be transferred from that location to other cities by HVAC transmission lines. Base on the above considerations, Keban and Adapazari are chosen as the DC station locations. Red lines in figure 1 indicate the desired HVDC lines and converter station locations from

Keban to Adapazarı. The distance between these two points is about 1000 km. The HVDC link route is assumed to be the same with of the exisiting 400 kV AC transmission system.

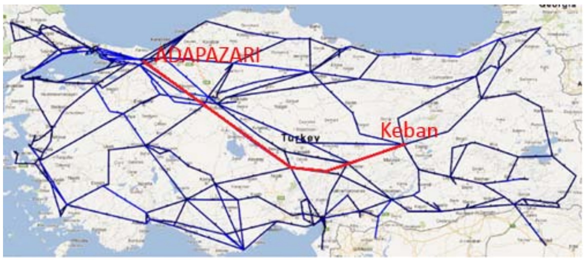

Fig. 1. Keban to Adapazarı HVDC power transmission system

The generation capacity of KEBAN and KARAKAYA Hydroelectric power stations are 1380+1800=3180 MVA. According to power capacity of the Keban hydro power plant and the power requirement of the west side of the Turkey, 3000 MW was selected as the rated power for the designed HVDC system.

For 3000 MW, the bipolar HVDC transmission system is more suitable due to its higher power capacity in comparison to the monopolar option. This configuration can carry a maximum of 1500 MW per pole. There is no need for metallic return electrode due to the long distance of the transmission line. Total length of the transmission lines is 1000 km approximately 2500 overhead line towers are needed. Compared with the other HVDC system in the world, voltage levels of the system were chosen either ±500 kV or ±600 kV. Maximum current carrying capacities are 3000 A for ± 500 kV and 2500 A for ± 600 kV.

A bipolar HVDC transmission system is the combination of two monopolar DC systems and a return path. During normal operation, a small unbalanced current flows through the return path. If the total power of transmission systems exceeds mono pole capacity, bipolar configuration must be used. This system can transmit some part of the power during an outage or in a maintenance situation in one pole. Another advantage over two monopolar solution, an option used when the outage of the complete system by external events wants to be avoided, is the reduced cost because of lower losses and lack of additional return path.

In figure 2, a bipolar HVDC system with balanced operation can be seen. The return path can be either ground or metallic according to transmission distance. If the distance is relatively short then a metallic return conductor is used as an alternative way to ground.

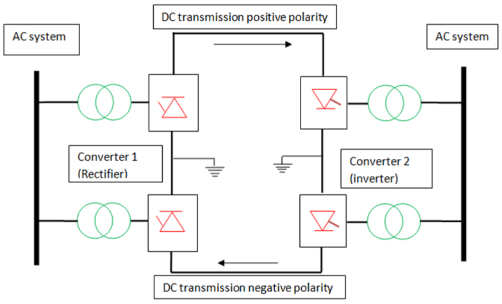

Fig. 2. HVDC Bipolar balanced operation

The conductor size of an HVDC transmission system is related with the power and current value of the poles. For 3000 MW, conductors were selected as 1272 MCM for the option of 2500 A, and 954 MCM for the option of 3000A. Besides conventional ACSR conductors, ACSR with trapezoidal wires, and new age conductors as AAC and AAAC were also considered as alternative solutions.. Triple and quadrupole bundling are selected as alternative conductor configurations in accordance with the intended power rating three or Three alternative bundle configurations; namely, 4x1272 MCM, 3x1272 MCM and 3x954 MCM were considered suitable for the design. As a shield wire a 9.5 mm^2 7-stranded conductor was selected.

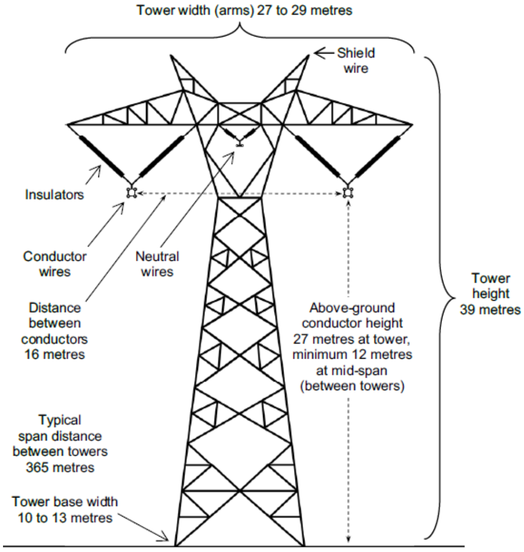

Fig. 3. HVDC tower geometry and dimensions [9]

Figure 3 illustrates the selected HVDC tower for both voltage levels, ± 500 kV and ± 600 kV. The total length of the tower is 39 m and tower base width is 10 m minimum. Conductor height is 27 m, and the distance between the poles and shield wire is 12 m. The distance between pole conductors is 16 m, long enough to avoid dielectric breakdown between them.

3. Calculation of Resistive (joule) Losses and Corona Losses

After defining the line parameters for the HVDC transmission system, several calculations are performed to assess the performance of the alternative solutions. In this study, Joule losses, corona losses and voltage drops are selected as the comparison parameters. These parameters were calculated for the designed transmission system. Each calculation was repeated for the different conductor types and bundle configurations.

Line (Joule) losses are one of the main design criteria for overhead lines with long distances. In the case of 3000 MW power and 600 kV rated voltage, the loss calculations are given below.

Current flowing per pole for 600 kV HVDC line is,

$$I = \frac{S_{max}/2}{U} = \frac{1500\;MW}{600\;kV} = 2500\;A. \tag{1}$$

Sub-conductor current for four-bundle conductor is calculated as:

$$I_1 = \frac{I}{4} = 625\;A. \tag{2}$$

Joule losses per km for four-bundle 1272 MCM ACSR conductor (DC resistance for 20 ºC is 0.044 Ω/km) is calculated as:

$$P = I_1^2 x 0.044 x 4 = 68.75\;kW/km \tag{3}$$

Total line losses then for two poles and 1000 km are:

$$P_{total} = 68.75x2x1000 = 137.5\;MW \tag{4}$$

It is clear this is the loss for the maximum transmitted power. In practice, the amount of transmitted power depend on the load profile. . A daily load curve for August 2016 is chosen as a representative load profile, and it is adopted for 3000 MW peak power. Figure 4 shows the adopted daily load profile used in this study, where the peak value of the load is set to 3000 MW.

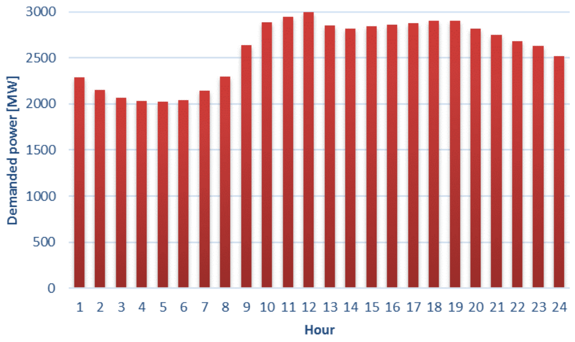

Fig. 4. Modified daily load curve

The transmission line loss calculations for every hour were done for all conductor sizes, bundle configurations, and transmission voltages of 500 kV and 600 kV. The average of the losses along 24 hours was assigned as the average hourly line loss for the related configuration.

Table 1. Line losses for different configurations

Configuration		Line Losses (MW)			
		AAC	ACSR	ACSR/TW	AAAC
500 kV	4x1272 MCM	173	149	149	169
	3x1272MCM	230	199	199	226
	3x954 MCM	271	267	267	298
600 kV	4x1272 MCM	120	**103**	**103**	117
	3x1272MCM	160	138	138	157
	3x954 MCM	188	185	185	207

The average values for all conductor types are shown in Table 1. Note that, this computation does not include conductor temperature variations with respect to transmitted power and assumes a constant DC resistance at 20 ºC. . According to the results, the best designs with respect to line losses are the 600 kV four-bundle ACSR and the 600 kV four-bundle ACSR/TW configurations.

Note that, since the capacity and the cost of the conductor configurations are not taken into account, such a global comparison on a loss basis may not be fair and objective. Besides the calculations of the line losses for 500 kV and for 600 kV DC lines, the same daily load curve was used to calculate the losses of a 380 kV three phase AC transmission system with the same length. Similar amount of active power than in the DC line was assumed to be delivered through the 1000 km AC system. During the calculations, the power factor (cosϕ) was selected as 0.95. The average line losses in the AC line, for 24 hours, was calculated and compared with the average line losses in the DC transmission systems. Figure 5 shows the comparison of the joule losses in AC and DC considering the 4x1272 MCM configuration, the results are presented for the four types of conductor. The 600 kV DC option shows the best performance with all the conductor types.

Fig. 5. AC and DC joule losses comparisons

One of the first formulas of the DC corona losses for both unipolar and bipolar systems was derived from field experiments using a test transmission line. According to Knutsen and Iliceto [10], corona losses for unipolar system can be written as;

$$P = U.k_c.n.r.2^{0{,}25(g-g_0)}.10^{-3} \tag{5}$$

where U is the line voltage, n is the bundles sub-conductor number, r is the radius of sub-conductor, g and g_0 are the maximum electrical filed of the bundle conductors and reference field value, respectively. The reference value of the electrical filed is dependent on relative air density (g_0=22.δ kV/cm). k_c is a constant and it varies with the state of the conductor surface. For flat, smooth and clean conductor, k_c is equal to 0.15. However, k_c is 0.35 for old, rough and polluted conductors.

For bipolar DC lines, corona losses are highly dependent on the height of the conductors and pole spacing. Hence the above formula can be written with some modifications for the bipolar system; [11]

$$P = 2U.\left(1+\frac{2}{\pi}tan^{-1}\frac{2H}{S}\right).k_c.n.r.2^{0,25(g-g_0)}.10^{-3} \qquad (6)$$

where U is the bipolar line voltage, H is the conductor height from the ground and S is the pole spacing. This formula was used in this work to compute the DC corona losses of the alternative conductor configurations..

Calculations were done for all three conductor configurations and two voltage levels. For the calculations, ambient conditions were assumed to be standard conditions (T=20 ºC and P=760 mmHg). Pole spacing and conductor height for the bipolar corona loss formula were chosen according to typical ±500 kV HVDC tower geometry.

Considering the conductor height of 27 m and the pole spacing of 16 m, the corona losses for a 1000 km HVDC transmission line were computed for different conductor types and configurations, the results are summarized in Table 2.

Table 2. Calculated DC Corona Losses

Voltage	**Corona losses [MW]**		
	4x1272 MCM	**3x1272 MCM**	**3x954 MCM**
500 kV DC	2,409	1,807	1,528
600 kV DC	2,891	2,168	1,834

The voltage drop is an important comparison parameter both for AC and for DC ststems. Therefore, it must be calculated for all alternative designs. In this study, the voltage drop values for 500 kV and 600 kV DC systems were calculated for all intended line configurations. Table 3 shows the percentage of voltage drop rates for all conductor types and voltage levels considered in the design. According to Table 3, the option with 600 kV and 4x1272 MCM ACSR conductor is the best alternative among the others. Compared with the AC voltage drops, the values are relatively high due to the lack of the tap-changers on the HVDC lines. Moreover, HVDC lines are only used for transmitting power and they do not directly feed any kinds of load, so the voltage drop values are acceptable.

Table 3. Calculated voltage drops

Configuration		**% Voltage Drop**			
		AAC	**ACSR**	**ACSR/TW**	**AAAC**
500 kV	4x1272 MCM	6,59	5,68	5,68	6,46
	3x1272MCM	8,78	7,58	7,58	8,61
	3x954 MCM	10,33	10,16	10,16	11,37
600 kV	4x1272 MCM	4,58	**3,95**	**3,95**	4,49
	3x1272MCM	6,10	5,26	5,26	5,98
	3x954 MCM	7,18	7,06	7,06	7,89

4. Electric Field Analysis

Electric field values on the conductor surfaces are very important for corona performance of the line. So, it must be calculated or simulated in order to find the maximum electrical stresses. For this reason, the DC transmission lines were modeled using COMSOL Multiphysics. The Bipolar transmission lines were modeled with three different configurations: 4x1272 MCM, 3x1272 MCM and 3x954 MCM. The distance between the sub-conductors was selected as 45 cm. The 600 kV HVDC tower was included in the geometry model with real dimensions and shield wires. The geometry can be seen in Figure 6 for the 4x1272 MCM four-bundle conductor configurations.

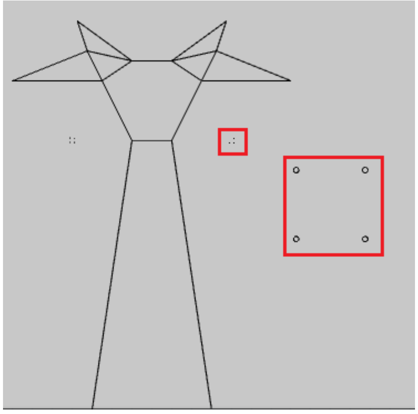

Fig. 6. FEM model geometry with tower (2D planar model)

Due to the bipolar operation, +600 kV was applied to the one pole (right side), and -600 kV was applied to the other pole (left side). The whole tower frame and the shield wires were kept at ground potential. In Figure 7, electrical field distribution of the DC transmission system is illustrated. The electric field on conductor surface is not uniform due to the bundle configuration and proximity effect of the tower.

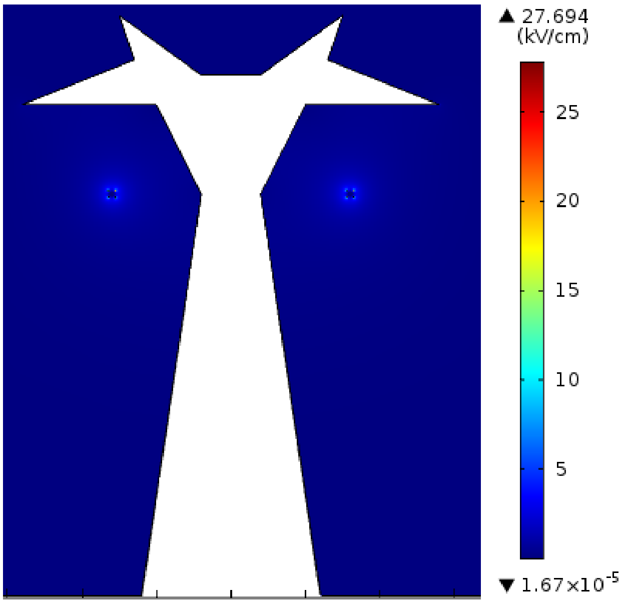

Fig. 7. Electrical field distribution of bipolar HVDC system (four-bundle configuration)

A detailed surface electrical field distribution of the sub conductors for the 4x1272 MCM configuration can be seen in Figure 8. Electrical field strengths of the conductors at the tower side were higher than of the conductors at the opposite side. Maximum electrical field strength for this configuration and voltage level was calculated as 28.951 kV/cm and average field value for all sub conductors was 23.28 kV/cm.

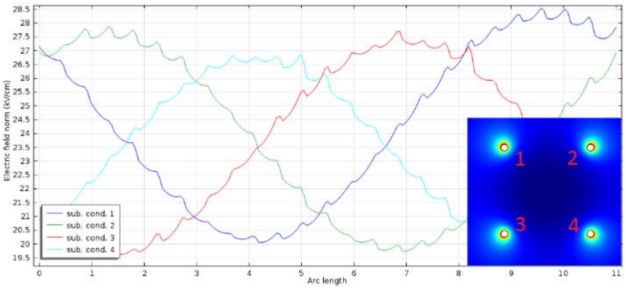

Fig. 8. Surface electric field distribution of four-bundle configuration

Maximum electric field strengths for all conductor, bundle configurations, and voltage levels are shown in Table 4. According to the table, the best configuration and voltage level was achieved for 4x1272 MCM with 500 kV. The highest surface gradients were obtained using triple-bundle configurations in the transmission system

Table 4. Maximum electrical field strengths on the sub-conductor surfaces

	Maximum electrical field stress [kV/cm]		
Voltage [kV]	**4x1272 mcm**	**3x1272 mcm**	**3x954 mcm**
500	23.376	27.360	31.846
600	28.951	32.833	38.215

5. Conclusion

In this study, several alternatives for a possible HVDC transmission application in Turkey is analysed.. The locations of converter stationsand power rating of the transmission system are selected according to power generation and consumptions density of Turkey. Voltage rating is then selected according to the intended power level Four different conductor types and three conductor bundle configurations were compared in terms of line losses, corona losses and voltage drops. Typical August daily load curve is used for line loss computations. In addition, an electrostatic field analysis was performed using bipolar system with transmission tower (2D planar). Maximum electrical field strengths on the conductor surfaces are computed and compared for the intended configurations.

The calculations showed that, all three configurations (4x1272 MCM, 3x1272 MCM and 3x954 MCM) are suitable for HVDC transmissions in Turkey. Different conductor types and bundles can be selected assuming different criteria. 3x954 MCM shows the best corona loss performance for 500 kV voltage level. However, 4x1272 MCM configuration at 600 kV showed the lowest resistive losses among all three configurations, as expected.

This initial study will later be improved to include more precise technical computations as well as to include economic considerations of the system.

Acknowledgments

This research is funded as a part of “215E262 Corona discharge characterization and electromagnetic effects of HVDC transmission lines” project under the framework of the “Bilateral Research and Technology Cooperation Turkey-Mexico” organized by “The Scientific and Technological Research Council of Turkey TUBITAK” and “The National Council of Science and Technology-CONACYT”.

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