Study on Probability Distribution Model of Air Density for Transmission Lines Corridor in High-altitude Regions

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Abstract. Data analysis on air temperature, relative humidity and atmospheric pressure from a typical national meteorological station in 4200m high-altitude regions was carried out. Time duration of the meteorological data is more than 30 years. Statistical values of air density in this national meteorological station were calculated. Whether analyzing by year average meteorological data, month average meteorological data or day average meteorological data in the month with the highest wind velocity, the air density in high-altitude meteorological station conforms to the normal distribution. The year average air density is basically equal to the month average value. The day average air density is higher than the year or month average value by 6.1%. When the altitude height is close and the terrain is similar, the statistical air density based on the field observation data near the transmission lines corridor basically meets well with the values based on 30-year data from national meteorological stations. The relative variances between the field measured 10min average air density and the year average air density, the month average air density as well as the day average air density are 2.3%, 2.4% and7.9% respectively.

Keywords: High-altitude; Air density; Normal distribution; Transmission lines; Field observation.

1. Introduction
The “transmission lines in high-altitude regions” generally refer to transmission lines passing through regions above 3,000m in altitude. With the construction of Sichuan-Tibet power grid and Tibet-Ali power grid connection projects, the length of transmission lines in Tibet and other high-altitude regions has increased by years. Wind load is an important control load for transmission line design, which is related to the economy, safety and reliability of line engineering in high-altitude regions. In the vast and sparsely populated high-altitude regions of Tibet, meteorological stations and observation data are limited. The meteorological observation data that can be used to guide the construction and operation of transmission line projects are seriously lacking. The impact on the reliability and economy of transmission lines is significant. Therefore, the study on wind field and wind load characteristics of
transmission lines in high-altitude regions with strong wind in Tibet can provide basic data and theoretical basis for the design load values of transmission lines in previously mentioned regions. This is of great significance for realizing lean wind-resisting design of transmission lines in the regions concerned.

In recent years, the change in air density in high-altitude regions and its influence on the design wind pressure of transmission lines have gradually received attention. Air pressure, air temperature and water vapor pressure all depend on the altitude to some extent. In the current codes for design of transmission lines, only IEC and ASCE take into account the influence of altitude and air temperature and give the calculation method for air density considering altitude correction, but its corrected altitude range is only 0-3,000m. Although the correction formula for air density is given in the Chinese standard - Technical Code for Meteorological Survey in Electric Power Engineering (DL/T 5158-2012), but the air density is still assumed approximately to be 1.25kg/m³ at the temperature of 15℃ under the air pressure of 101.325kPa due to lacking the field observation verification in the corridor area of transmission lines.

There are few studies on the field observation and wind load characteristics of transmission lines at altitudes above 4,000m at home and abroad. They mainly focus on the theoretical analysis of the changes in air density along with the altitude and its influence on the design wind pressure of transmission lines. YANG Fengli et al studied the temperature, humidity and pressure field observation near the transmission lines corridor in high-altitude region, Tibet; they believed that the basic wind pressure in the region with an altitude of 4,300m is at least 31.7% lower than the basic wind pressure based on the standard air density.

The air density is the most important parameter affecting the wind load of transmission lines in high-altitude regions. Determining the probability distribution of high-altitude air density is the key to accurately calculate the fundamental wind pressure and design wind load of transmission lines in high-altitude regions; however, there are few studies on this subject. The air density in a natural year changes with the environmental characteristics such as temperature and humidity. The differences between the annual average and maximum of air densities can be more than 15%. Similarly, there is also certain differences between the average and maximum air densities in different years. The design wind velocity during the recurrence period is determined with reference to the annual maximum average wind velocity samples according to the type-I extreme value distribution. However, it is not known whether the air density conforms to the type-I extreme value distribution or normal distributions. It should be determined by collecting the temperature, humidity, and pressure samples from existing stations over the years and combining them with the field observation data of typical sites for statistical analysis.

In this paper, by analyzing the temperature, humidity and pressure field observation data from typical national meteorological stations at altitudes above 4,000m for the past 30 years, the statistical values of air density from the typical meteorological stations were calculated. The probability distribution model of high-altitude air density was determined. The statistical values of air density from meteorological stations were compared with the field observation values of transmission line corridors with similar altitudes and landforms. The differences between the average values of air density from the meteorological stations and the field observation values of transmission line corridors were presented. The study results can provide a reference and basis for wind load calculation of transmission lines in high-altitude regions.

2. Site Selection
The Dangxiong meteorological station at the altitude of 4,200m with higher grade, less number of relocations, fewer changes in the surrounding environment and better continuity of meteorological data are selected in view of the construction time, instruments and station site changes. The meteorological data of the last 30 years are used as the base data to analyze the statistical value of air density and probability distribution model. As the national meteorological station and transmission lines corridor are far apart, a high-altitude field observation tower for gradient wind and total meteorological information is established in Yangbaijing, Dangxiong County in order to verify the validity and applicability of the air density statistical values and probability distribution models for transmission line
design. It is located in a mountainous region at an altitude of 4,307m with the same landform as the national meteorological station (Dangxiong); the field observation period is 1.5 years. The air density statistical values obtained from this field observation site are compared with the data from the national meteorological station.

![Figure 1. Yangbajing Anemometer Tower in Dangxiong County](image)

3. Calculation Method for Air Density

Air consists of dry air and wet air, and air density is the sum of dry air density and wet air density. Considering the effect of temperature, humidity and air pressure, the air density $\rho$ can be expressed as:

$$
\rho = \frac{0.001276}{1 + 0.00366t} \left( \frac{p - 0.378 p_{vap}}{100000} \right)
$$

(1)

Where $t$ is air temperature, °C; $p$ is air pressure, Pa; $p_{vap}$ is vapor pressure, Pa.

DL/T 5158-2012 stipulates that $t$, $p$ and $p_{vap}$ shall be calculated based on the local long-time annual average value. The calculation formula of vapor pressure $p_{vap}$ based on air temperature, air pressure and humidity is:

$$
p_{vap} = \frac{10(10.286T - 2148.4909)}{T - 35.85}
$$

(2)

Where $T$ refers to the annual average absolute temperature in Kelvin, $T=273.16+t$, °C.

4. Analysis on Field Observation Data and Probability Distribution Model

4.1. Analysis of Meteorological Station Data

The transmission lines are designed with reference to the basic wind velocity with high wind velocities in the recurrence period, so it is also necessary to pay more attention to the situation corresponding to large wind velocity samples when studying air density or basic wind pressure. In this paper, the study on high-altitude air density is classified into two cases: In case I, the annual average and monthly average temperature, atmospheric pressure and relative humidity of the last 30 years are used to calculate the annual average air density value; in case II, the daily average minimum temperature, maximum atmospheric pressure and maximum relative humidity of the last 30 years in the months with relatively high wind velocity are used to calculate the air density value.

The calculated annual average air density and monthly average air density of the last 30 years at Dangxiong Station are given in Table 1 and Table 2 respectively. The maximum wind velocity at Dangxiong Station occurs generally from January to March, which is commonly observed in February. The daily average data of February for the last 30 years is statistically analyzed. The minimum air temperature, maximum atmospheric pressure, and maximum relative humidity are taken with consideration to higher air density, and the daily average air density values thus calculated are given in Table 3.
### Table 1. Annual Average Air Density Values of Last 30 Years at Dangxiong Station

| Year | $t^\circ\text{C}$ | $p$/hPa | $p_{vap}$/hPa | $\rho$(kg/m$^3$) |
|------|----------------|---------|--------------|----------------|
| 1980 | 1.1            | 604.4   | 28.210       | 0.755          |
| 1981 | 1              | 604.1   | 28.178       | 0.754          |
| 1982 | 1.4            | 603.8   | 28.304       | 0.753          |
| 1983 | 1.1            | 604.2   | 28.210       | 0.754          |
| 1984 | 2.2            | 603.7   | 28.553       | 0.751          |
| 1985 | 2.2            | 603.8   | 28.553       | 0.751          |
| 1986 | 1.7            | 604.3   | 28.397       | 0.753          |
| 1987 | 1.9            | 605.5   | 28.459       | 0.754          |
| 1988 | 2.3            | 605     | 28.584       | 0.752          |
| 1989 | 1.9            | 604.1   | 28.428       | 0.753          |
| 1990 | 1.8            | 604.8   | 28.272       | 0.755          |
| 1991 | 1.9            | 604.3   | 28.490       | 0.753          |
| 1992 | 0.4            | 604.7   | 27.990       | 0.757          |
| 1993 | 1.9            | 605.2   | 28.459       | 0.753          |
| 1994 | 1.3            | 605.1   | 28.272       | 0.755          |
| 1995 | 2.5            | 604     | 28.646       | 0.750          |
| 1996 | 2.4            | 604.2   | 28.615       | 0.751          |
| 1997 | 1              | 604.4   | 28.178       | 0.755          |
| 1998 | 2.6            | 605.3   | 28.676       | 0.751          |
| 1999 | 2.7            | 604.4   | 28.707       | 0.750          |
| 2000 | 2.1            | 603.5   | 28.522       | 0.751          |
| 2001 | 2.4            | 604.4   | 28.615       | 0.751          |
| 2002 | 2              | 604.9   | 28.490       | 0.753          |
| 2003 | 2.4            | 604.6   | 28.615       | 0.751          |
| 2004 | 1.8            | 604.7   | 28.428       | 0.753          |
| 2005 | 2.5            | 603.6   | 28.646       | 0.750          |
| 2006 | 3.1            | 604.9   | 28.831       | 0.749          |
| 2007 | 3.1            | 604.2   | 28.831       | 0.749          |
| 2008 | 2.6            | 604     | 28.676       | 0.750          |
| 2009 | 3.5            | 604.2   | 28.954       | 0.747          |
| 2010 | 3.2            | 604.7   | 28.862       | 0.749          |
| 2011 | 2.6            | 604     | 28.676       | 0.750          |
| 2012 | 2.8            | 603.2   | 28.738       | 0.748          |
| 2013 | 2.5            | 604.8   | 28.646       | 0.751          |
| 2014 | 2.9            | 604.5   | 28.769       | 0.750          |
| 2015 | 2.9            | 605.2   | 28.769       | 0.750          |
| 2016 | 3.2            | 605.3   | 28.862       | 0.750          |
| Average | 2.19 | 604.4 | 28.548 | 0.751 |

### Table 2. Monthly Average Air Density Values of Last 30 Years at Dangxiong Station

| Month | $t^\circ\text{C}$ | $p$/hPa | $p_{vap}$/hPa | $\rho$(kg/m$^3$) | $V$(m/s) |
|-------|----------------|---------|--------------|-----------------|----------|
| Jan.  | -8.6           | 600.9   | 25.044       | 0.779           | 2.1      |
| Feb.  | -5.5           | 600.2   | 26.084       | 0.769           | 2.7      |
| Mar.  | -1.5           | 601.9   | 27.387       | 0.759           | 2.9      |
| Apr.  | 2.2            | 603.7   | 28.553       | 0.751           | 2.6      |
| May   | 6.4            | 604.6   | 29.833       | 0.740           | 2.5      |
| Jun.  | 10.6           | 604.7   | 31.070       | 0.728           | 2.4      |
| Jul.  | 11.3           | 605.8   | 31.272       | 0.728           | 2.1      |
| Aug.  | 10.5           | 607     | 31.041       | 0.731           | 2        |
| Sept. | 8.3            | 607.6   | 30.398       | 0.738           | 1.9      |
| Oct.  | 2.9            | 606.9   | 28.769       | 0.753           | 2        |
| Nov.  | -3.4           | 605.8   | 26.774       | 0.770           | 1.5      |
| Dec.  | -7.4           | 603.8   | 25.450       | 0.779           | 1.6      |
| Average | 2.15 | 604.4 | 28.473 | 0.752 | 2.2 |
Table 3. Daily Average Air Density Values of Last 30 Years at Dangxiong Station

| Feb./Day | t/℃  | p/hPa | p_vap/hPa | ρ/(kg/m³) |
|----------|------|-------|-----------|-----------|
| 1        | -14.5| 602.7 | 22.983    | 0.800     |
| 2        | -14.6| 602.8 | 22.947    | 0.801     |
| 3        | -14.8| 603.2 | 22.875    | 0.802     |
| 4        | -14.4| 602.9 | 23.019    | 0.800     |
| 5        | -14.9| 602.4 | 22.839    | 0.801     |
| 6        | -15.4| 603.5 | 22.659    | 0.804     |
| 7        | -16.2| 604.2 | 22.369    | 0.808     |
| 8        | -14.4| 602.8 | 23.019    | 0.800     |
| 9        | -14.1| 603   | 23.126    | 0.800     |
| 10       | -15.3| 604   | 22.695    | 0.805     |
| 11       | -14.7| 603.2 | 22.911    | 0.802     |
| 12       | -12.7| 602.6 | 23.623    | 0.794     |
| 13       | -13.2| 603.1 | 23.446    | 0.797     |
| 14       | -12.7| 602.4 | 23.623    | 0.794     |
| 15       | -12.6| 601.5 | 23.658    | 0.793     |
| 16       | -12.8| 601.6 | 23.588    | 0.793     |
| 17       | -14   | 601.7 | 23.162    | 0.797     |
| 18       | -11.9| 601.5 | 23.904    | 0.790     |
| 19       | -11.8| 601.8 | 23.939    | 0.790     |
| 20       | -13.8| 602.1 | 23.233    | 0.797     |
| 21       | -13   | 602.4 | 23.517    | 0.795     |
| 22       | -13.1| 602.2 | 23.482    | 0.795     |
| 23       | -14.4| 603.1 | 23.019    | 0.801     |
| 24       | -12.7| 602.5 | 23.623    | 0.794     |
| 25       | -11.3| 602.3 | 24.114    | 0.790     |
| 26       | -11.1| 601.9 | 24.184    | 0.788     |
| 27       | -11.7| 602.2 | 23.974    | 0.791     |
| 28       | -11.3| 602.6 | 24.114    | 0.790     |
| 29       | -12.5| 602.1 | 23.694    | 0.793     |
| Average  | -13.44| 602.6 | 23.357    | 0.797     |

4.2. Probability Distribution Model of Air Density

The W test and QQ test diagrams are used in Origin software to test whether the annual average, monthly average and daily average air densities at Dangxiong Station in the last 30 years are in accordance with normal distributions. The sample sizes N of annual average, monthly average and daily average air densities Dangxiong Station are 37, 12 and 29 respectively. The Shapiro-Wilk method in the Normality Test module of ORIGIN software is used for verification; when the significance level α is 0.05, the statistical magnitude W obtained via calculation is 0.971, 0.914 and 0.963; it thus can be judged that the threshold value Wα is 0.936, 0.859 and 0.926, and the annual average, monthly average and daily average air densities at Dangxiong Station comply with the assumption of normal distributions as W>Wα. The QQ diagrams of annual average, monthly average and daily average air densities at Dangxiong Station are shown in Figure 4. It can be obtained from Figure 4 that the annual average, monthly average and daily average air densities at Dangxiong Station comply with normal distributions. The probability density histograms of the annual average, monthly average and daily average air densities at Dangxiong Station are shown in Figure 5. In the case of normal distribution, the probability density distribution function of air density ρ is:

\[
f(\rho) = \frac{1}{\sqrt{2\pi}\sigma_\rho} \exp\left(-\frac{(\rho - \mu_\rho)^2}{2\sigma_\rho^2}\right)
\]

(3)

Where \[ \mu_\rho \] refers to average value of air density, \[ \sigma_\rho \] refers to standard deviation of air density.
Figure 2. QQ Test Diagram of Normal Distribution of Air Densities at Dangxiong Station
For the meteorological data obtained from field observation of transmission lines corridor at Yangbajing station in Dangxiong County, its time sequence is from March 20 2017 to July 2018, and the sampling interval is 10min. The changing curves of air temperature, humidity, pressure and density with the time are shown in Figure 4.
The frequency ratio and probability distribution curves of field observation air density $\rho$ of transmission lines corridor are shown in Figure 5, where the air density obtained at an interval of 10min conform to the normal distribution basically. The average value $\mu_\rho$ of air density is 0.734kg/m$^3$; as mentioned in Section 3.1, the annual average, monthly average and daily average values of air density at the national meteorological station are 0.751kg/m$^3$, 0.752kg/m$^3$ and 0.797kg/m$^3$ respectively; and their relative variances with the average values of field observations of transmission lines corridor are 2.3%, 2.4% and 7.9%, respectively.
5. Conclusion
(1) The air density at the national meteorological stations in high-altitude regions conforms to the normal distribution according to the annual average value, monthly average value or the daily average value of the month with the highest wind velocity for the past 30 years. The annual average value of air density is basically consistent with the monthly average value. In the month with the highest wind velocity, the average air density at Dangxiong Station is 0.797kg/m³, and the corresponding annual (monthly) air density value is 0.751kg/m³. The daily average value at Dangxiong Station is 6.1% higher than the annual (monthly) average value.

(2) When the altitude and landform are similar, the short-term measured air density statistics of the transmission line corridor are basically consistent with those of national meteorological station. The relative variances from the average, monthly average and daily average values of the national meteorological station over 30 years are 2.3%, 2.4% and 7.9%, respectively.

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