Deformation Monitoring for High-Voltage Transmission Lines Using Sentinel-1A Data

Wenxian Wang¹, Liping Wu¹, Hao Gong², Peng Fan², Weiqing Wu¹, Yuantao Zhou³ and Zhengjia Zhang¹,*

¹Yangquan Power Supply Company, State Grid Shanxi Electric Power Company, Yangquan, 045000, China
²Wuhan Nari Limited Company of State Grid Electric Power Research Institute Wuhan 430074, China
³Faculty of Information Engineering, China University of Geosciences, Wuhan 430074, China

*Corresponding author e-mail: zhangzj@cug.edu.cn

Abstract. Ground subsidence occurs continually due to underground coal mining in Yangquan, Shanxi and has had a serious impact on transmission lines. In this paper, the Differential Synthetic Aperture Radar Interferometry (DInSAR) method is applied to retrieve the deformation of mining area. In particular, orbit error and atmosphere delay have been corrected by combining a biquadratic model and a linear model. Seven Sentinel-1 images acquired from 15 December 2017 to 25 February 2018 to monitor Yangquan coal mining area. In this study, the deformation of the study area have been analyzed as well as the transmission power lines and their towers. Analysis results reveal the influence law of coal mining on transmission lines and provide useful information for the management and safe operation of transmission lines.

1. Introduction

With the rapid development of China's economy, the demand for electricity is growing. High-voltage transmission lines, as an important carrier of electric power transportation, have become an important part of promoting economic development. Due to the impact of costs, local topography and other factors, some high-voltage transmission lines are erected within the mining area. The underground coal mining could cause the original stratum stress damage, leading to geological environmental disasters such as ground collapse, cracks and landslides [1], which will pose a serious threat to the transmission lines. Therefore, it is necessary to monitor the stability of the ground surface of coal mining area as well as the high-voltage transmission lines.

The surface deformation caused by mining is mainly in the vertical direction, with characteristics of nonlinearity, large gradient, and positional dispersion [2]. As the surface subsidence intensifies and extends, the attitude of the transmission tower will be tilted and deformed, which will affect the operational safety of the transmission line. Many scholars have carried out a lot of studies on the influence of mining subsidence on high-voltage transmission lines. Zhang and Yuan used the numerical method to simulate coal mining subsidence under the high-voltage line, analyzed the influence of surface deformation on the transmission towers, and then evaluated the stability of the transmission towers [3].
Xu et al. combined remote CORS service technology, GPS carrier phase difference technology and other electronic technologies to monitor the attitude of transmission towers, which brings convenience for maintenance of transmission lines [5]. However, these methods are difficult to monitor transmission lines in the wide area.

Differential Synthetic Aperture Radar Interferometry (DInSAR) is a technology applied to the surface deformation monitoring. The coverage of DInSAR ranges from several km to hundred kms and its measurement accuracy can reach up to centimeters. Moreover, it can monitor the transmission lines and their surrounding surface environment within a large area [6]. These advantages enable it to monitor the deformation of high-voltage transmission lines with sufficient accuracy and to judge the safe state of the transmission towers. In 2014, Wang et al. used ALOS PALSAR images and DInSAR to monitor surface subsidence on the goaf near the Shanxi section of the 1000 kV Jincheng-Jingzhou transmission line. The results shown that the maximum accumulated settlement of 137# tower in the subsidence area reaches 14 cm, the maximum inclination along the transmission line is 1.27%, and the maximum inclination perpendicular to transmission line is 0.46% [7]. In 2017, Kang et al. used DInSAR technology to retrieve the time series deformation of transmission towers in a mining area in Shanxi. The results shown that two towers have been sinking from July 2007 to February 2009, and their maximum cumulative deformation has reached 0.23 m and 0.11 m, Therefore they need to be protected and reinforced [8].

This paper uses C-band Sentinel-1A images and DInSAR technology to obtain vertical subsidence in the mining area, and analyzes ground subsidence for the transmission lines and time series deformation of partial towers in detail. It can provide helpful information for the management and safe operation of transmission lines.

2. Method

The process of the DInSAR firstly obtains an interferogram by conjugate multiplication of two SAR images in the same region, and then removes flattened phase and topography phase by digital elevation model simulation, and finally calculates the deformation information of the target object. The differential interferometric phase can be decomposed into:

$$\varphi_x = \varphi_{orb,x} + \varphi_{e,x} + \varphi_{def,x} + \varphi_{atm,x} + \varphi_{n,x}$$ (1)

Where $\varphi_{orb,x}$ is the orbit error phase, $\varphi_{e,x}$ denotes the residual topographic phase caused by unaccurate DEM, $\varphi_{def,x}$ represents the phase about ground deformation in line of sight, $\varphi_{atm,x}$ is the atmosphere contribution component, $\varphi_{n,x}$ is the noise phase due to coregistration error, thermal noise etc.

It can be seen from equation (1) that the interferometric phase includes several error terms such as orbit error, atmospheric delay, noise, etc. The noise phase usually can be removed by filtering technique [9]. The orbit error and atmospheric delay can be monitored and weakened by polynomial fitting method [10].

$$\varphi_{error} = a_0 + a_1 \cdot x + a_2 \cdot y + a_3 \cdot xy + a_4 \cdot x^2 + a_5 \cdot y^2 + a_6 \cdot h$$ (2)

Where $\varphi_{error}$ represents error phase, $x, y$ denote the range and azimuth coordinates of the pixel; $h$ is the elevation of the pixel; $a_0$ is the bias term; $a_1$-$a_5$ are the coefficients for the orbital error phase related terms; and $a_6$ is the term related to the topography associated atmospheric delay.

In order to observe the deformation of transmission lines, we need to convert phase into vertical subsidence [11], which can be expressed as equation (3):

$$d_{ver} = -\frac{\lambda \varphi}{4\pi \cos \theta}$$ (3)
Where $\lambda$ is the wavelength, $\theta$ is the incidence angle, $\varphi$ denotes residual deformation phase after removal of orbit error and atmospheric contribution.

3. Study area and Dataset

Yangquan mining area is one of China’s high-quality coal-producing regions and is located in Yangquan, Shanxi province. In the study area, there are several high-voltage transmission lines, including 110KV Haima I, 220KV Haibai II and Haiyu lines etc (Figure 1). Due to long-term mining, there are large areas of goafs, which have serious impacts on the safe operation of high-voltage transmission lines. For example, according to field investigation, 220KV Haibai II line has some abnormal situations between 2014 and 2016 that overhead ground wire and OPGW appear inclined and cracks appear around transmission tower.

In our study area, seven Sentinel-1A images acquired from Dec 2017 to Feb 2018 are selected are collected with Interferometric Width mode, VV polarization. The pixel spacings are 2.32m and 13.96m in range and azimuth direction, respectively. The 3-arc-second SRTM DEM of the area is used for topographic phase removal and geocoding. The interferometric pairs are shown in Table 1.

![Figure 1. Transmission lines and mining area in the study area.](image)

| No. | Master      | Slave        | Temporal baseline (day) | Perpendicular Baseline (m) |
|-----|-------------|--------------|--------------------------|-----------------------------|
| 1   | 2017-12-15  | 2017-12-27   | 12                       | -36.78                      |
| 2   | 2017-12-27  | 2018-01-08   | 12                       | -66.79                      |
| 3   | 2018-01-08  | 2018-01-20   | 12                       | 12.70                       |
| 4   | 2018-01-20  | 2018-02-01   | 12                       | 98.84                       |
| 5   | 2018-02-01  | 2018-02-13   | 12                       | -67.11                      |
| 6   | 2018-02-13  | 2018-02-25   | 12                       | -43.34                      |

4. Results and Analysis

According to data processing steps described above, the interferograms from image pairs in Table 1 have been obtained. However, it is found that the differential interferograms are still affected by satellite orbit errors and atmospheric signal related to topographic height. To get accurate deformation, orbit errors and atmospheric delay are approximated by combining a biquadratic model [12] and a linear model [13]. Figure 2 shows that differential interferogram, simulation error and corrected phase of image...
pairs 20180201-20180213 (Figure 2 (a)-(c)) and 20180213-20180225 (Figure 2 (d)-(f)). Significantly, orbit errors and atmospheric signal are removed, highlighting deformation signal in the differential interferogram.

Figure 2. Error simulation and correction of interferometric pairs 20180201_20180213 and 20180213_20180225. (b, e) error simulation, (a, d) (e, f) before and after correction.

Figure 3. Cumulative deformation map along time series.

Figure 3 shows time-series vertical deformation from Dec 2017 to Feb 2018 in the study area and the location of transmission lines and transmission towers. We can see that the location of those subsidence funnels distributed discretely and the radius of single subsidence funnel ranges from several meters to hundreds of meters. During one repeat cycle (12 days), maximum subsidence in the study area
could reach up to 4cm. As observation time increases, the maximum subsidence reaches up to 20cm within 72 days, the location of which is in the range of known mining areas. Furthermore, we also see that 220KV Haiyu, 220KV Suhai I and 110KV Haima I are located in mining area and affected by subsidence funnels. Especially subsidence funnels have a serious impact on 220KV Haiyu line. Other transmission lines are not or only partially affected by ground deformation.

Based on above analysis and field investigation, the 220KV Haiyu line and its partial towers have been analyzed in detail. We first plot the time series subsidence profiles of 220KV Haiyu line (see Figure 4). As shown in Figure 4, we can see complete dynamic development of two subsidence funnels, the maximum subsidence of which reach up to 10.3cm and 12.55cm respectively. There are six transmission towers in 220KV Haiyu line, of which tower 10# and 16# are located in subsidence funnels. The maximum cumulative subsidence of tower 10# and 16# reaches 7.16cm and 11.38cm, respectively (as shown in Figure 5). Therefore, it is necessary to strengthen the protection of the transmission towers.

![Figure 4. Time series settlement curves along transmission lines.](image1)

![Figure 5. Time-series vertical subsidence of transmission tower.](image2)
5. Conclusion
In this paper, we have employed DInSAR technology to extract subsidence due to underground coal mining in Yangquan, Shanxi province, using 7 Sentinel-1A images acquired from Dec 2017 to Feb 2018. In the processing, a method combining a biquadratic model and a linear model is introduced to simulate and remove orbit error and atmosphere delay from the interferometric phase. The results show that several obvious subsidence funnels are found in the study area, and the maximum subsidence reaches 20cm during the observation period. Three transmission lines are obviously affected by underground mining, especially 220KV Haiyu which can observe dynamic development of two subsidence funnels. Moreover, tower 10# and 16# are located in subsidence funnels, and the maximum cumulative subsidence reach 7.16cm and 11.38cm, respectively. The surface subsidence caused by coal mining could cause great damage to the stability of the transmission towers. Therefore, transmission lines on the goaf should be continuously monitored to ensure their safe operation.

Acknowledgments
This work was financially supported by Science and Technology Support Project of Shanxi Electric Power Company (5205C160007).

References
[1] Liu Z M, Li Y S, Zhang J F et al. an analysis of surface deformation in the changzhi mining area using small baseline InSAR. Remote Sensing for Land and Resources, 2014, 26 (3): 37-42.
[2] Zheng B. Research on the Security of High Voltage Transmission Line Towers under Mining Influence. Henan Polytechnic University, 2009.
[3] Zhang Y, Zhao W L, Zhao Y Y et al. Influence research of coal seam mining and pole foundation stability of 1 000 kV UHV transmission line. Rock and Soil Mechanics, 2009, 30 (4): 1063-1067.
[4] Yuan G L et al. Influence of dynamic ground deformation on internal force and structural deformation of transmission towers. Journal of Hohai University (Natural Sciences), 2010, 38 (3): 284-289.
[5] Xu M S. Research on monitoring and analysis of goaf transmission tower posture. Taiyuan University of Technology, 2016.
[6] Liao M S, Lin H. Synthetic aperture radar interferometry-principle and signal processing. Surveying and mapping press, 2003.
[7] Wang M. Z., Li T, LIU Y. Study on Monitoring the Subsidence Area above Goaf and the Transmission Tower Foundation Deformation with L-band Radar Satellite. Bulletin of surveying and mapping, 2014 (7): 58-62. 11-2246. 2014. 0226
[8] Kang X., Zhu J., Geng L. Y. Application of InSAR Technique to Monitor Time-series Displacements of Transmission Towers Located in Mining Area. Electric Power Survey & Design, 2017 (2): 11-14.
[9] Goldstein R M, Werner C L. Radar interferogram filtering for geophysical applications. Geophysical Research Letters, 1998, 25 (21): 4035-4038.
[10] Sun Q, Zhang L, Ding X L, et al. Slope deformation prior to Zhouqu, China landslide from InSAR time series analysis. Remote sensing of environment, 2015, 156: 45-57.
[11] Cascini L, Fornaro G, Peduto D. Advanced low-and full-resolution DInSAR map generation for slow-moving landslide analysis at different scales. Engineering Geology, 2010, 112 (1-4): 29-42.
[12] Zhang L, Ding X, Lu Z, Jung H S, Hu J, Feng G. A novel multitemporal InSAR model for joint estimation of deformation rates and orbital errors. IEEE Transactions on Geoscience & Remote Sensing 2014, 52 (6), 3529-3540.
[13] Chaabane F, Avallone A, Tupin F, et al. A Multitemporal Method for Correction of Tropospheric Effects in Differential SAR Interferometry: Application to the Gulf of Corinth Earthquake. IEEE Transactions on Geoscience & Remote Sensing, 2007, 45 (6): 1605-1615.