Journal of Computer and Communications, 2015, 3, 220-228
Published Online May 2015 in SciRes. http://www.scirp.org/journal/jcc
http://dx.doi.org/10.4236/jcc.2015.35028

Tracking Galloping Profile of Transmission Lines Using Wireless Inertial Measurement Units

Kai Xie[1], Chao Zhang[2], Qing Li[1], Wang-Lin Wu[2,3*], Yi-Qing Ni[2,3]

[1]State Grid Henan Electric Power Research Institute, Zhengzhou, China
[2]Research Center for Advanced Sensing and Monitoring Technology (RCASMT), PolyU Shenzhen Research Institute, Shenzhen, China
[3]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
Email: *wanglin.wu@connect.polyu.hk

Received April 2015

Abstract

Galloping of power transmission lines might bring about huge damage such as massive power outage and collapse of the transmission towers. To realize forecast of the galloping and provide data for study on the galloping mechanism, this paper proposes an online monitoring system for tracking galloping profile of power transmission lines based on wireless inertial measurement units (WIMUs). The system is composed of three modules: wireless inertial measurement nodes, monitoring base station, and remote monitoring station. After detailing the hardware system, the corresponding software which positions and displays galloping profile of the transmission line in real-time is outlined. The feasibility of the proposed on-line monitoring system is demonstrated through a series of experiments at the State Grid Key Laboratory of Power Overhead Transmission Line Galloping (Zhengzhou, China) by taking into account different vibration patterns.

Keywords

Power Transmission Lines, Galloping, Vibration, On-Line Monitoring, Wireless Inertial Measurement Units

1. Introduction

Galloping of an iced transmission line is characterized by low frequency, large amplitude, self-excited oscillation under wind loads [1]. The frequency range of galloping is normally about 0.1 - 3 Hz, and the galloping amplitude is usually 20 - 300 times the diameter of the transmission line [2]. Galloping of power transmission lines might bring about electrical hazards such as flashover between different interphases, damage of armor clamp, strand breakage, insulator string flipping and broken or even huge damage such as massive power outage and

*Corresponding author.

How to cite this paper: Xie, K., Zhang, C., Li, Q., Wu, W.-L. and Ni, Y.-Q. (2015) Tracking Galloping Profile of Transmission Lines Using Wireless Inertial Measurement Units. *Journal of Computer and Communications*, **3**, 220-228.
http://dx.doi.org/10.4236/jcc.2015.35028

collapse of the transmission towers [3]. While a great deal of research has been made, it is difficult to fully understand the galloping mechanism by theoretical analysis only, as the transmission line galloping is a complex fluid-solid coupling vibration problem that involves solid mechanics, aerodynamics, electrical engineering, meteorology, and so on. Reliable measurement data would greatly facilitate the research on understanding the galloping mechanism and curing and preventing the transmission line galloping; but it is extremely difficult to physically simulate natural frozen environment in laboratory, which is necessary for generating galloping of transmission lines. Thus, on-site measurement of the transmission line galloping by an online monitoring system provides a vital alternative to collect authentic data for the research on the galloping mechanism and its mitigation/prevention measures.

Tracking galloping profile of transmission lines is one of the most important issues in this research area, and research efforts have been made on this topic in recent years. Sun *et al.* [4] developed a remote monitoring system for transmission lines based on image target tracking technique. Aota *et al.* [5] proposed a method to calculate transmission line galloping profile and rotation angle based on image processing. Yang *et al.* [6] presented a monocular image processing method that could obtain vertical and horizontal displacement time histories as well as galloping frequency of transmission lines through tracking profile of spacers with a camera system. Huang *et al.* [7] proposed an optical flow-based method to process transmission line galloping images. However, most of the above methods depend largely on the quality of videos taken during galloping, which is influenced by weather and daylight. Hu *et al.* [8] developed a transmission line galloping track monitoring system based on Differential Global Positioning System (DGPS), where galloping velocity and galloping profile were obtained by real time kinematic method. Huang *et al.* [9] proposed an online monitoring system of transmission line galloping based on micro-mechanical accelerometers. Rui *et al.* [10] presented an online monitoring system of transmission line galloping based on two degree-of-freedom fiber grating accelerometers. However, these linear accelerometer-based methods couldn't account for the torsion effect of cross section of the transmission lines. The motion of transmission lines during galloping is actually a combination of translation and rotation, and gravitational acceleration will bring about components in the measuring-point-adhered local coordinates. To eliminate the gravitational acceleration induced component from the measured acceleration, it is necessary to obtain the relationship between the local coordinate system and the geographical coordinate system by measuring angular acceleration or velocity of transmission lines when galloping occurs.

This paper presents a new online monitoring system for tracking galloping profile of power transmission lines based on WIMUs. The three hardware modulus (wireless inertial measurement nodes, monitoring base station, and remote monitoring station) comprising the monitoring system are detailed, followed by a brief description of the algorithms (attitude updating algorithm, gravitational acceleration filtering, and quadratic integral of linear acceleration) and software to reconstruct the galloping track of transmission lines based on the monitoring data from WIMUs. The feasibility of the proposed on-line monitoring system is demonstrated through a series of experiments at the State Grid Key Laboratory of Power Overhead Transmission Line Galloping (Zhengzhou, China) by considering different vibration patterns.

2. Hardware System for Galloping Track Online Monitoring of Transmission Lines

2.1. Overall Scheme of Hardware System

The overall scheme of the WIMU-based galloping track online monitoring system for power transmission lines is shown in **Figure 1**. The hardware system is composed of three modules: WIMU nodes, monitoring base station, and remote monitoring station. The WIMU nodes are deployed on the power transmission line to collect measurement data such as angular velocity, linear acceleration and magnetic field, and to transfer them to the monitoring base station through Zigbee wireless module. The monitoring base station plays a role as information transfer station which undertakes the delivery of data between WIMU nodes and remote monitoring station. Since the distances between the monitoring base station and each WIMU node are short, the communication path between them adopts a star network with master slaver topological structure formed by Zigbee technique. The communication path between the monitoring base station and WIMU nodes can keep the information of each WIMU node separate from the others, making troubleshooting and individual control of each WIMU node fast and convenient. The monitoring base station gathers and processes information uploaded by each WIMU node, and then exports valid data to the remote monitoring station by wireless ad hoc network. The remote monitoring station is a data receiving, storing, analyzing, and monitoring control center. The remote monitoring

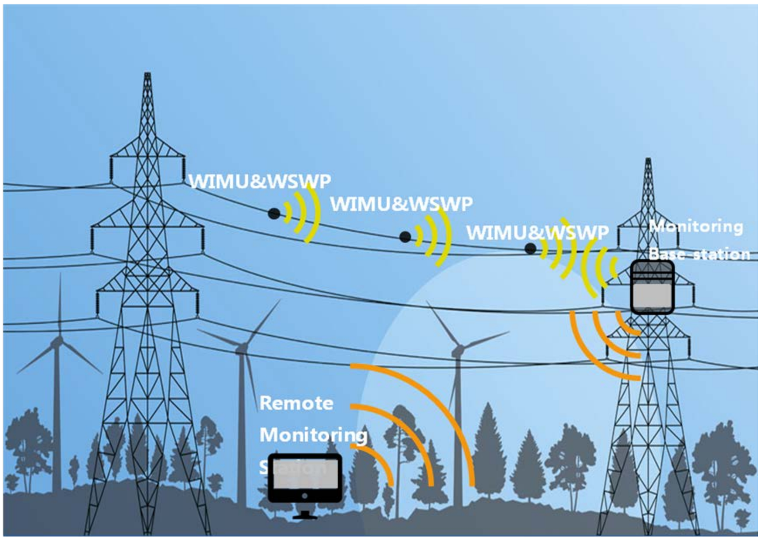

Figure 1. Schematic of WIMU-based galloping track online monitoring system for transmission lines.

station has two main functions: one is to automatically receives, stores, analyzes, and processes data sent from the monitoring base station and displays the galloping track of the transmission line in real-time; the other is to control the working status of each WIMU node through the monitoring base station.

2.2. WIMU Nodes

Linear accelerometer-based methods obtain information about galloping of transmission lines such as galloping amplitude and galloping frequency through quadratic integration of linear accelerations measured by linear accelerometers. However, the accuracy of galloping monitoring will be influenced by the torsion effect of cross section of the transmission lines. The motion of transmission lines when galloping occurs is actually a combination of translation and rotation, and gravitational acceleration will bring about components in the measuring-point-adhered local coordinates. Thus, the value measured by linear accelerometers fixed on the transmission lines is the sum of motion acceleration and gravitational acceleration component rather than pure motion acceleration. To remedy this deficiency of the existing linear accelerometer-based methods, the present study presents a WIMU-based galloping track online monitoring system for power transmission lines. The WIMU is made by a linear accelerometer and a gyroscope, together enabling the measurement of linear accelerations and angular velocities of the transmission line simultaneously. Once the data of angular velocities have been collected, the torsion effect of cross section of the transmission line could be eliminated by obtaining the relationship between the measuring-point-adhered local system and the geographical coordinate system, thereby filtering out the gravitational component from the measured acceleration.

Each WIMU node comprises an inertial measurement unit (IMU), a Zigbee wireless module and an electrical power unit, as shown in **Figure 2**. The IMU includes two sensors (MPU-6050, HMC588L) and one main controller (STM32), which collect data including angular velocity, linear acceleration and magnetic field. Sensor MPU-6050 consists of a tri-axis gyroscope with a measuring range of $\pm 1000^\circ / s$ for collecting the angular velocity and a tri-axis linear accelerometer with a measuring range of ±8g for collecting the linear acceleration. Sensor HMC588L is a tri-axis magnetometer with a measuring range of ±8 gauss for collecting the magnitude and direction of magnetic field. Main controller STM32 controls both data acquisition frequency and status of the two sensors and communication between them.

The core component of the Zigbee wireless module is the radio frequency chip CC2430, which takes charge of communication between IMU and the monitoring base station that includes transferring measurement data to the monitoring base station and receiving control commands sent from the monitoring base station. The radio frequency chip CC2430 is supported by an integrated development environment (IDE), and interoperability test of the circuit obeyed internal area router (IAR) environment of IDE. The radio frequency chip CC2430 supports

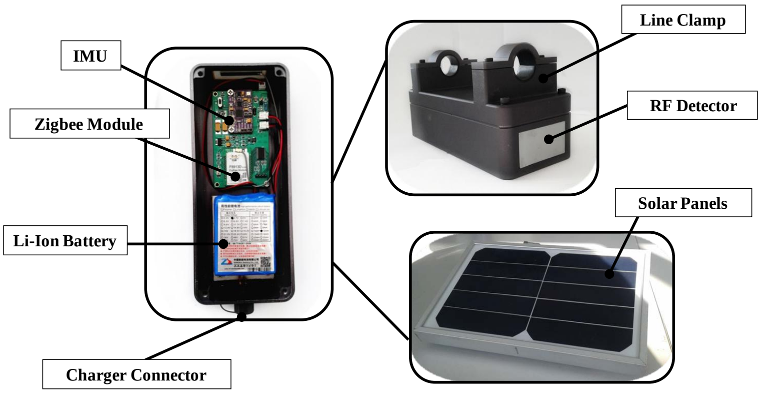

Figure 2. Hardware components of WIMU.

2.4 GHz IEEE 802.15.4 protocol, and integrates a 2.4 GHz direct sequence spread spectrum (DSSS) radio frequency transceiver core and a compact, efficient and industrial grade 8051 controller.

The electric power unit is made up of a solar panel, a polymer lithium battery and a charging management integrated circuit, which could provide stable electric power for WIMU nodes. The solar panel converts solar energy into electricity and then charges the polymer lithium battery through the charging management integrated circuit, while the polymer lithium battery provides the instruments with electric power directly. The charging management integrated circuit could keep the charging voltage constant, and prevent the polymer lithium battery in working under over current, overcharge, or under-voltage situations.

2.3. Monitoring Base Station

The monitoring base station comprises solar panels, battery charger circuit, high performance storage battery, data flash storage memory, wireless Ethernet gateway, and network bridge transport module, as shown in **Figure 3**. The monitoring base station plays a role as information transfer station which takes charge of the delivery of data between WIMU nodes and remote monitoring station. Measurement data are collected directly by the WIMU nodes deployed on power transmission lines, and are transferred to the wireless Ethernet gateway unit of the monitoring base station for packing. The packed valid measurement data are then sent to the remote monitoring station through network bridge transport module.

The wireless Ethernet gateway is used to pack measurement data collected by the sensors. The wireless Ethernet gateway has one wireless receiver module based on 2.4 GHz IEEE 802.15.4 protocol that can receive measurement data from sensor network, and one 10/100 Mbits/s Ethernet port that can link to Windows or LabVIEW real-time OS main controller flexibly. Moreover, the wireless Ethernet gateway has excellent adaptability to working environmental; for instance, it works well when the temperature is between −30˚C and 70˚C, and can resist impact strength of 50 g.

To realize continuous monitoring of transmission line galloping in real-time, it is essential to adopt a proper power source for providing stable electric power supply. A 5W solar panel and a 6V/4A·h storage battery form a power supply system used in the monitoring base station. The solar panel charges the storage battery when solar energy is sufficient to insure the monitoring system running stably all year round. Moreover, data flash storage memory is chosen to store data in the monitoring base station, which could safely store data more than ten years even under the situation of interruption of power supply.

2.4. Remote Monitoring Station

The remote monitoring station is comprised of a server, a monitor, and an Ethernet communication module. The sever takes charge of storing and analyzing measurement data for the purpose of reconstructing the galloping track of the transmission line according to the algorithms provided in Section 3. The monitor is in charge of information visualization which positions and displays the galloping track of the transmission line in real-time. The Ethernet communication module undertakes the communication between the remote monitoring station and the monitoring base station that includes transferring control commands to the monitoring base station and receiving measurement data sent from the monitoring base station.

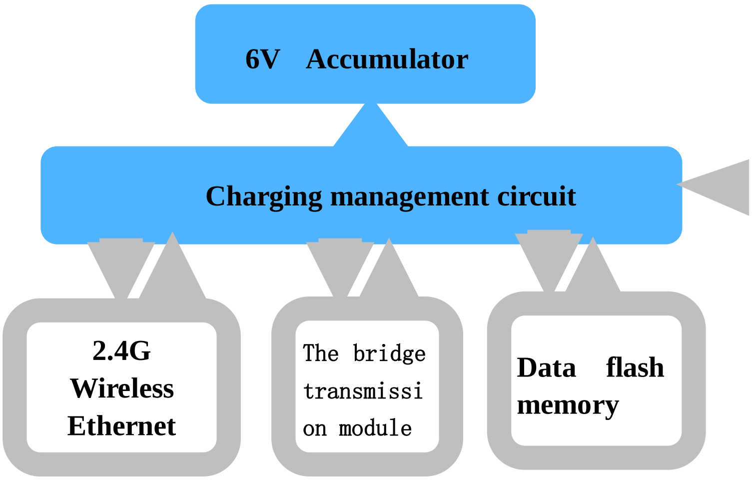

Figure 3. Hardware architecture of monitoring base station.

3. Algorithms for Reconstructing Galloping Track of Transmission Lines

Each IMU in the WIMU nodes contains one tri-axis gyroscope, one tri-axis linear accelerometer and one tri-axis magnetometer. By considering three translations and three rotations, the attitude of IMU is updated in real time through a gradient descent fusion algorithm, and the three measured linear accelerations are rectified by coordinate transformation accordingly. Making use of the gravitational acceleration filtering, the gravitational acceleration component is derived from the rectified acceleration. Then the three-dimensional galloping track of the transmission line is captured via processing the acceleration data in the time domain. The flow chart of computational procedures for reconstructing galloping track of transmission lines is shown in **Figure 4**.

The above algorithms have been encoded as software embedded in the remote monitoring station to execute measurement data storage, galloping track reconstruction, and WIMU working status control. Microsoft Visual C++6.0 is chosen to encode the software and SQL Server 2005 is used to establish database required to run the software.

4. Experimental Study

To verify the feasibility of the proposed on-line monitoring system, a series of experiments have been conducted at the State Grid Key Laboratory of Power Overhead Transmission Line Galloping (Zhengzhou, China). Different vibration patterns are generated by the galloping testing machine during the experiments.

4.1. Power Transmission Line Model

Aluminum clad steel wire is the most widely used transmission line for transmission voltage over 10 KV in China. In the aluminum clad steel wire, steel wire is used to transmit current while aluminum is used to wrap steel wire and reduce corona losses; its cross section area depends on the target transmission voltage. LGJ-300/40 aluminum clad steel wire is chosen in the present study, which comprises 7 steel wires with a diameter of 2.66 mm as steel core and 24 aluminum wires with a diameter of 3.99 mm as wrapping material. The specification parameters of LGJ-300/40 aluminum clad steel wire are given in **Table 1**.

4.2. Setup and Experiments

A galloping testing machine, as shown in **Figure 5**, is used to generate different types of vibration, such as vertical motion, horizontal motion, and approximate circular motion. The experimental setup is illustrated in **Figure 6**.

Table 2 summarizes the three test cases with different vibration patterns. The experiments for all the cases are conducted in the following procedure:

1) Keep the WIMU node in the horizontal direction and keep it static on the power transmission line for 20 seconds;

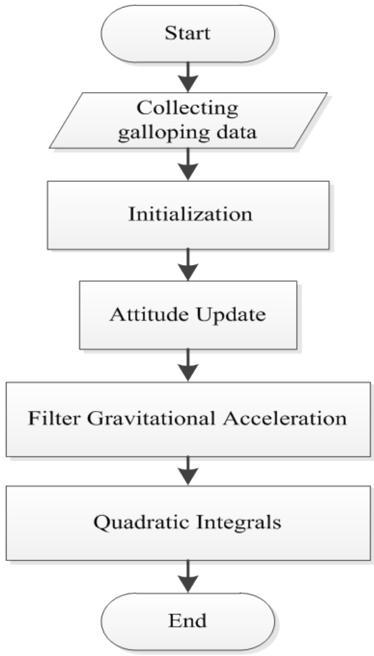

Figure 4. Algorithms for reconstructing galloping track of transmission lines.

Figure 5. Galloping testing machine.

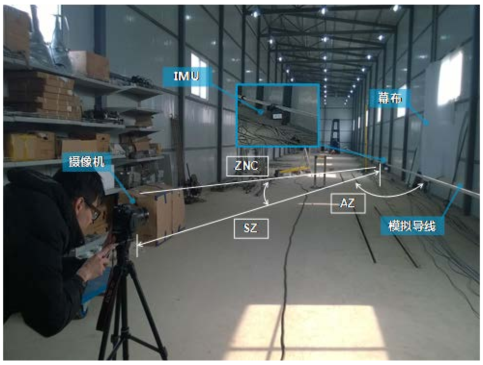

Figure 6. Experimental setup.

Table 1. Specification parameters of LGJ-300/40 aluminum clad steel wire.

Specification Parameters		LGJ-300/40
Nominal cross-section/mm^2 (Al/Steel)		60 s
Calculation section/mm	Al	300.09
	Steel	30.90
	Sum	338.99
Outside diameter/mm		23.94
DC resistance is not greater than/ Ω•km^{-1}		0.09614
Calculated weight/ kg•km^{-1}		1133
Elastic modulus/ KN•mm^2		7300

Table 2. Three cases of experiments.

Galloping state	Frequency	Initial static time	Motion time	Response characteristics		
				Linear distance	Elevation angle	Horizontal angles
Vertical motion	1 Hz	20 s	60 s	4.2 m	3.4˚	136.9˚
Horizontal motion	1 Hz	20 s	60 s	4.2 m	3.4˚	135.2˚
Circular motion	1 Hz	20 s	60 s	4.2 m	3.4˚	134.9˚

Table 3. Test results.

Galloping state	Motion direction	Amplitude analysis			Frequency (Hz)
		Maximum amplitude	WIMU	RMS of peak value (m)	
Vertical motion	Y	Positive direction (m)	0.071	0.019	1.13
		Minus direction (m)	0.077	0.038	
	Z	Positive direction (m)	0.273	0.134	
		Minus direction (m)	0.310	0.081	
Horizontal motion	Y	Positive direction (m)	0.313	0.161	0.92
		Minus direction (m)	0.313	0.164	
	Z	Positive direction (m)	0.056	0.029	
		Minus direction (m)	0.066	0.024	
Circular motion	Y	Positive direction (m)	0.297	0.118	1.15
		Minus direction (m)	0.416	0.108	
	Z	Positive direction (m)	0.242	0.072	
		Minus direction (m)	0.365	0.145	

2) Activate the galloping testing machine to work, and maintain the galloping frequency at 1 Hz;
3) Stop the galloping testing machine after galloping has happened for 60 seconds;
4) Analyze the measurement data and reconstruct galloping track of the power transmission line.

4.3. Experimental Results

The WIMU node is kept in the horizontal direction and in static equilibrium on the power transmission line for 20 seconds before starting each vibration test. The maximum amplitudes and galloping frequency identified by the WIMU node are shown in **Table 3**. A comparing of the excitation and identified frequencies shows that the proposed WIMU node accurately identifies the galloping frequencies.

The galloping tracks of the power transmission line with vertical motion, horizontal motion, and approximate circular motion identified by the WIMU node are shown in **Figure 7** and **Figure 8**. The results show that the proposed WIMU node reliably recognizes the vibration patterns, and enables reconstructing the galloping tracks of the power transmission line.

5. Concluding Remarks

In this study, an online monitoring system for tracking galloping profile of power transmission lines based on wireless inertial measurement units (WIMUs) has been developed and experimented in laboratory. The three hardware modulus of the system, *i.e.*, wireless inertial measurement nodes, monitoring base station, and remote monitoring station) have been described in detail. The software to reconstruct galloping track of transmission lines from WIMU monitoring data has been encoded with the following algorithms: attitude updating, gravitational acceleration filtering, and quadratic integral of linear acceleration. The feasibility of the proposed on-line

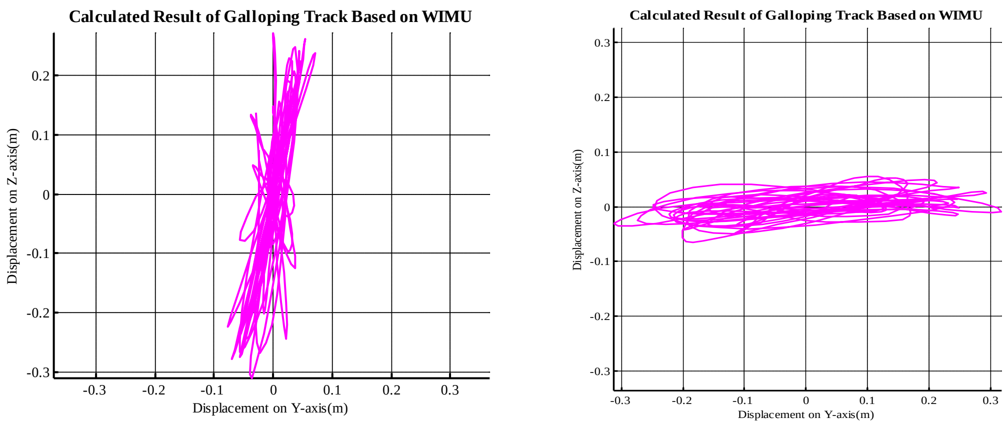

Figure 7. Reconstructed motion track: a) in vertical motion case; b) in horizontal motion case.

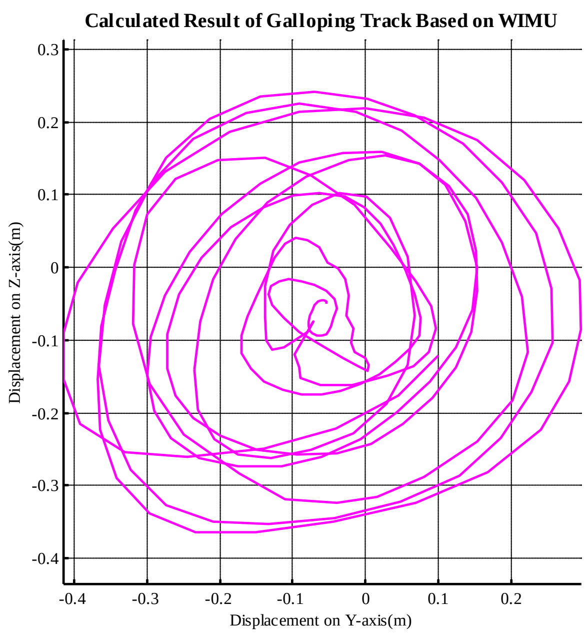

Figure 8. Reconstructed motion track in approximate circular motion case.

monitoring system has been demonstrated via a series of experiments in laboratory by considering three vibration cases: vertical motion, horizontal motion, and approximate circular motion. The experimental results show that the proposed WIMU node reliably recognizes the vibration patterns, and enables the reconstruction of galloping tracks of the power transmission line.

Acknowledgements

The authors wish to acknowledge the financial support from the State Grid Henan Electric Power Research Institute (Grant No: 20131325).

References

[1] Wang, S.H., Jiang, X.L. and Sun, C.X. (2005) Research Status of Conductor Galloping on Transmission Lines. *High Voltage Engineering*, **10**, 11-14.

[2] Wang, J. (2008) Overhead Transmission Line Vibration and Galloping. *International Conference on High Voltage Engineering and Application*, Chongqing, 9-11 November 2008, 120-123. http://dx.doi.org/10.1109/ichve.2008.4773888

[3] Zhu, K.J., Liu, B., Niu, H.J. and Li, J.H. (2010) Statistical Analysis and Research on Galloping Characteristics and Damage for Iced Conductors of Transmission Lines in China. *IEEE International Conference on Power System Technology*, Hangzhou, 24-28 October 2010, 1-5.

[4] Sun, C.H., Zhang, Z.L., Liu, H.Y., Maoand, Y.X. and Deng, J. (2008) Long-Distance Monitoring System on Galloping of Transmission Lines. *Automation Congres*, Hawaii, 28 September-12 October 2008, 1-4.

[5] Aota, H., Yaguchi, Y. and Oka, R. (2008) Feature Detection of Electrical Feeder Lines with Galloping Motion. *IEEE International Conference on Computer and Information Technology*, Sydney, 8-11 July 2008, 327-332.

[6] Yang, W., Shao, Y.B., Lv, Z.B., Yang, X.H., Li, Q., Xie, K., *et al.* (2014) Study on Monitoring for Power Transmission Line Galloping Based on Monocular Vision Method. *International Conference on Power System Technology*, Chengdu, 20-22 October 2014, 1571-1575. http://dx.doi.org/10.1109/powercon.2014.6993883

[7] Huang, X.B., Tao, B.Z. and Feng, L. (2012) Transmission Line Galloping Monitoring Based on Optical Flow Field. *Electric Power Automation Equipment*, **32**, 99-103.

[8] Hu, Z.J. and Li, H.J. (2010) Differential GPS-Based Transmission Conductor Wave and Wind Galloping Real-Time Measurement. *Power and Energy Engineering Conference*, Chengdu, 28-31 March 2010, 1-4. http://dx.doi.org/10.1109/appeec.2010.5448977

[9] Huang, X.B., Huang, G.B. and Zhang, Y. (2009) Designation of an On-Line Monitoring System of Transmission Line's Galloping. *International Conference on Electronic Measurement & Instruments*, Beijing, 16-19 August 2009, 655-659. http://dx.doi.org/10.1109/icemi.2009.5274780

[10] Rui, X.M., Huang, H.R., Zhang, S.Q. and Teng, W. (2011) On-Line Monitoring System on Power Transmission Line Galloping Based on Fiber Grating Sensors. *Control Conference*, Yantai, 22-24 July 2011, 4327-4330.