A Novel Transmission Line Safety Monitoring System for Smart Grid

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Abstract. A smart grid is defined as novel electric power grid infrastructure that improves the efficiency, reliability and safety of the grid, by integrating renewable and alternative energy sources through automated control and novel communication technologies. The increasing demand for more effective electrical power system control has led to the rapid development of smart grids. In this study, a novel transmission line safety monitoring system for smart grid is proposed. The proposed system consists of transmission line sensor modules and wireless communication gateways. To verify the proposed system, a number of experiments are conducted in real extra high-voltage laboratory environment.

Keywords: Smart grids · Transmission line · Safety monitoring system · Sensor modules · Wireless communication gateway

1 Introduction

With the growth of global economy, the demand for electricity increases [1]. To meet the increasing demand, power companies have to supply more electricity. Traditional power systems may face several problems, such as inefficiently manual transmission line inspection and high costs associated with the manual inspection [2]. In Taiwan, most of the power transmission lines pass through the mountain and coast areas. When power towers are destroyed by significant natural disasters, it is difficult to repair malfunctioned towers immediately. Moreover, grid related parameters cannot be monitored and served as a reference for power companies in measuring overhead conductor sags and estimating conductor temperature and line dynamic thermal capacity [3, 4].

To overcome the drawbacks of using traditional power system inspection methods, smart grids, as a next generation of electrical power grids, have been introduced, which integrate modern information, communications, and electronic technologies. The modern communication infrastructure plays an important role in managing, controlling, and optimizing different functional and smart devices and systems in a smart grid. Wireless technologies can be used in different parts of smart grids to achieve flexible and low-cost data communication and networking [5–8]. With the data collected from

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the real-time monitoring, many useful services which provide power companies advanced information to manage power grids can be developed to make traditional grids become smart grids [9–12].

In this study, a novel transmission line safety monitoring system for smart grid is developed, and the system includes a transmission line sensor modules and wireless communication gateways. At the deployment site, the transmission line sensor modules collect power line information in real-time. Specifically, the optimal cooperative transmission of sensed data in smart grids is considered. The sensed data collected from the sensed modules are transmitted to the gateways located at the towers. The gateways relay the sensed data to the database at the substations and use the big data for data mining in the future. With the transmission line parameters, the central dispatch control center can use complete and accurate information for making decisions on electrical power allocation.

2 Transmission Line Safety Monitoring System

In this study, a transmission line safety monitoring system is proposed, and it can be divided into two subsystems, including transmission line sensor modules and wireless communication gateways. The transmission line sensor modules are attached to the power transmission lines to measure and collect the line-related parameters (e.g. environmental parameters, line temperature, vibration, and current) automatically and periodically. After the sensing data are collected, the transmission line sensor modules transmit the data to the wireless communication gateway on electric towers through the ZigBee protocol, and the wireless communication gateway transmits the data to the database via the 3G/4G protocol. The architecture of the entire transmission line safety monitoring system for smart grid is depicted in Fig. 1. Each subsystem is described in detail in the following subsections.

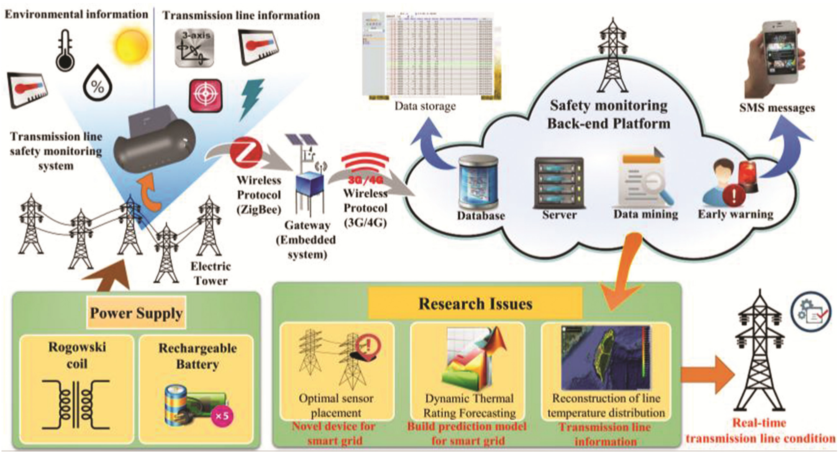


Fig. 1. The architecture of the IoT-based extra high voltage power grid safety monitoring system

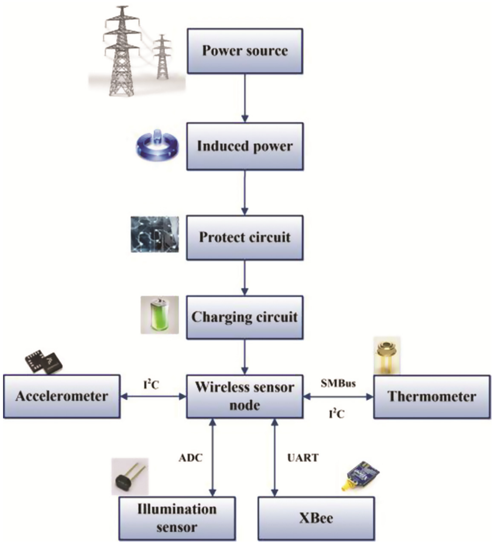


Fig. 2. The architecture of the EHVSM

2.1 Transmission Line Sensor Module

The evolution of sensor technology and communication networks has allowed sensors doing more intelligent jobs. In this study, sensors not only collect data but also perform some local processing tasks and transmit the results through a wireless communication (i.e., radio transmission) module to a gateway. A transmission line sensor module prototype is developed for the system validation, as depicted in Fig. 2. The major circuits/ components of the transmission line sensor module and their functions/specifications are briefly described as follows.

(1) *Power module*

Wireless applications, including the proposed transmission line safety monitoring system, still face many challenges. Finding a proper power source is one of the challenges [13, 14]. In this study, the power for sensing device operation cannot be directly supplied by commonly used power sources, because the sensors are placed on the transmission lines and the line voltage is too high. Currently, some studies have utilized an electromagnetic induction sensing device as the power source for the sensing devices deployed on the transmission lines by using a Rogowski coil [15, 16]. The Rogowski coil establishes the electromagnetic coupling between an overhead transmission conductor and the power supply system. The conductor, also the primary side of the coil, delivers the electric energy to the secondary side. The coil is a crucial element in the power module, which determines the amount of power that the power supply can deliver to operate the transmission line sensor module and recharge redundant batteries on the modules.

Moreover, a protection mechanism is designed to prevent lightning surge, overvoltage, and overcurrent caused by channeled to the bypass if an event of lightning or surge occurs, so the electronic components of the proposed system are protected and not compromised. Furthermore, a charging circuit is added to the protection circuit. By improving the power storage capacity of the battery, the endurance of the wireless sensor module is also improved. Such a design not only prevents the EHVSM from electrical damage (such as switching and lightning surge) but also prolongs the operational time of the wireless sensor module.

(2) *Sensor module*

The sensor module is responsible for sensing and transforming the data to the wireless communication gateway. The transmission line sensor modules are devices capable of performing data acquisition and data processing and transmitting/receiving the data. All subsystems are managed by a microcontroller unit (MCU). There are many commercial microcontrollers. The Atmega328 (Atmel Corporation) [17] is selected as the MCU of the proposed sensor module, because it can easily integrate the sensing devices with the wireless communication module (XBee Series 2, Digi International Inc.) [18].

The transmission line sensor module is equipped with four types of sensors to measure conduct temperature, illumination, 3-axis accelerator, and environmental temperature and humidity. The transmission line sensor module receives and sends the data via a wireless network. After the aforementioned parameters are measured, the sensor board transmits the sensed data to the wireless communication gateway through the ZigBee protocol. The configuration of the sensor module is shown in Fig. 3; where the communication interfaces used in-between the different sensors and the MCU of the transmission line sensor module are also indicated. As illustrated in Fig. 3, the transmission line sensor module will be installed on power grid lines, the problems of electromagnetic compatibility (EMC) and electromagnetic interference (EMI) are inevitable when they are in service.

(3) *Communication module*

The XBee Series 2 was selected as the communication module in this study to implement the proposed transmission line safety monitoring system. XBee Series 2 modules allow to create networks such as point-to-point and multi-point networks based on the ZigBee

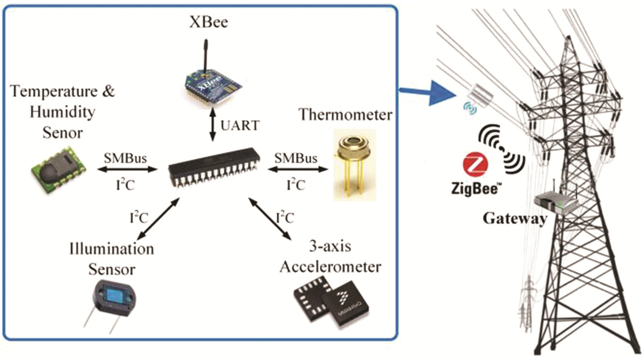


Fig. 3. The configuration of the transmission line sensor module on a power tower.

protocol (IEEE 802.15.4). It could provide a reliable and simple communication between microcontrollers and systems. The XBee Series 2 also had an external I/O board with 6 10-bit ADC input pins and 8 digital IO pins for general purpose input/output, which made the connection of XBee Series 2 mote to other devices or sensors quick and easy. In order to improve the quality of communication, each node was also equipped with a 3 dBi antenna (Maxim Integrated, Inc., Taiwan).

2.2 Wireless Communication Gateway

Wireless communication gateways are responsible for monitoring the changing parameters and rapidly relaying them to the database. The configuration of a wireless communication gateway is illustrated in Fig. 4. Each wireless communication gateway is equipped with a hybrid wireless communication module (ZigBee/3G/4G) to transmit the sensed data to a control center. Moreover, systems designed for monitoring the safety of a grid must be capable of regression analysis results: (a) temperature resisting severe weather variations. For this reason, this study utilizes an embedded-based system, BeagleBoard-Xm [19], with an IP 65 case as the prototype of the wireless communication gateway. The wireless communication gateway is also equipped with algorithms developed earlier to guarantee the quality of service (QoS) for the operation of the transmission line sensor modules deployed in the wild field [20, 21]. In addition, according to the IEEE Std. 738–2006 [22], ambient temperature and wind speed will affect the temperature of the transmission lines, so microclimate variables around the tower need to be monitored. For this purpose, a weather sensing module is integrated into the wireless communication gateway. The gateway was mainly responsible for collecting the sensing data and transmitted them to the database through the mobile communication protocol, i.e., 3G/4G.

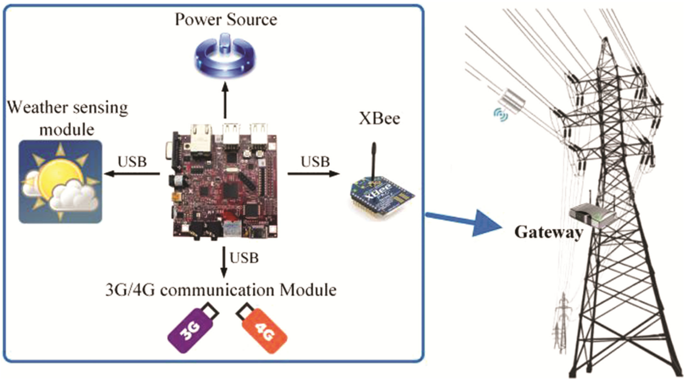


Fig. 4. The configuration of the wireless communication gateway on a power tower.

3 Experiment Results

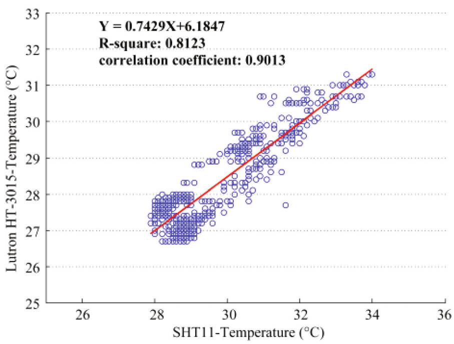
This study focuses on the reliability of applying a transmission line safety monitoring system to get the real-time transmission line information. The end goal of the study is to provide the transmission line parameters, the central dispatch control center can use complete and accurate information for making decisions on electrical power allocation by using the proposed monitoring system. Thus, the accuracy of the sensors used in the proposed monitoring system must be sufficiently high to obtain accurate analysis results. Before conducting the long-term field trials, the basic performance of the main components/modules used in the transmission line safety monitoring system were first examined, including the calibration of sensors of transmission line sensor module, data delivery rate between transmission line sensor module and wireless communication gateway. The testing and the results are described as follows.

3.1 Sensor Reading Calibration

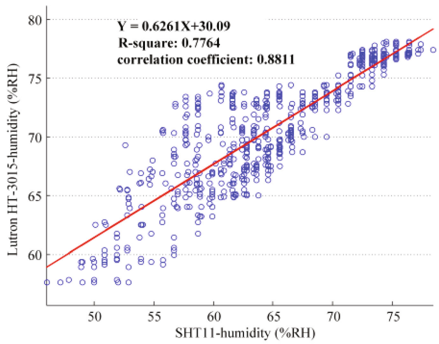
(1) *Calibration of temperature/humidity sensors*

A commercial electronic hygrometer (HT-3015, Lutron Electronic Enterprise Co., Ltd.) [23] were employed to conduct the performance comparison with the temperature/humidity sensor (SHT11, SENSIRION.) [24] used in the proposed system. The sensing ranges of SHT11 in temperature (T) and relative humidity (%RH) are from −40 to 123.8 C and from 0 to 100%RH, respectively, and the measurement resolutions in temperature and relative humidity are 0.01 C and 0.05%RH @ 25 C, respectively. The measurement accuracy in temperature and relative humidity of SHT11 and HT-3015, i.e., (T, %RH), are (0.4 C, 3.0%RH) and (0.8 C, 3.0–4.0%RH), respectively.

To conduct the basic performance comparison between the sensors SHT11 and HT-3015, both sensors were mounted on the proposed transmission line sensor module, which were placed at the top balcony of the Tomatake Hall at campus of National Taiwan University (NTU) for long-term environmental data collection. During the experiment, the lowest and highest measured temperature were 27 °C and 35 °C, respectively. The measured relative humidity ranged from 45% to 85%. The regression analysis results between the temperature data sets measured by SHT11 and HT-3015 are shown in Fig. 5(a). It is found that the correlation coefficient of temperature measured by the two sensing devices is 0.9013 and R2 value is closed to 0.8123. The performance comparison between SHT11 and HT-3015 in measuring the relative humidity was also conducted. Figure 5(b) depicts the regression analysis results between relative humidity measurements by using SHT11 and HT-3015, in which the correlation coefficient of the relative humidity measured by both sensing devices is 0.8811. The correlation of both sensing devices in measuring relative humidity was slightly worse than that of temperature measurements, but the test results indicate that the SHT11 still provided satisfactory performance in measuring the relative humidity under outdoor testing environment. The results of performance comparison test imply that the temperature readings provided by SHT11 are reliable and stable, and the data can be served as a reference of follow-up ecological analysis between honey bees' in-and-out activities and environmental factor.



(a)



(b)

Fig. 5. The regression analysis results: (a) temperature; (b) relative humidity

(2) *Calibration of the infrared (IR) thermometer*

A commercial electronic thermometer, TM-363 (Tenmars Electronics Co., Ltd.) [25], was employed to conduct the performance comparison with the IR thermometer, MLX90614 (Melexis Semiconductors) [26], used by the proposed system. The sensing range of theTM-363 in temperature is from −200 to 1372 °C, and the measurement resolutions is 0.1%. The sensing range of MLX90614 in temperature (T) is from −70 to 380 °C for object temperature, and the measurement resolution is 0.01 °C.

To conduct the basic sensor calibration experiment between the sensors MLX90614 and TM-363, both sensors were mounted on the proposed sensor module system, and the experiment was conducted at the high-current laboratory of the Taiwan Power Research Institute for conductor temperature data collection. During the experiment, the lowest and highest measured temperature was 25 °C and 54 °C, respectively. The regression analysis results between the temperature measured by MLX90614 and TM-363 are shown in Fig. 6. It is found that the average accuracy of the MLX90614 is 96.71%, and R2 is closed to 0.99555. The results indicate that the two sensed datasets provided by the two sensing devices are very similar. The calibration results imply that the temperature readings provided by MLX90614 is reliable and stable, and the data can be served as a reference for the follow-up smart grid analysis between conductor temperature and DTR.

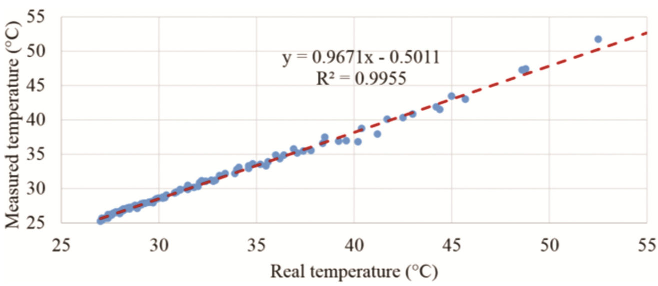


Fig. 6. The correlation and fit curve of the two temperature sensors.

3.2 Communication Test of the Transmission Line Safety Monitoring System in a Real EHV Laboratory Environment

The proposed transmission line safety monitoring system used the ZigBee as a wireless transmission protocol, through which the sensor module was able to communicate with the gateway. However, high-power disturbances cause by HV may affect wireless communication systems and their electronic circuits that operate within the 2.4 GHz industrial-scientific-medical (ISM) band [27]. The power system transients that may interfere with ZigBee networks are crucial for the effective operation of a smart grid [28]. To examine whether the proposed sensor module and gateway was able to stably transmit the sensed data in an extra high voltage environment. This study conducted a wireless communication transmission test in a high voltage environment. The successful data delivery rate served as an index to estimate the reliability of the proposed sensor module. In this study, the successful data delivery rate (DDR) of data delivery for the proposed system in a deployed WSN was defined as

$$DataDeliveryRate = \frac{\sum Packets\ from\ Transmission\ line\ Sensor\ Module\ Recieved\ by\ Gateway}{\sum Packets\ Sent\ by\ Transmission\ line\ Sensor\ Module} 100\%, \quad (1)$$

where the DDR is the successful data delivery rate of the sensor module. Note that the packet size of the sensor data was 43 bytes, which was the same size as the packets that would be transmitted in a real smart grid scenario. The packet included the basic information of the sensor module, such as the header, the cyclic redundancy check (CRC) code, and the sensed data such as transmission line temperature, environmental temperature and humidity, etc.

This experiment was conducted at the high-voltage laboratory of the Taiwan Power Research Institute. During the experiment, the average temperature and relative humidity of the experimental room were 22.8 °C and 40.6%RH, respectively. The maximum test line voltage reached 279 kV. The experimental results were shown in Fig. 8. The test line voltage was from 0 V and then stepwise increased to 120 kV, 173 kV, and finally was up to 279 kV. The time periods that the voltage remained at 120 kV, 173 kV and 279 kV were 9’57”, 3’53”, and 1’36”, respectively, as shown in Fig. 7(a). Moreover, it can be seen from Fig. 7(b), that the data delivery rate reduces to about 90% as the voltage increases, and that when the voltage rises from 173 kV to 279 kV, the MCU would reset. The transmission line sensor module can still stably and continuously transmit the data packets after the voltage remains at 279 kV. The voltage tested in this study was higher than the line voltage of the 161 kV EHV transmission grid in Taiwan. Therefore, this test verifies that the sensor module is able to steadily and reliably transmit monitoring data for an extra high voltage grid.

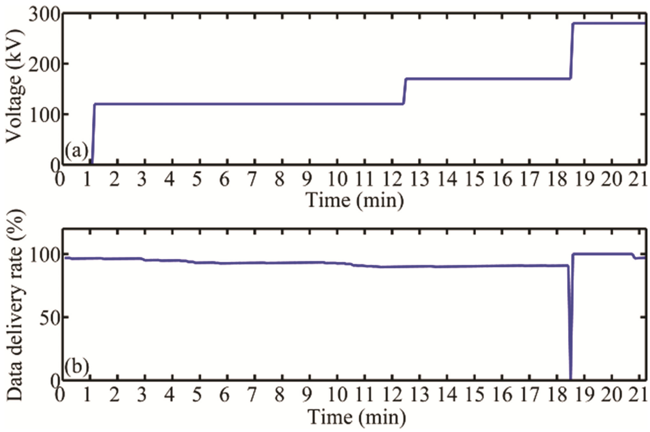


Fig. 7. The transmission line safety monitoring system tested in an extra high voltage environment: (a) the extra high voltage in the experiment; (b) data delivery rates of the EHVSM

4 Conclusion

Based on WSN technology, this study developed a transmission line safety monitoring system for smart grid. The designed system can detect the real-time transmission line parameters such as environmental parameters, conduct temperature. The sensing data collected by the system were transmitted by wireless sensor nodes to the gateway nearby. The gateway then transmitted the data to the database by 3G/4G. This study has successfully implemented an automatic and wireless monitoring prototype system that is suitable to monitor transmission line condition.

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