

## A Laboratory-Based Smart Grid Sensor Network Testbed

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**Abstract.** A laboratory-based sensor network testbed for Smart Grid was developed at the Smart Grid and High Power System Laboratory of The University of Hong Kong. The setup is featured by a scaled transmission-line model, visualization of sensor measurement, optical communication network, and integration with global positioning system (GPS). The transmission-line model consists of a power cable and towers in which various types of sensors including magnetic sensors, infrared sensors, strain gauges, and accelerometers are installed to monitor the condition of the transmission line and the transmission towers. Magnetic sensors and infrared sensor are employed as advanced sensors which can provide more accurate and comprehensive information of the transmission line. The sensor data is transferred to the computer for analysis and visualization. Graphical user interface (GUI) was designed in LabVIEW to integrate the data acquisition and display of measurement results including cable position, inclination and vibration of the tower, frequency and waveform of the cable current. The host computer also forms an IP network with five remote computers, via optical fiber and optical interface card, for testing various communication protocols. The topology and connectivity of the network is graphically displayed. The sensor network is integrated with GPS and can perform synchronized measurement with the GPS timing. This sensor network testbed provides a platform for the implementation testing, experimentation, and feasibility evaluation of new sensor applications under test in Smart Grid.

### Introduction

Smart Grid is an idea of modernizing the power grids to overcome the existing limitations, shortcomings, challenges of the power systems. Due to environmental issues, the expansion of transmission grid has been stagnant for decades which largely constrain the delivery of renewable energy. The ever-interesting cost of fossil fuel is pushing the usage of alternative energy. More and more customers voice out the need of transparency and liberty in the power market, high quality/price ratio electricity, and freedom to interact with the grid. The existing infrastructure is aging while the load demand keeps on growing. To prevent possible decline in reliability, the grid needs to equip with the latest technology such as wide-area measurement and self-healing capability [1]. As a result, many countries are pushing forward the Smart Grid. Slootweg *et al.* [2] defines Smart Grid as a common denominator for a wide range of developments that make medium and low voltage grids more intelligent and flexible than they are nowadays. The development of Smart Grid can improve utilization of renewable energy, promote interactive power market, and enhance compatibility and reliability.

Sensors play an important role to make the grid smarter [3]. Smart Grid will need information more than simply voltage and current. A variety of sensors will be used to detect environment around the facilities and condition of the infrastructure [4]. Advanced sensors are necessary because of their superior sensitivity, accuracy, and compatibility. Since developmental testing may present interruption or reliability threat to a live power system, a testbed for experimenting various kinds of sensing technologies and communication protocols in Smart Grid is needed for testing in an isolated fashion. Gang *et al.* [5] designed a Smart Grid testbed to enable the research community to analyze their designs and protocols in lab environment. Qiu *et al.* [6] built a real-time cognitive radio network for Smart Grid. Nevertheless, their testbeds do not provide a real transmission model for experiments. To the best of our knowledge, we are the first to develop a testbed for studying transmission line in

TABLE I. SENSOR RESPONSES IN VARIOUS EVENTS

	Strain Sensor	Accelerometer (Vibration)	Accelerometer (Tilting)	Temperature Sensor	Magnetic Sensor
Normal	Normal	Normal	Normal	Normal	Normal
Sagging	Increase	Normal	Normal	Increase	Change in magnetic field waveform or distribution
Galloping	Increase	Low frequency, High amplitude	Oscillating	Normal	
Explosion	Increase	Sharp Increase	Oscillating	Temporary Increase	
Tower Collapse	Sharp Increase, Then zero	No Information	Appreciable tilt 0-90 degree	No Information	
Electrical Fault	No Information	No Information	No Information	No Information	

smart grid. Our test bed is designed to perform sensor testing, concept verification, simulation on sensor network, intra system communication, and wide area synchronization.

Our design features visualization, multi sensor network, use of advanced sensors, networking control, and GPS monitoring. The sensor network employs various types of sensors to provide multi-type information to the host computer. The uses of optical communication and IP network enhance compatibility and scalability of the setup. The control system processes the sensor data to visualize the transmission line infrastructure and display complicated charts in real time. GPS is deployed to perform synchronization. All components of this testbed are commercially available, and researcher can build their own setup easily.

## Testbed Features

### A. Platform with Multiple Advanced Sensors

A complete sensing solution for all the transmission system conditions requires multiple types of sensors [7]. Table I shows the responses of accelerometer, temperature sensor, strain gauge, and magnetic sensor in sagging, tilting, explosion, tower collapse and electric fault. Different type of sensor is sensitive to different kinds of scenarios. For example, electrical fault can only be sensed by magnetic field sensor while tower collapse can be sensed by both strain sensor and accelerometer. Therefore, a sensor network with multiple types of sensors is essential for comprehensive monitoring of the transmission line. Our setup includes a multi-sensor network consisting of strain gauges, accelerometers, infrared sensors, and magnetic sensors. The advanced magnetic sensing technology is adopted because a magnetic sensor is sensitive to all types of abnormal events. As shown in Table I, the magnetic field waveform and distribution are sensitive to sagging, galloping, explosion, collapse, and electrical fault. Thus the magnetic field can signify these abnormal events. Due to its extensive sensing ability, it can be used as a universal sensor. In addition, the magnetic field measured by the magnetic sensor can be used to find out the cable position and perform power quality analysis which is difficult to achieve by conventional sensors. The advanced temperature sensing technology is also applied in the setup. The infrared sensor can measure the cable temperature without physical contact with the high-voltage cable, which makes installation and maintenance easier and safer. Furthermore, it is equipped with a laser tracking device to measure temperature of a galloping cable.

### B. Visualization of Measurement Information

Visualization of the measurement information is a key component of the setup because it conveys abstract information in intuitive ways and thus enables users to perceive and understand large amount of information instantaneously [8]. The monitoring part of our setup is highly visualized in order to enhance situational awareness and reduce cognitive demand on the operators. The graphical user interface (GUI) displays the measurement and analysis results of the electrical and spatial information of the transmission line in the forms of images, diagrams, and charts. The magnetic field waveform is presented in graphs while the power quality analysis calculated by performing Fourier Transform on the magnetic waveform is presented in a spectrum.

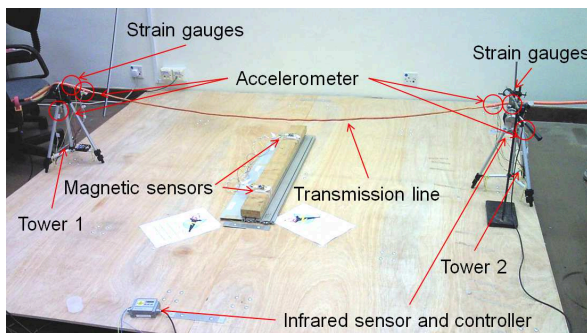


Fig. 2 Laboratory setup of the testbed: transmission towers, transmission line, and sensors are indicated by red arrows.

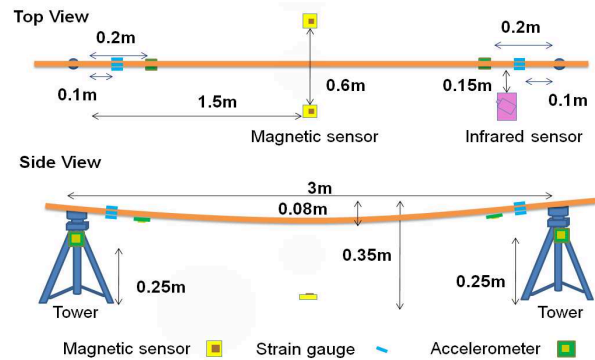


Fig. 1 Schematic diagram of the setup.

### C. Integration with Global Positioning System (GPS)

Our setup is integrated with GPS for providing position and time. As a result, the synchronization accuracy of the sensor network can be boosted from 1 millisecond up to 1 microsecond which is 1000 times better than the current standard [9]. The time provided by the GPS enables time synchronization for wide area measurement. The geographical coordinates obtained from the GPS is fed to the Google Earth to provide satellite aerial map of the sensor network location in the GUI.

## Hardware Architecture

### A. Transmission Line, Sensors, and Electrical System

The laboratory setup of the testbed is established in the Smart Grid and High Power System Laboratory at the University of Hong Kong (Fig. 1). Figure 2 illustrates the schematic diagram of the transmission line model and the associated sensors. The setup consists of a power transmission line suspended by the two towers and connected to a power source. The sensor network includes several types of sensors: magnetic sensors, infrared sensors, strain gauges, and accelerometers. Each end of the transmission line is installed with one set of strain gauges and one accelerometer. Another accelerometer is mounted on each tower. The transmission line is 3 meters long. The height of each tower is adjustable. In normal situation, the degree of sagging at the mid-span of the transmission line is 0.08 m measuring from the horizontal level of the tops of the towers. The cross section of the transmission line is  $35\text{mm}^2$ . Two magnetic sensors are placed on each side of the transmission line at the mid-span on the ground level. The vertical and horizontal distance between each magnetic sensor and the cable are 0.35m and 0.6m respectively. An infrared sensor is placed 0.15m horizontally from the transmission line. Figure 2 shows the dimension of the single phase system. The power source used is FOSTER PCITS 2000/2. The current supplied is 50 Hz sine wave, either 2000A at 0 – 3V or 1000A at 0 – 6V, with current resolution 1A.

### B. Sensor Data Transmission and Network Connection

A data-acquisition (DAQ) card (National Instruments NI USB 6211 M) establishes a link between the host computer (monitoring station) and the sensors (Fig. 3). It collects the analog data from the sensors, converts them into digital form, and sends them via USB hub to the host computer which plays the role of a monitoring station that analyzes the information from sensors and monitor the transmission line. There are 16 analog input channels with  $\pm 10\text{V}$  voltage range (16 bits) with high sample rate of 250k sample per second. In order to provide a platform for testing and implementing communication protocols, there are five computers simulating other monitoring stations and they are connected with the actual monitoring station by optical communication links. Fig. 4 shows the schematic diagram of this monitoring station network. Between the host and each of other five monitoring stations, there are optical fibers and optical interface cards (OLYCOM OM910-FE/S25).

The optical interface cards convert digital signals into optical signals in order to be conveyed by the optical fibers. These interface cards are capable of operating at 100Mbps, providing a network throughput of 200Mbps in full-duplex mode. The single-mode optical fibers are connected to the optical interface cards with the FC/PC connectors.

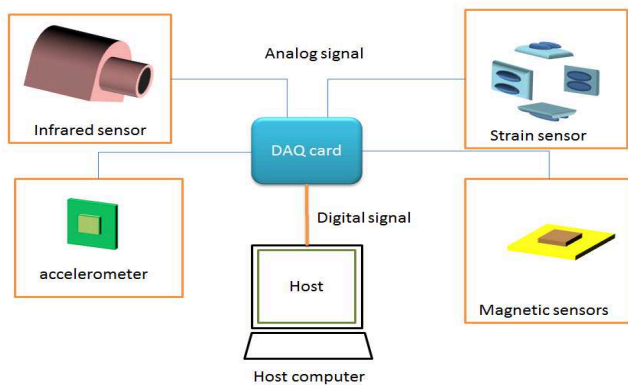


Fig. 3 Illustration of the sensor network. The sensors are connected to the computer via the DAQ card.

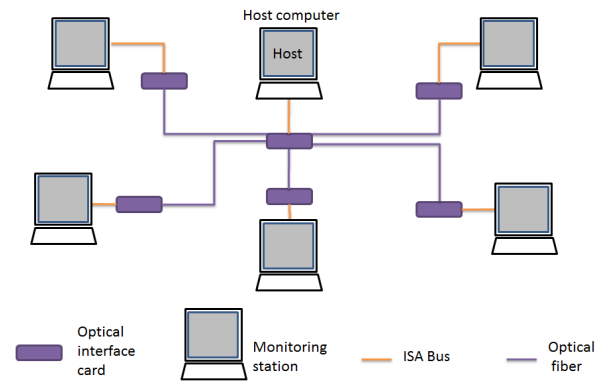


Fig. 4 Illustration of the monitoring station network. The host computer is connected to five other monitoring station computers via optical link.

### Testbed in Operation

The GUI of the monitoring station is shown in Fig. 5. The diagram labeled by (1) is the position chart indicating the position of the mid-span of the transmission line. The position is derived from the magnetic field measured by the two magnetic sensors based on the Biot-Savart Law. As the transmission line is monitored by the two magnetic sensors, there are two magnetic waveforms displayed in the graphs labeled by (2). The inclination diagrams (3) show the front and side views of Tower 1 and Tower 2 and users can observe if there is any inclination for the transmission towers. The inclination is calculated from the tilting angle values measured by the accelerometers mounted on the transmission towers. The diagram (4) is the three-dimensional monitoring of the transmission line derived from the tilting angle values measured by the accelerometers mounted on the transmission line. The spectrum (5) is the power quality analysis by taking Fourier Transform with the magnetic field measured by the magnetic sensors. The GUI also provides numerical measurement information in the panel labeled by (6). The numerical information including the cable temperature measured by the infrared sensor, cable tension measured by the strain gauges, magnitude of the electric current carried by the transmission line as determined by inverse calculation from the magnetic field measured by the two magnetic sensors, and the exact values of the tower inclinations. If these values exceed certain pre-determined safety levels, the corresponding warning indicators are lit up to alert the operators. When there is strong vibration to the tower due to, for example, explosion by terrorist sabotage, the oscillation is sensed by the accelerometers mounted on the transmission towers and the corresponding “Shocked” indicator is lit up to alarm the operators. As such, all the abnormal events listed in Table I can be effectively monitored in this sensor network testbed.



## Summary

The laboratory-based sensor network testbed is featured by a platform with multiple advanced sensors, a GUI visualizing the measurement information, and integration with GPS. The monitoring station has access to all the sensor data and it can carry out further analysis to provide monitoring of the transmission line. The system can detect various electrical and spatial abnormal events of the transmission line including cable sagging and galloping, tower collapse and explosion, and electrical faults. Moreover, it is equipped with GPS receiver and can perform time synchronization for wide area measurement. This setup provides a comprehensive platform for experimenting various sensor network scheme and protocols for Smart Grid.

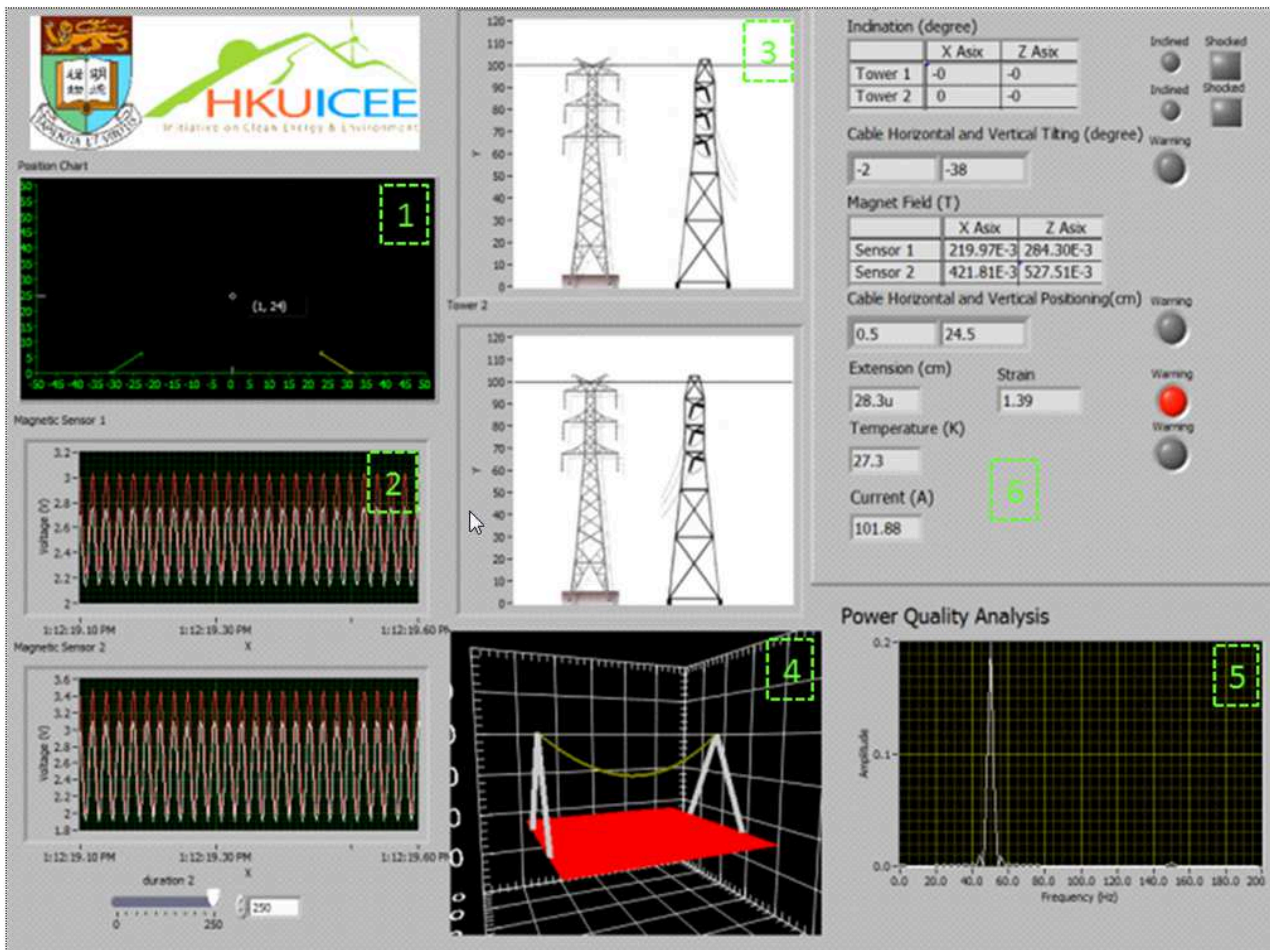


Fig. 5 GUI of the monitoring station. The interface includes (1) position chart, (2) magnetic field waveform, (3) inclination of Tower 1 and 2, (4) three-dimensional monitoring of the transmission line, (5) power quality analysis spectrum, and (6) numerical measurement information panel. The setup is sponsored by HKUICEE (Initiative on Clean Energy and Environment of the University of Hong Kong) which is displayed in the upper left corner.

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