

# A solar-powered wireless data acquisition system for monitoring electrical substations

N. HARID\*, A. C. BOGIAS AND A. HADDAD

School of Engineering Cardiff University, Queen's Building, The Parade, Cardiff,  
UNITED KINGDOM

\*College of Engineering, Prince Muhammad bin Fahd University, Khobar,  
SAUDI ARABIA

[nharid@pmu.edu.sa](mailto:nharid@pmu.edu.sa), [www.pmu.edu.sa](http://www.pmu.edu.sa)

**Abstract:** -This paper describes a wireless data acquisition system for monitoring electrical substations. The proposed system consists of a Wireless Local Area Network (WLAN – IEEE 802.11b/g) transmitter module equipped with a data acquisition system, having current and voltage sensors, a solar power supply with battery energy storage, and a receiver module connected to a remote controller for data processing. The system can be used to continuously monitor a variety of plant within the substation and has low power consumption with inbuilt overvoltage protection. A prototype has been built, and validation tests have been used to check its performance for monitoring of the leakage current of a distribution surge arrester and an insulator. The measured results are in close agreement with those recorded directly through a Data Acquisition (DAQ) card with fibre-optic and coaxial cable connected systems. The operation of this wireless system has been tested and proven resilient under high-frequency interference signals such as those generated by corona and surface discharges.

**Key-Words:** - Wireless communication, Data acquisition, Monitoring, High-Voltage Substation, Solar panel, transmitter, receiver, leakage current, transducer, microcontroller

## 1 Introduction

Electric power utilities are increasingly installing monitoring devices in high-voltage substations, buried electric cables and on overhead power lines to ensure reliable operation and quality of energy supply. Such devices are used in conjunction with fibre optic links or copper wires to transmit information to a central control centre, and in SCADA systems [1]. Their deployment on a large scale would require considerable cost and installation effort. Wireless communication systems, however, offer an alternative to wired or fibre-optic systems for monitoring operation. Their flexibility, low cost and the immunity to earth potential rise problems are some advantages that may be attractive to utilities. For example, the Wireless Local Area Network (WLAN), IEEE 802.11b/g and Wireless Personal Area Network (WPAN) can be successfully applied for monitoring high-voltage substations [2], electric power lines and plant.

However, wireless communication systems are susceptible to noise and electromagnetic interference. In addition, they need to be immune to information loss errors and unauthorised access to data. Unauthorised access can be resolved with the selection of a wireless technology that provides robust security, both in terms of data encryption and network connectivity. Issues of overloaded bandwidth, disruption of the wireless signal due to electromagnetic interference (EMI) and faded

signals need to be examined. If transducers and wireless transmitters are mounted on high-voltage conductors, interference from high frequency signals such as corona may affect the performance of wireless devices. One study showed a clear correlation between both vacuum and SF<sub>6</sub> gap breakdown on one hand, and, on the other, a sharp decline in the data rate of two 802.11b devices [3].

In this paper, a wireless data acquisition system which uses WLAN – IEEE 802.11b/g technology and the (TCP/IP) transmission protocol is developed for monitoring electrical substations. A prototype was experimentally tested both in laboratory and in an outdoor test facility. It uses a solar panel power supply and a battery charger; making it a self-powered monitoring system. The measured signals are in close agreement with those recorded directly through a Data Acquisition (DAQ) card using wired conventional techniques.

## 2 System overview

A simplified operational block diagram is shown in Figure 1. The WLAN-IEEE 802.11b/g module receives the input signals from the transducers installed at the monitoring location. The signals are pre-conditioned then transmitted to the remote control station comprising a WLAN transceiver and a personal computer. A control platform, such as the LabVIEW™ graphical programme, is used for data

processing. This control structure allows real time, continuous monitoring of high-voltage equipment while allowing large amounts of captured data to be stored for post-processing. In addition, the system features two-way communication capability which enables synchronised data transfer and acquisition.

### 3 Architecture of WLAN transmission module

The WLAN transmitter module consists of four main components: the signal conditioning unit, the microcontroller, the transceiver module and a solar power supply with energy storage. The signal conditioning unit contains a surge protection circuit, a low-pass filter and an external Analogue-to-Digital Converter (ADC). The components are PCB mounted and the overall assembly is placed in a metallic enclosure with connections for signal input and power supply. Figure 2 (a) shows a more detailed schematic block diagram showing the components of the wireless transmitter unit. Figure 2(b) shows the PCB layout of the WLAN prototype device, its metallic enclosure with the external aerial and the solar panel. The following sections detail the role of each component of the device.

#### 3.1 Signal conditioning unit

The input signals are fed directly from the voltage and current transducers. The transducers' output signals are chosen to meet the input voltage limits of the WLAN transmitter module ( $\pm 5V$ ). A three-stage protection circuit consisting of a Gas Discharge Tube (GDT), a Transient Voltage Suppressor (TVS) consisting of a Zener type diode and Metal Oxide Varistors (MOV) is used for protecting the WLAN unit against excessive input and surge overvoltages. This circuit was developed to combine the high energy absorption capacity of the GDT with the fast response of the MOV and TVS. A low-pass filter with an operational amplifier is then used to suppress any high frequency interference. The external bipolar ADC samples the filtered signals at a rate of 20 kHz per channel, allowing transmission of 400 data points per channel per cycle.

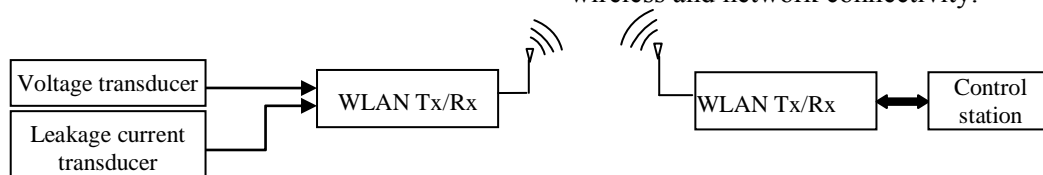


Figure 1. Simplified operational diagram of the wireless data acquisition system.

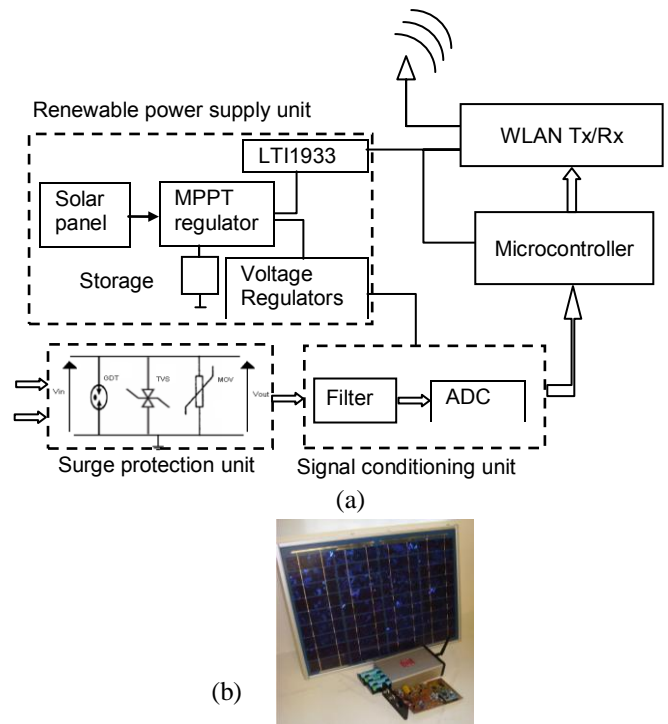


Figure 2. (a) Block diagram of the wireless data acquisition system, (b) The wireless sensor with its metallic enclosure and solar panel

#### 3.2 Microcontroller

A 16-bit high performance, low-power microcontroller with on-board serial communication module is used here to control the data acquisition process. The use of a separate microcontroller has the advantage of allowing the user to choose the programming language as well as the microprocessor that best suits the needs of the application under consideration. The microcontroller, which receives waveform data via a Serial Peripheral Interface (SPI), has full control of the analogue-to-digital conversion by triggering the ADC at the correct sampling rate. Data is stored sequentially in an internal memory buffer, and subsequently transmitted in the RS-232 format to the WLAN transceiver module.

#### 3.3 WLAN IEEE 802.11 b/g Module

The WLAN module is a wireless dual processor communication device that enables both 802.11b/g wireless and network connectivity.

Information received from the microcontroller is encapsulated using the TCP/IP protocol by the WLAN module to ensure the integrity and accuracy of the data prior to transmission.

The device supports 256-bit Advanced Encryption Standards (AES) for end-to-end secure data transfer, and has a maximum power consumption of 740mW. At the remote end, the WLAN receiver module converts the TCP/IP packets back into RS-232 format and feeds data into the PC using the LabVIEW™ program. An analysis subroutine was also developed to allow batches of data to be processed and compiled into one manageable and user-friendly database in real time.

### 3.4 Power supply unit

#### 3.4.1 Renewable power supply and solar panel source

Solar power is common for powering wireless networks, and many devices have been proposed in the literature [4-7]. Here a 492mmx467mm semi crystalline silicone solar panel was used as the main renewable power supply unit, backed up with a rechargeable battery pack for energy storage. Under standard irradiance and temperature conditions, the panel typically generates 20W peak power, capable of supplying the system for up to 19 hours, with an output voltage of 16.8V and a current of 1.19A.

#### 3.4.2 Battery charger

The battery charger is a Linear Technology LT3652 monolithic step-down (buck) type that operates over an input range of 4.95V to 16.8V. The charger incorporates a Maximum Power Point Tracker (MPPT) regulator to optimise power output under varying light irradiance conditions and adjusts the solar panel output between 5.6V and 8.4V, according to the operational requirements of the battery. The battery pack consists of an array of rechargeable Lithium-Ion batteries each with normal operating range between 2.8V and 4.2V. These batteries have high-energy density and long discharge time constant and can provide full power continuously for 19 hours during low or no irradiance periods, with the advantage of being recharged whenever required, without completing the full charge or discharge cycle.

The battery charger was tested using a laboratory solar test facility using a halogen-tube array light source. The measured voltage and current profiles during the charging time are shown in Figure 3, with the WLAN sensor in non-transmitting mode. This voltage reaches 8.2V when the battery is fully charged, with only half an hour charging time is required to reach 90% battery voltage.

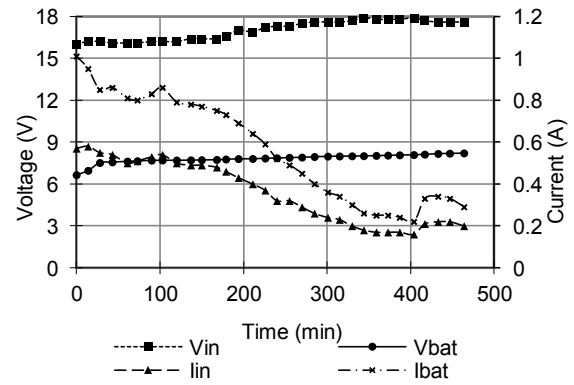


Figure 3. Battery voltage and current profiles over entire charging time

$V_{in}$ ,  $I_{in}$ : Input voltage and current,  $V_{bat}$ ,  $I_{bat}$ : Battery voltage and current

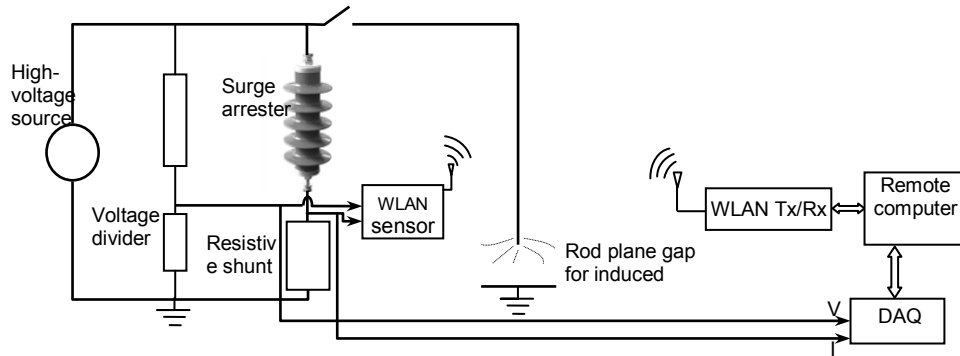
#### 3.4.3 Output regulator

To provide stable supply voltage and ensure reliability of transmitted data, voltage output regulators are used. A step down DC/DC converter model LT1933 was used to provide a regulated voltage of 3.3V at 500mA to supply the microcontroller and the WLAN module. When operating within the voltage range of the Li-Ion battery pack, this converter has an efficiency of about 80%. For the active filtering and ADC circuits, a buck/boost type MCP1253 DC/DC converter is used to generate a regulated 5V output voltage, and a TC1121 voltage converter is used for providing a negative -5V output voltage for the ADC. These converters are suitable for use in applications requiring low noise and high efficiency. The measured output currents from each converter are 26mA and 24mA respectively.

## 4 Experimental Validation

### 4.1 Measurement of surge arrester leakage current

Monitoring of surge arresters in substations usually involves the measurement of the leakage current and can provide fairly accurate diagnostic information when appropriate signal processing techniques are used [8-9]. The leakage current is made up of a capacitive component and a resistive component. The resistive, third harmonic component can be used as an indication of the arrester ageing and degradation condition. Several devices are available for condition monitoring of surge arresters [10], but these are not ideal for continuous monitoring applications because they require the presence of an operator in-situ to download the measured data.



**Figure 4. Experimental set-up for validation of developed wireless system using surge arrester leakage current measurement**

Laboratory tests performed in this investigation are based on leakage current measurement and were used for assessing the developed WLAN system performance and its suitability for on-line continuous monitoring operation. The tests were carried out in the high-voltage laboratory using the arrangement shown in Figure 4. A high-voltage transformer was used to generate a controlled AC voltage to be applied to the surge arrester. A metal oxide surge arrester having a rated voltage of 15kV and a nominal current of 10kA was used as the test object. A variable shunt resistance was used to measure the total leakage current of the surge arrester. Both voltage and leakage current signals were connected to the inputs of the developed WLAN device and, to enable direct comparison, it is also input directly to a Data Acquisition (DAQ) card via coaxial cables. The DAQ card has a 16-bit resolution, a  $\pm 10V$  input range and 20kHz sampling rate.

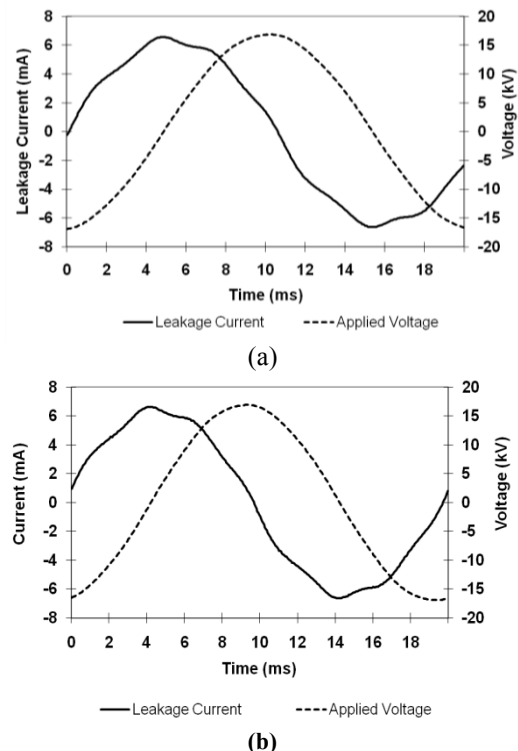
#### 4.1.1 Voltage and current measurement results

Measurements were carried out at several voltage levels up to the arrester rated voltage. Examples of the voltage and current signals recorded with a 12kVrms applied voltage using the WLAN sensor and the DAQ card are shown in Figures 5(a) and 5(b) respectively. In the non-conduction regime, the surge arrester has a very high resistance and the leakage current consists of a small, predominantly capacitive current. This behaviour is well reproduced by the WLAN sensor which shows voltage and current signals almost identical in magnitude and shape to those measured with the DAQ card. The phase difference between the voltage and current signals is also accurately measured. The frequency spectrum of the leakage current signal shows a very small third harmonic component (less than 8% of the fundamental).

#### 4.1.2 Measurements under corona discharge conditions

In a substation environment, high-frequency signals produced by high-voltage equipment or impulsive

noise can be a significant source of interference that may disturb data communication of WLAN devices [11]. Of particular significance is the corona discharge from live conductors and equipment terminals, characterised by high-frequency partial discharges in the vicinity of high-voltage terminals and conductors.



**Figure 5. Example of applied voltage and leakage current signals, surge arrester in non conduction mode (a) WLAN sensor, (b) DAQ card**

The surge arrester tests described in section 4.1 were repeated with the presence of a corona source (a rod-plane electrode gap) close to the arrester, as shown in Figure 4. The WLAN device was tested for its sensitivity to high-frequency discharges. The waveforms measured with the WLAN sensor and the DAQ card are shown in Figure 6 for an applied voltage of 14.5kVrms. At this voltage, the surge arrester exhibits a higher leakage current with a large resistive component. The corona discharge is

detected as small pulses superimposed on the current signals, which occur when the voltage exceeds a threshold value on the positive and negative half cycles. In practice, bad weather conditions usually intensify the corona discharge and the pulse amplitude may exceed the input voltage limit of the WLAN device, activating the overvoltage protection circuit. During the tests, the communication data throughput was not affected by corona activity over the measurement period, and this is an important feature for long term continuous monitoring.

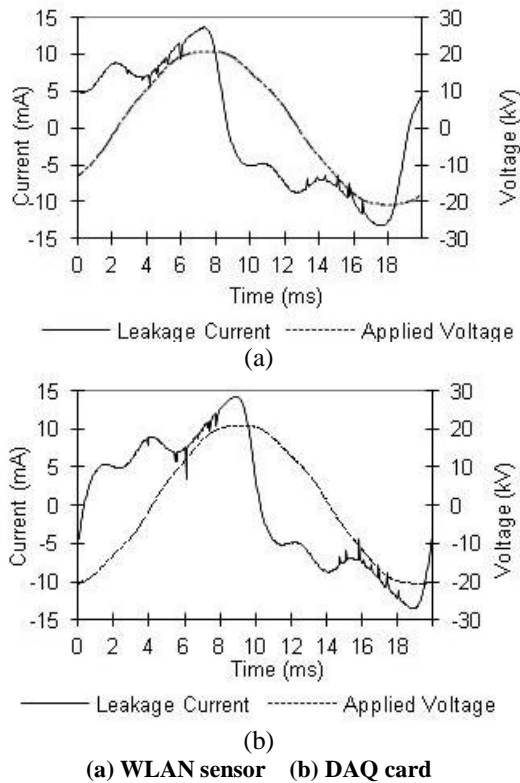


Figure 6. Effect of corona discharge on WLAN sensor signals

## 4.2 Monitoring of leakage current of polluted insulator

The leakage current on outdoor insulator surfaces is a good measure of insulation condition and can be used to detect incipient faults and defective insulators. In heavily polluted areas, the conduction increases due to contamination by salts and other conducting particles. To reproduce such conditions, a measurement was made on an artificially-polluted ceramic outdoor insulator placed in a fog test chamber. The surface leakage current was monitored with the WLAN device and a DAQ card using a set-up illustrated in Figure 7. The data at the remote end was processed to display indicators of insulator surface condition such as rms conduction current, power dissipation and accumulated energy.

Figures 8(a)-(b) show examples of recorded data for a polluted, wet insulator for an applied voltage of 8.9kV. The conduction current monitored using the WLAN sensor is similar to that obtained through the DAQ card (Fig. 8(b)). To check immunity against noise resulting from surface discharges and other high-frequency sources, the WLAN data rate was monitored throughout the test period and found to be unaffected when it is transmitted at an average of 675.2 kb/s as shown in Figure 9.

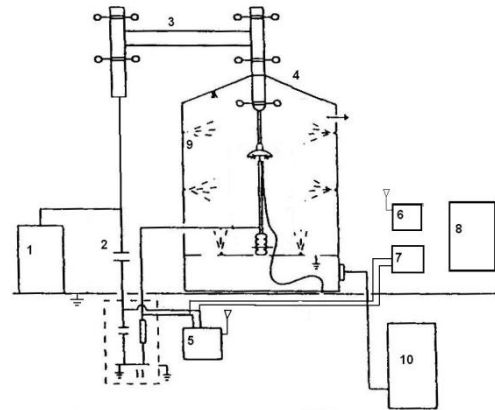


Figure 7. Test arrangement for outdoor polluted insulator

1: High-voltage source, 2: Capacitive divider, 3: High-voltage conductor, 4: Fog chamber, 5: WLAN Tx/Rx, 6: WLAN Tx/Rx, 7: DAQ card, 8: Monitoring platform, 9: Spray nozzles, 10: Fog/rain control unit

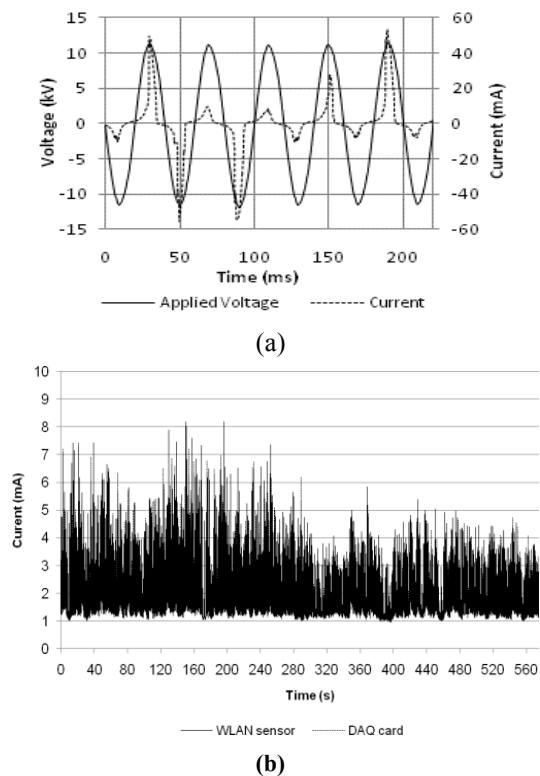
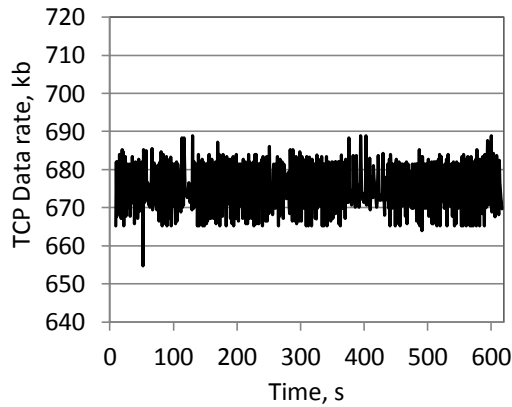


Figure 8. Monitoring of an 11kV polluted insulator using WLAN sensor.

(a) WLAN voltage and current signals,  
(b) rms leakage current  
(c) Average dissipated power,  
(d) accumulated energy



**Figure 9.** WLAN transmission data rate during insulator surface current monitoring

## 5 Conclusion

A wireless data acquisition system for monitoring high-voltage substations has been built based on WLAN-IEEE 11.2 b/g technology. High-energy density Lithium-Ion batteries with relatively fast charging time are used to ensure continuous operation over periods of low irradiance. The system can be configured to provide continuous data acquisition at 20 kHz sampling rate and/or monitor specific quantities at regular time intervals. It has been successfully tested for monitoring the leakage current of a surge arrester and the surface leakage current of a polluted insulator. The results were validated against those measured directly using a wired DAQ acquisition card. The effect of high-frequency interference signals generated by corona discharges and surface discharges on the performance of the device was examined. The device was able to detect such discharges and no effect on the wireless transmission rate was observed.

## 6 Acknowledgments

The UK Engineering & Physical Sciences Research Council (EPSRC) is gratefully acknowledged for the financial support.

## 7 References

- [1] IEEE Std C37.1-2007 (revision of IEEE Std C37.1-1994), *IEEE standard for SCADA and automation systems*.
- [2] Cleveland, F., 'Use of Wireless Data Communications in Power System Operations' *Power Systems Conference and Exposition, PSCE '06 IEEE PES*, pp. 631 - 640, Oct. 29 - Nov. 1, 2006.
- [3] Wang, Y., F.A.M. Mir, and W.H. Siew, 'Digital wireless data acquisition system for measurement in high-voltage substations', *IEEE Power Engineering Society General Meeting*, pages: 1-6, 2006.
- [4] Raghunathan V, Kansal A, Hsu J, Friedman J and Srivastava M, 'Design considerations for solar energy harvesting wireless embedded systems', *4<sup>th</sup> Int. Symposium on Information Processing in Sensor Networks*, IPSN 2005, pp. 457-462, April 2005.
- [5] Dondi D, Bertacchini A, Brunelli D, Larcher L and Benini L, 'Modeling and optimisation of solar energy harvester system for self-powered wireless sensor networks', *IEEE Transaction on Industrial Electronics*, Vol 55, No. 7, pp. 2759-2766, July 2008.
- [6] Li Y, Yu H, Su B and Shang Y, 'Hybrid micropower source for wireless sensor network', *IEEE Sensors Journal*, Vol. 8, No. 6, pp. 678-681, June 2008.
- [7] Kimball J W, Kuhn B T and Balog R S, 'A system design approach for unattended solar energy harvesting supply', *IEEE Transactions on Power Electronics*, Vol. 24, No. 4, pp. 952-962, April 2009.
- [8] BS EN 60099-4 2004 'Surge arresters. Metal-oxide surge arresters without gaps for a.c. systems'.
- [9] IEEE Std C62.22-1 1991, 'IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating-Current Systems'.
- [10] IEC 99-5 IEC 99-5: 1996, Surge arresters – Part 5: Selection and application recommendations –Section 1: General.
- [11] Shan Q, Glover I A, Moore P J, Portugues I E, Watson R J, Rutherford R, Atkinson R and Bhatti S, 'Laboratory assessment of WLAN performance degradation in the presence of impulsive noise', *International Wireless Communications and Mobile Computing Conference 2008, IWCMC '08*, pp. 859-863, Crete Island, 6-8 August 2008.