Impulsive Noise Environment of High Voltage Electricity Transmission Substations and its Impact of the Performance of ZigBee

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Abstract

A measurement system for the characterisation of impulsive noise at frequencies above 700 MHz is presented. The system consists of a pair of ultra-wideband (UWB) quasi-TEM horn antennas, a digital storage oscilloscope and an external hard disk. The particular application of interest is the recording of partial discharge and radiation arising from switching/fault transients in high-voltage electricity transmission substations. A preliminary assessment of the impact of such substation noise on the performance of ZigBee equipment is also described. The results, based on more than 200 MB of transmitted data, suggest that the substation electromagnetic environment has no significant adverse impact on performance.

1. Introduction

An investigation into the vulnerability of wireless network technologies to impulsive noise in electricity transmission substations (ETSs) is currently being undertaken at the University of Strathclyde in collaboration with Scottish Power [1]. The objectives of the proposed research programme are to: (1) characterise the particular impulsive noise environment of high voltage (HV) electricity substations, (2) assess the vulnerability of WLAN and WPAN technologies to impulsive noise; (3) assess the suitability of a range of WLAN and WPAN technology for deployment in HV substations.

Impulsive noise within ETSs can be divided into two principal types: partial discharge (PD) and sferic radiation (SR). PD is a result of incomplete electrical breakdown in insulating dielectrics resulting in a quasi-continuous random train of current impulses. SR is the result of switching (and/or fault) transients and results in sporadic, but potentially large, impulsive radiation events.

WLAN and WPAN technologies most commonly operate in the 2.4 GHz ISM frequency band. WLAN equipment may also operate in the 5 GHz band, however, and WPAN technologies (in particular ZigBee) may operate, in Europe, at 868 MHz. Since (with the possible exception of the lowest band) these frequencies reside in the spectral window between galactic and thermal noise, PD and SR in ETSs may be dominant noise processes for these technologies. No existing impulsive noise measurements covering WLAN, Bluetooth and ZigBee frequency bands relating specifically to ETSs have been found in the literature.

As part of the susceptibility assessment of WLAN and WPAN technologies to impulsive noise a laboratory test and a field trial of ZigBee equipment have been carried out. The field trial comprises a deployment of ZigBee transceivers in a 400 kV ETS [2]. The laboratory test replaces the antennas and radio path between ZigBee transceivers with high-quality coaxial cable and appropriate microwave attenuators. Comparison of the observed bit error ratio for the two cases yields some early information about the likely impact of the ETS noise environment on system performance and reliability.

2. ETS noise measurements

Since the potential interfering effects of PD and SR may depend, not only on power spectral density, but also on their time domain waveforms, it is important, in the context of any measurements to, as far as possible, retain

pulse shape information. In view of this the measurement system has been designed not only to have wide bandwidth but also to have good impulse response.

The block diagram of the measurement system is shown in Figure 1. It consists of four antennas, a LeCroy SDA9000 4-channel oscilloscope (sampling rate 20 GS/s per channel, analog channel bandwidth 6 GHz), an external 1 TB hard disk (for storing the sampled signals) and a laptop computer for data processing. Two of the antennas are TEM half-horns designed to capture signals in the frequency bands 0.716 – 1.98 GHz and 1.92 – 5 GHz. The third antenna is a disk-cone [3] to capture signal frequencies below 700 MHz. This will provide data at the highest frequencies for which measurements already exist. The fourth antenna is a dual-band (2.4/5.5 GHz) commercial WLAN dome antenna. The system has been tested in the laboratory using a novel device designed and constructed by one of the authors for the specific purpose of emulating PD [4]. The test setup is shown in Figure 2.

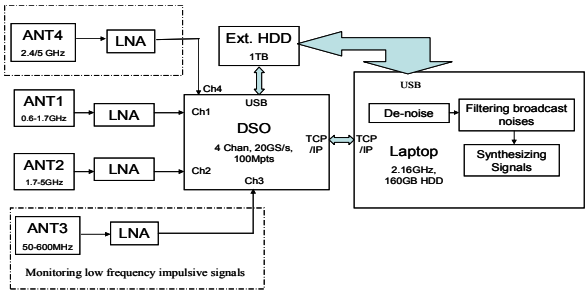


Figure 1. Block diagram of noise measurement system

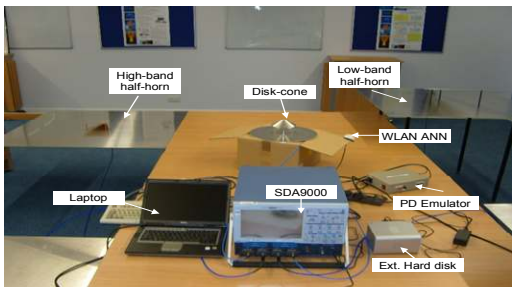


Figure 2. Measurement system test setup

Quasi-TEM horns were selected for the frequency bands of greatest interest due to their potential for wide bandwidth, excellent impulse response, simplicity and low cost. The resulting end-fire structure results in a directive antenna having significant gain. The gain can be used to advantageous in this application since once a significant source of PD in a substation has been identified the antennas can be pointed at it. The TEM horn, in its basic form, consists of two isosceles conducting plates. The apex of the plates (i.e. the corners with the smallest angle) forms the antenna feed-point. The sides opposite the apex are parallel and form the antenna aperture. The flare angle (the angle between the planes of the plates), apex angle and plate length are chosen such that the characteristic impedance at the feed-point is equal to that of the feeding transmission line (typically 50 Ω), and the impedance at the aperture is equal to the plane-wave impedance of free space (approximately 377 Ω). The intention is to create a smooth transition from the impedance of the transmission line to the impedance of free-space with consequent minimal reflection [5]. In practice reflection is not avoided entirely since there are residual impedance discontinuities at both feed-point and aperture. Various techniques have been suggested to reduce these reflections including more sophisticated shaping of the plates [6] and resistive loading at the aperture [7]. The three principal design parameters (see Figure 3) are the length of antenna (measured perpendicularly from aperture to feed point, L; the azimuth angle of the antenna plates, α; and the flare angle between the antenna plates, β. L determines the lower end of the antenna frequency response. This length should be at least one half-wavelength at the lowest frequency of interest. The upper end of the frequency response is inversely proportional to the separation between the plates at the feed point.

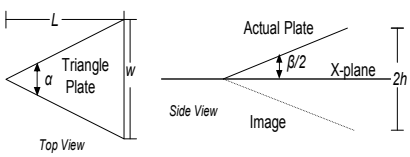


Figure 3. TEM horn parameters

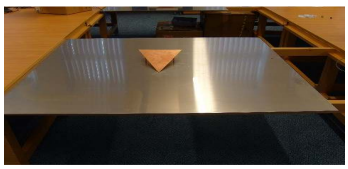


Figure 4. High-band half-horn antenna

Figure 5. Low-band half-horn antenna

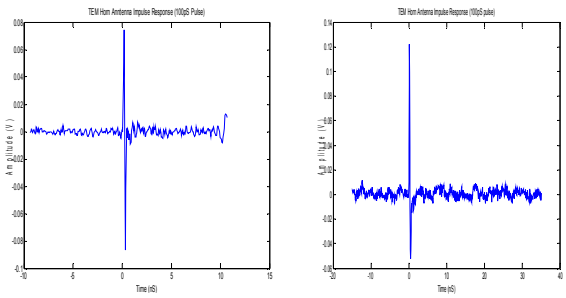
The TEM half-horn comprises a single triangular plate mounted above a ground plane. Two TEM half-horns have been designed to cover the frequency range previously unexplored in the context of PD (716 MHz – 5 GHz); a high-band half-horn and low-band half-horn. The bandwidth definition adopted here is the frequency range between S_{21} -3dB points where S_{21} was measured between the input terminals of the transmitting antenna under consideration and the output terminals of an identical receiving antenna.

The high-band antenna is constructed using a PCB for the triangular flange and a 122 cm×122 cm aluminium plate for the ground plane. The flange width (*w*) at the aperture is 21.7 cm and its length (*L*) is 28.0 cm. The aperture height (*h*) is 6.7 cm. The antenna feed is a 50 Ω SMA connector with its flange in electrical contact with the ground plane and its centre-conductor connected to the triangular plate apex. Its bandwidth is 1.92 -- 5 GHz.

The low-band antenna is constructed from a triangular aluminium plate and an aluminium ground plane. The triangular plate's width (*w*) at the aperture is 65.1 cm, its length (*L*) is 84.0 cm and its aperture height (*h*) is 20.1 cm. The feed structure and ground plane are identical to those of the high-band horn. Its bandwidth is 716 MHz - 1.98 GHz.

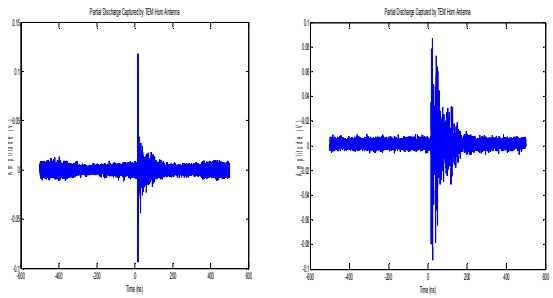
The two antennas are shown in Figures 4 and 5. The impulse responses of the two antennas are shown in Figure 6. Examples of artificial PD captured by the antennas are shown in Figure 7.

The measurement system is currently being deployed in a 400 kV air insulated substation (Strathaven) in the UK. At the time of writing no measurements are available but early results summarising the impulsive noise environment at frequencies above 700 MHz will be presented at the conference.



(a) (b)

Figure 6. (a)High-band and (b) low-band half-horn impulse responses



(a) (b)

Figure 7. (a) High-band and (b) low-band half-horn captured PD

3 Preliminary assessment of the impact of ETS noise on ZigBee performance

The field trial for ZigBee technology was carried out at the same ETS in which the impulsive noise measurement system is being deployed. The laboratory test was carried out in the Geoffrey Smith Intelligent Dynamic Communications Laboratory at the University of Strathclyde. The laboratory test is effectively a control which replicates the field trial test but excludes all external noise and interference. The objective is to assess whether the ETS noise environment significantly degrades the performance of the ZigBee equipment from that observed under the quasi-ideal noise conditions represented by the laboratory test.

The field trial system consists of two terminals, a data source and a data sink, as shown in Figure 8. Each terminal comprises a ZigBee module interfaced to a laptop computer. The source and sink were located in different rooms of the 400 kV control building within the substation compound. The transmitter powers of the ZigBee modules were set to their maximum value (5 dBm). The separation between transmitter and receiver terminals was 21 m and the line-of-sight path intersected two internal walls. The data sink received signal strength indicator (RSSI) was -87 dBm, i.e. 11 dB above the ZigBee receiver sensitivity. 21 m therefore represents close to the maximum separation in this environment. Data was transmitted constantly from the source to the sink. Two transmission modes were used; raw data transmission (mode 1) and cyclic redundancy check (CRC) transmission (mode 2). In the former data is neither encoded nor error checked. In the latter data are CRC encoded at transmitter and checked for errors at receiver. Each data transmissions were of pseudo fixed code blocks. The block lengths were 114 symbols for mode 1 transmissions and 65 symbols for mode 2 transmissions (representing the maximum block lengths specified by the ZigBee chip manufacturer). The durations of the trials were a little more than four days and 10 days for mode 1 and mode 2, respectively. These durations were chosen to yield a comparable volume of transferred data in both cases.

In the laboratory test the terminal hardware, interface and settings were identical to those in the field trial. The communications channel between data source and sink, however, was replaced with a microwave coaxial cable and adjustable microwave attenuators, as shown in Figure 9. The cable and attenuators are specified for operation between DC and 18 GHz, and DC and 20 GHz, respectively. The ZigBee modules were enclosed in

metallic boxes to provide shielding from external electromagnetic interference. The attenuators between source and sink modules were adjusted to give an RSSI of -84 dBm for mode 1 transmission and an RSSI of -87 dBm for mode 2 transmission. -84 dBm was found to be required for mode 1 transmissions (i.e. 3 dB more than that used for mode 2) in order to avoid transmission termination.

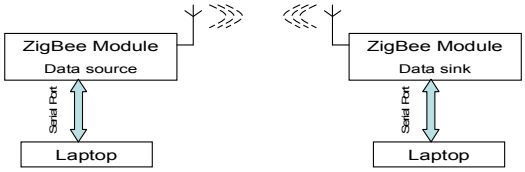


Figure 8. Field trial system

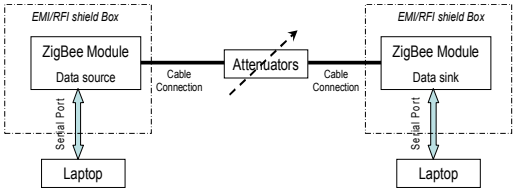


Figure 9. Laboratory test system

The mode 1 field trial bit error ratio (BER) for more than 1.6 Gbit of data transmitted was 5.2179×10^{-7} and the corresponding BER for the laboratory test was 3.5335×10^{-7}. The BERs differ by a factor 1.48. Furthermore the larger (poorer) BER is for the laboratory test.

The mode 2 field trial BER for more than 1.8 Gbit data transmitted was 7.4196×10^{-7} and the corresponding BER for the laboratory test was 7.1813×10^{-7}. These BERs differ by a factor of 1.03 – this time in favour of the laboratory test. These early results suggest that the electromagnetic environment of the substation does not significantly affect ZigBee performance.

4. Conclusion

A system for the measurement of impulsive noise covering a total frequency range from 716 MHz to 5 GHz has been presented. The utility of the system for the measurement of PD has been demonstrated in the laboratory using a PD emulator. The system is currently being deployed in a 400 kV electricity transmission substation for the characterisation of the substations noise environment at frequencies higher than has hither to been attempted. An experiment to determine the degrading effect of substation noise on the performance of ZigBee technology has been described. The results of this experiment suggest that there was no significant adverse impact on the performance of ZigBee technology by the electromagnetic environment (including partial discharge) of the substation.

5. Acknowledgments

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6. References

1. I. A. Glover, Q. Shan, P. J. Mooore, I. E. Portugues, and R. J. Watson "An investigation into the vulnerability of WLAN and WPAN technologies to impulsive noise in electricity transmission substations," in *Ninth International Symposium on Communication Theory and Applications, ISCTA'07*, Ambleside, Lake District, UK, 2007.
2. Q. Shan, I. A. Glover, P. J. Moore, I. E. Portugues, R. J. Watson, and R. Rutherford, "Performance of Zigbee in Electricity Supply Substations," in *Wireless Communications, Networking and Mobile Computing, 2007. International Conference on*, 2007, pp. 3866-3869.
3. P. J. Moore, I. E. Portugues, and I. A. Glover, "A nonintrusive partial discharge measurement system based on RF technology" in *Power Engineering Society General Meeting, 2003, IEEE*, 2003, p. 633 Vol. 2.
4. S. Xiao, P. J. Moore, M. D. Judd, and I. E. Portugues, "An Investigation into Electromagnetic Radiation due to Partial Discharges in High Voltage Equipment" in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-7.
5. K. L. Shlager, G. S. Smith, and J. G. Maloney, "Accurate analysis of TEM horn antennas for pulse radiation," *Electromagnetic Compatibility, IEEE Transactions on* vol. 38, pp. 414-423, 1996.
6. R. J. Whohlers, *The GWIA, an extremely wide bandwidth low-dispersion antenna*. Buffalo, NY: Calspan Corp., 1971.
7. C. Li, T. Chang, and W. D. Burnside, "An ultrawide-bandwidth tapered resistive TEM horn antenna," *Antennas and Propagation, IEEE Transactions on,* vol. 48, pp. 1848-1857, 2000.