

A Self-Calibrating Partial Discharge WSN for Condition Monitoring in the Future Smart Grid

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Abstract-- A self-calibrating wireless sensor network (WSN) of radiometers designed to detect PD radiation is proposed as a low-cost approach to real-time condition monitoring, asset management and operational optimization in the future smart grid. The principles of the proposed PD WSN are described in detail. Some early progress in the development of subsystems for a proof-of-principle prototype is also presented.

Index Terms-- Asset Management, Condition Monitoring, Partial Discharge, Radiometer, Smart Grid, Wireless Sensor Network.

I. INTRODUCTION

PARTIAL discharge (PD) refers to a discharge that does not completely bridge the space between the conductors causing it. It occurs in power systems insulation that is inhomogeneous in dielectric constant due, for example, to air voids in solid insulation or gas bubbles in oil insulation. It also occurs in gaseous insulation as corona due to damaged, or otherwise modified, conductors having regions with small radius of curvature. In these respects the emission of radio frequency (RF) energy via the mechanism of PD is known to be characteristic of insulation imperfection in high voltage (HV) equipment.

PD has been detected using a wide range of sensor technologies including acoustic, ultrasonic, infra-red and electrical. Each of these sensors requires physical contact with the plant being monitored and each item of plant, therefore, requires (at least) one dedicated sensor. The pulse-like nature of PD and their short duration results in radio frequency (RF) components which are readily radiated either from the discharge site directly or from conductors leading away from the site. This makes possible the wireless detection of PD using an appropriate, broadband, radio receiver [1-4].

PD is already used as a tool in condition monitoring of HV plant. In the UK, for example, HV substations are typically surveyed for PD radiation biennially. Such surveys are conducted by trained engineers using a wideband (10 - 900

MHz) radio receiver designed to detect RF interference (RFI) of substation origin. The engineer detects the presence of insulation defects by interpreting signal intensity, visually using a received signal strength indicator (RSSI) or aurally using headphones, as the receive antenna position and receiver frequency band are varied.

The wireless detection of PD using a radio receiver has the advantage that no physical connection need be made to HV (or any other) equipment. Primary insulation remains unbridged and the installation/reconfiguration of detection equipment does not require any item of plant to be taken out of service.

Interest in the routine and continuous detection and measurement of RFI for the diagnosis of defects in transmission and distribution equipment has recently intensified due to the falling costs of RF digital signal processing and the advantages to be gained of moving towards condition-based, rather than time-based, maintenance. Techniques for the detection of insulation faults in gas-insulated substations [5] are well-established and the use of UHF signals for locating and diagnosing internal transformer faults has been reported [6]. Routine PD monitoring and analysis would represent a positive step change in the management of electricity substation plant. Such monitoring would offer not only the immediate benefit of identifying equipment with severely degraded insulation (thus avoiding potentially catastrophic plant failure with consequent unplanned outages), but also the economic advantages of reducing the planned outage of equipment for maintenance and the confident utilization of aging equipment wherever this is warranted by the equipment's insulation integrity and health. The successful analysis and interpretation of PD intensity as a diagnostic tool for plant management promises high rewards. The benefits of being able to identify insulation defects and diagnose their severity (from inconsequential to imminent catastrophic failure), in real-time across an entire substation, are obvious.

II. VISION

The vision is of a low-cost PD radiometer network distributed throughout the power systems network measuring PD intensity. In each substation a primary node radiometer would be co-located with each significant item of plant. Significant, here, means an item of plant whose expense, or strategic function, warrants particular protection from insulation failure. Auxiliary node radiometers would be deployed to ensure an approximately uniform sensor density

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facilitating the interpretation of radiometer data and location of plant defects. The deployment strategy would be such that no item of electrical plant, with the possible exception of some segments of overhead transmission line, would be further than (say) 30 m from a radiometer. (A substation with an area 40,000 m² is unlikely to require more than around 30 radiometers, therefore, allowing for significant non-uniform overall distribution due to clustering of significant plant.)

Such a radiometer network takes advantage of two well-established properties of PD, i.e.:

- PD intensity is incontrovertibly linked to insulation defects.
- PD is a fundamentally local phenomenon.

The noise temperatures measured by the radiometers would be communicated wirelessly to a data-collection station which itself would be connected to the Internet. The wireless links would use a frequency (almost certainly in the 2.4 GHz ISM band) well above the PD measurement band (10-1000 MHz). If necessary a low-pass RF filter would be incorporated into the front-end of each radiometer to ensure such interference from the wireless links do not inflate the radiometer measurements.

Data analysis software would continuously monitor the effective noise temperatures reported by the radiometers and form a space-time map of noise activity. Absolute values, and rates-of-change, of radiometer noise temperatures in both spatial and temporal domains will be used to flag events requiring action or further investigation. As experience with the system is gained, and confidence in it grows, it will become a primary indicator of plant health. Experienced operators (and eventually automated expert systems) will be able to use the information provided by the network to operate aging plant to its maximum potential without the risk of catastrophic failure.

III. OPERATING PRINCIPLES

Each radiometer will make a measurement of total power within its receiver bandwidth using an integration time of around 300 s. This is short enough to capture changes in PD activity due to changes in physical insulation state but long enough to make the measurement a reliable estimate of PD intensity. A 300 s integration time would also mitigate against high-power, but short-lived, transients produced by switching events, for example, from falsifying the PD intensity estimate. Each radiometer will report its measurement to an on-site data-collection station using a wireless sensor network (WSN) technology such as ZigBee or WirelessHart. (WirelessHart is a recent variant of Zigbee developed specifically for industrial environments.) ZigBee has a maximum bit-rate of 250 kbit/s and a nominal maximum range of 100 m. Technologies exist, however, which can extend this range [7].

The problem of contamination by external noise and signals of non-PD origin, including coherent interference represented by communications, navigation and radar transmissions, is addressed in two ways. Firstly, the large radiometer bandwidth mitigates against undue influence of signals with high spectral density provided they are narrowband. Secondly, the radiometer network takes advantage of the local character of PD signals. A communications, or other, signal originating far from the substation will affect all radiometers (approximately) equally. A PD signal occurring close to one radiometer will have decayed (relatively) to low levels at the locations of other radiometers. Radiometer 'hot-spots' superimposed on a map of the substation will therefore reflect signals of substation origin only. The approximately uniform density of radiometer nodes gives the network an inherent localization capacity. (The PD source will be close to those radiometers with elevated temperatures.) The localization of PD sources can be refined, however, by inverting the transmission-loss law of the PD signal modelled by (1):

$$P_R = \frac{k}{r^n} \quad (1)$$

where P_R is received power, r is range from the source of radiation, k is a constant that depends on systems parameters (radiated power, antenna gains, radiometer bandwidth etc), and n is a path-loss index. If the value of n is independent of range Eq. (1) is referred to as a single-slope law. The path-loss index for propagation in free space, for example, is 2 corresponding to a single-slope transmission loss law of 6 dB/octave [8]. For ranges beyond those producing interference fringes due to direct and ground reflected paths the propagation index over a perfect ground-plane is 4 corresponding to a transmission loss of 12 dB/octave. The transmission-loss law can be inverted (as in [9]) to give an estimate of the ratio of distances from a PD source to any two radiometers. A PD source detected by three or more radiometers can therefore be located from the intersection of loci. In practice this location estimate will be subject to error determined, principally, by the spatial and path-orientation variability of the transmission-loss index. It is unlikely, therefore, that there will be a single, unique, point of intersection of multiple loci. If this variability in transmission-loss index were known, however, an initial location based on an assumed transmission-loss law (independent of location and path-orientation) could be refined by using path-loss laws particular to the initial location estimate. This refinement could be applied iteratively to further improve the location estimate if necessary.

To facilitate the location algorithm outlined above it is proposed to incorporate a PD emulator (i.e. a transmitter that radiates a PD-like signal) in each radiometer node. Each node

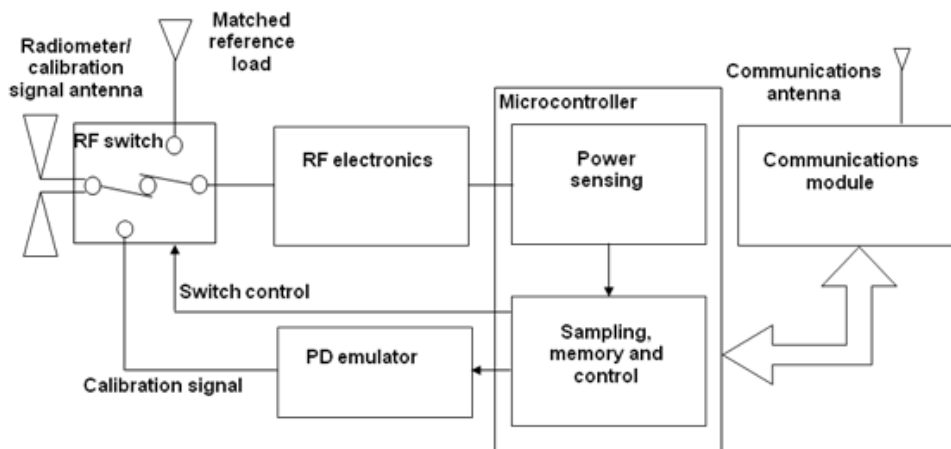


Fig. 1. Proposed radiometer architecture.

will then briefly (e.g. for 100 ms), but periodically (e.g. once per hour) radiate a PD-like signal of known power, via an omnidirectional antenna of known gain, in a pre-arranged time-slot. All other nodes will receive this ‘calibration’ signal and will thus be able to measure the path-loss index for the path between itself and the radiating node. The resulting values of transmission-loss index as a function of source location, path-length and path-orientation can then be interpolated to provide appropriate inputs to the location algorithm.

The use of a realistic emulation of a PD signal and an operational radiometer as transmitter and receiver respectively will improve the estimate of the transmission-loss index measurements over those that would be found using an unmodulated carrier, for example. This is because transmission loss is a function of frequency and the broadband nature of PD will make the resulting ‘effective law’ a weighted average over the measurement bandwidth of many simpler, narrow-band, laws. Using a PD-like transmitted signal and an operational radiometer as receiver will ensure the weighting employed in establishing the effective law is precisely correct for accurate PD location.

Such a location algorithm will be subject to residual errors due to (i) deviation from an omnidirectional pattern of the PD radiation, (ii) SNR variations of the transmission-loss measurements and (iii) transmission-loss index interpolation errors. A best estimate of PD location will therefore minimize an appropriate, confidence-weighted, error metric.

PD sensing device simplicity is central to the strategic vision, both to ensure low deployment costs and (perhaps more importantly) to ensure robust and reliable operation. Figure 1 shows proposed radiometer architecture.

The proposed architecture for the radiometer is basically divided in five functional blocks: the sensing block, the RF electronics block, the partial discharge emulation block, the wireless communication block and the management block. The sensing block is composed by the fundamental part of the system, the antenna, responsible for monitor partial discharge activity. This sensor is connected to the signal conditioning circuit represented by the RF electronics block which is responsible for convert the noise obtained by the antenna to a voltage level proportional to the noise level. That information is managed by the management block, composed by a

microcontroller which transmits the information about the noise level by a serial communication to the communications block. Beyond information management, the microcontroller is responsible for control the PD emulation block, used to generate a PD like signal with purposes of network calibration.

The final version of the radiometer will employ automatic gain control (AGC) and/or logarithmic detection to ensure it has sufficient dynamic range to operate successfully in both low, and high, signal level environments. It will be self-calibrating, periodically connecting a matched (reference) load via an RF switch in place of its antenna. (This calibration relates to the measured noise temperature and is not to be confused with the transmission-loss calibration for the location algorithm described previously.) During the calibration cycle the radiometer will measure the thermal noise from the reference load. This load constitutes a black body radiator and will therefore have a noise temperature, T_{ref} , equal to its physical temperature. The radiometer calibration temperature, T_{cal} , will be the sum of the reference temperature and the radiometer’s internal equivalent noise temperature, T_e . T_{cal} can be effectively subtracted from the radiometer noise temperature reported during the PD measurement phase. The calibrated measurement will therefore represent the excess noise temperature (principally representing PD) over and above the background noise temperature expected due to normal thermal processes. The proof-of principle prototype units will be battery powered.

IV. SOME EARLY PROGRESS

The radiometer WSN concept described above is fairly well-advanced but progress towards realization is at an early stage. Two hardware elements of a proof-of-principle system have been developed, however. These are the radiometer antenna and a simple impulse generator to emulate PD.

Figure 2 shows a schematic diagram of the disk-cone antenna.

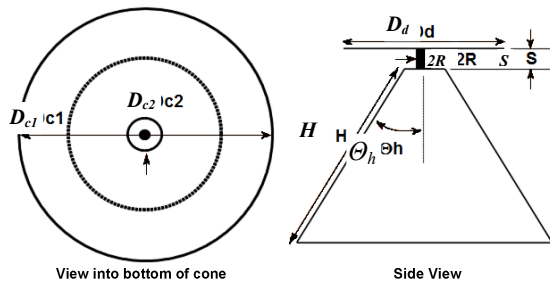


Fig. 2. Diskcone antenna diagram [11].

The geometry of the antenna can be related to the lowest (cut-off) frequency, f_c , of its design band [12] by:

$$D_d = \frac{52500}{f_c} \quad (2)$$

$$H = \frac{75000}{f_c} \quad (3)$$

$$S = \frac{1}{4} D_{c2} \quad (4)$$

with D_d and H in mm and f_c in MHz. The half-angle of the cone apex controls the impedance of the antenna.

For a cut-off frequency of 200 MHz $D_d = 262$ mm, $H = 375$ mm and $S = 3$ mm. For an input impedance of 50Ω , $\theta_h =$

30° . (The non-critical dimensions R , D_{c1} and D_{c2} were chosen to be 0.8 mm, 381 mm and 12 mm, the latter two being related by θ_h .) This antenna was simulated using CST Studio Suite 2010. Figure 3 shows the simulated $|s_{11}|$.

Figure 3 predicts a good (better than 10 dB) return-loss between 260 MHz and 800 MHz. The apex angle was varied to minimize the lower frequency of the 10 dB return-loss window. Figure 4 shows the improvement realized with a cone flare angle of 20 degrees. The lower frequency of the 10 dB window is reduced to 227 MHz (and the higher frequency of the window is increased to 1050 MHz). The antenna was constructed from aluminium sheet (thickness 0.82 mm). The measured return-loss and input impedance of the antenna, determined using a vector network analyzer, are shown in Figure 5(a) and (b) respectively.

The measured results are (somewhat surprisingly) better than the simulated results.

A crude but useful test of the antenna's usefulness for detecting PD has been undertaken using a spark generator, Figure 6. The antenna was located 1.0 m from the spark generator and a spectrum analyzer was used to observe the power spectrum of the received signal in the presence and absence of sparks.

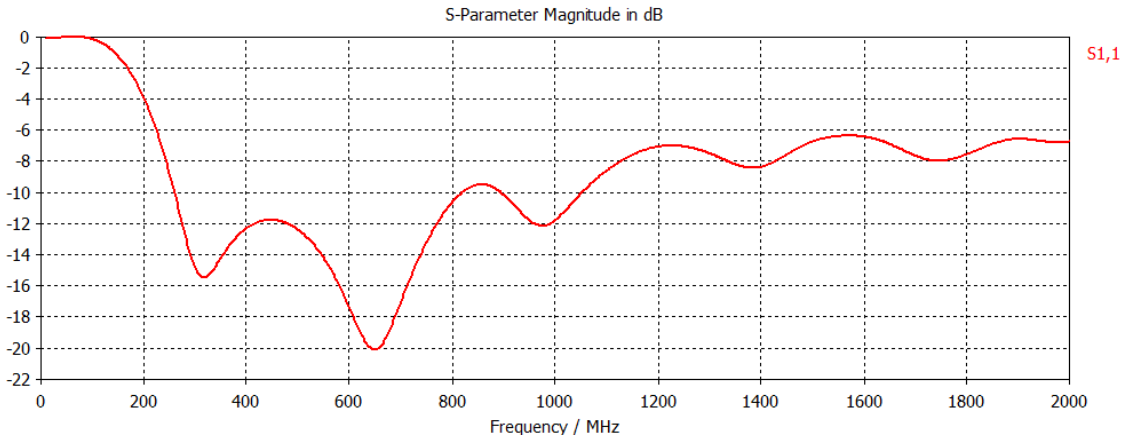


Fig. 3. $|s_{11}|$ for simulated antenna.

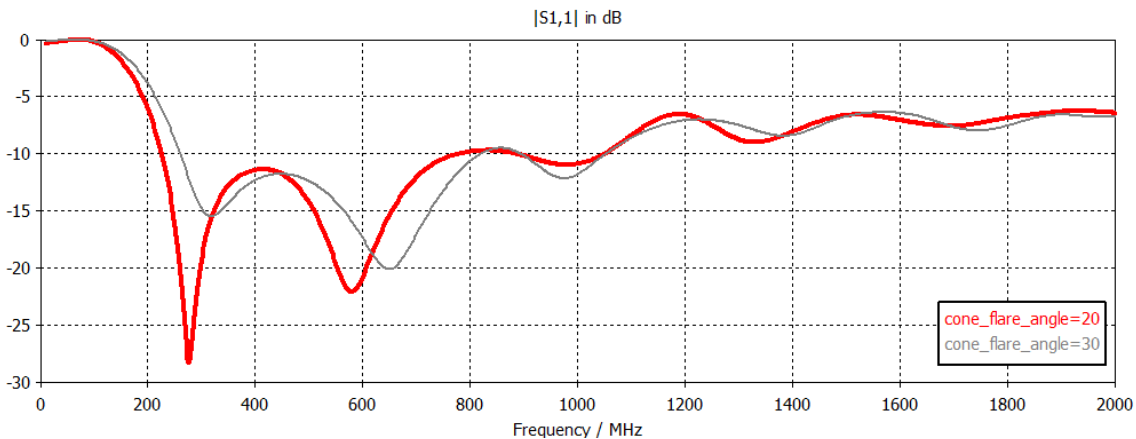


Fig. 4. $|s_{11}|$ for optimized simulated antenna.

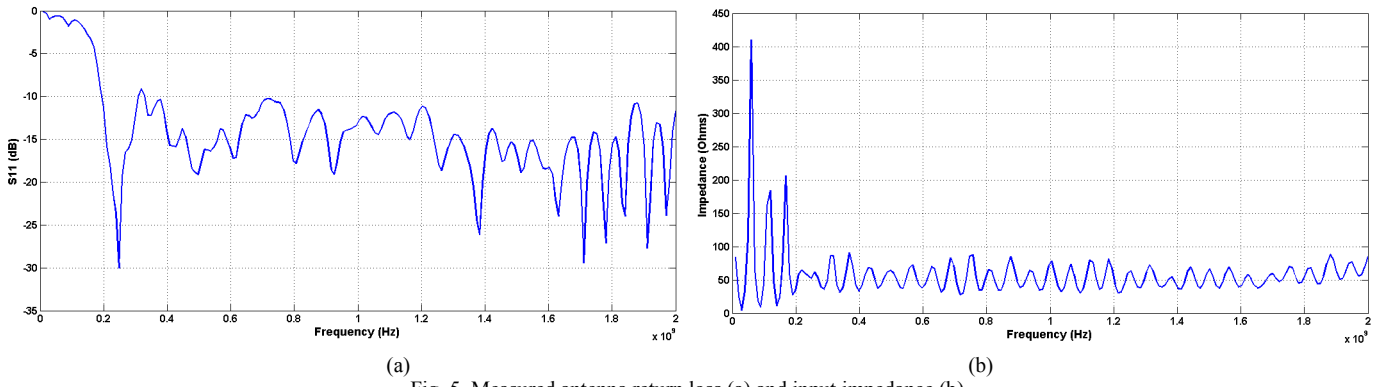


Fig. 5. Measured antenna return loss (a) and input impedance (b).

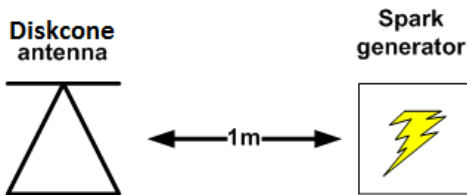


Fig. 6. Schematic diagram of antenna test.

spark) are shown in Figure 7. It can be seen that the power radiated by the spark generator is easily observable in the band between 200 MHz and 800 MHz. A simple test with a cell phone has shown the antenna to be sensitive to signals up to at least 1.8 GHz. Further, and more rigorous, characterization of the antenna is required but these early result are encouraging.

The spectrum analyzer IF band used in the measurement was 10 - 2000 MHz and the sweep speed was 1.3724 GHz/s. The observed spectra (in the presence and absence of the

A simplified radiometer the antenna described above, an RF power detector (LT5538) and a microcontroller has been constructed, Figure 8. The spark generator has been used to demonstrate the plausibility of a radiometer based on these components, Figure 9.

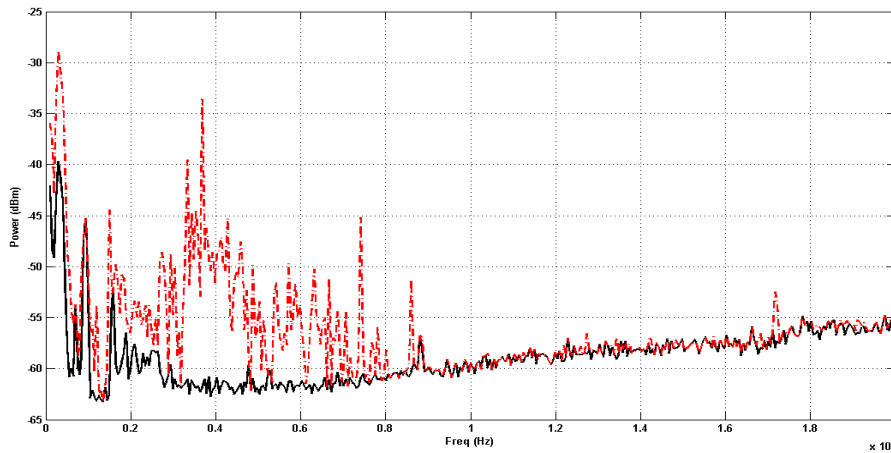


Fig. 7. Power spectrum between 10 and 2000 MHz. Red dashed line is measured power spectrum in the presence of spark generator, black solid line is the power spectrum in the absence of the spark generator.

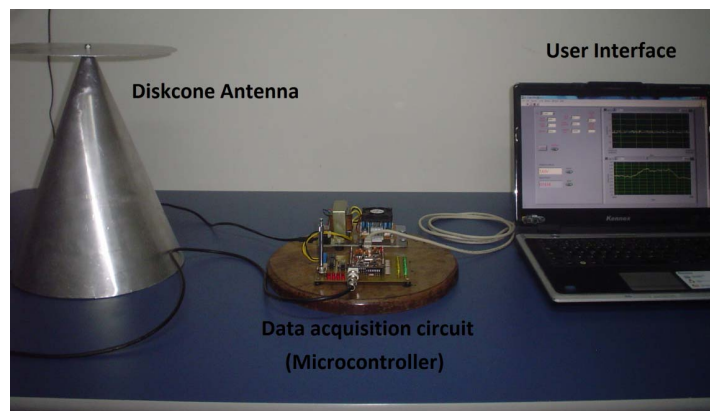


Fig. 8. Simplified radiometer prototype.

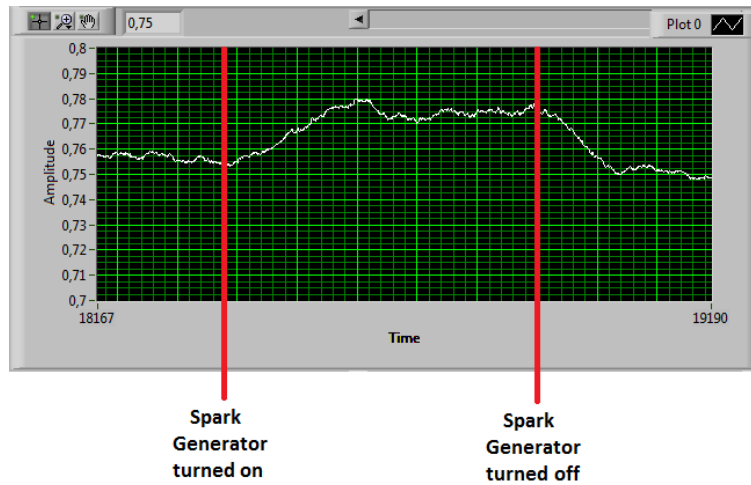


Fig. 9. Prototype radiometer output using spark generator as simple PD model..

A. PD emulator circuit

Consideration has been given to the realization of the PD emulator that would be used for transmission-loss calibration in the iterative location algorithm described above. The core of such an emulator is a low-cost short-duration pulse generator. Figure 10 shows just such a low-cost circuit described by Lee and Nguyen [13]. The pulse duration must be comparable with those pulses that occur in realistic PD.

The step recovery diode (SRD) in Figure 10 is designed to change from conducting to non-conducting state especially rapidly. When driven by a negative-going voltage (even with relatively slow rate of change) the voltage of across the diode changes with much more rapidly.

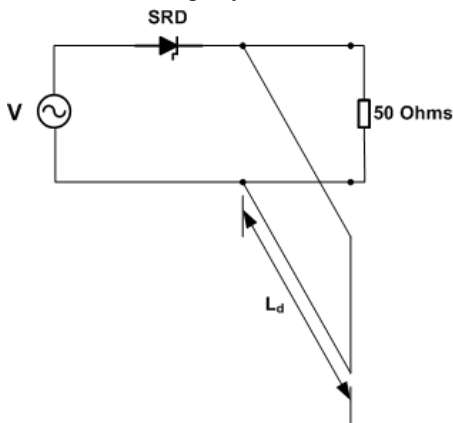


Fig. 10. Schematic circuit diagram of impulse generator.

This process is referred to as pulse sharpening. The resulting step change in voltage travels down the transmission line to the right of the diode until it comes the transmission line junction. The pulse splits into two equal parts, one part being directed along the short-circuited stub and the other being directed along the main transmission line. The pulse in the stub is inverted at the short-circuited end of the line and travels back along the stub where it adds to the pulse in the main transmission line. Since the stub pulse is delayed (by a time corresponding to twice the length of the stub) the inverted and non-inverted pulses approximately cancel at all

times (measured from the start of the non-delayed pulse) greater than the delay introduced by the stub, Figure 11. The result is a particularly narrow pulse travelling in the main transmission line towards the load.

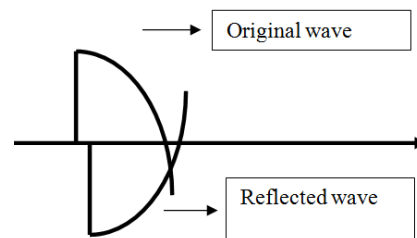


Fig. 11. Pulse cancelling principle of impulse generator.

A microstrip realization of the circuit shown in Figure 12 was designed and fabricated using FR-4 substrate (substrate thickness 1.6 mm, conductor thickness 0.035 mm, dielectric constant approximately 4.3). The transmission line impedance was 50 Ω . Since the aim of the pulse generator is to achieve 200 picoseconds pulse width the design frequency for the transmission lines was chosen to be 10 GHz (i.e. twice the reciprocal of the target pulse width). The calculated width of the microstrip line was 3.342 mm.

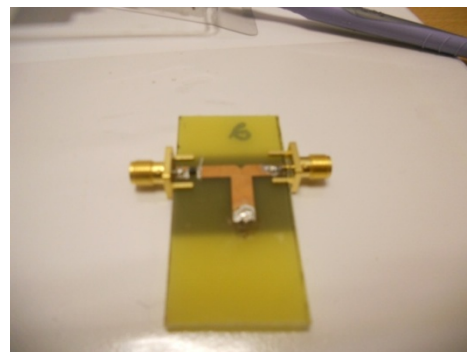


Fig. 12. Microstrip implementation of impulse generator.

The circuit was tested by driving it with a signal generator set to give a square-wave of 4.2 MHz. The circuit output was examined with a fast digital storage oscilloscope (DSO) with a

sampling rate of 40 GS/s and an analogue bandwidth 12 GHz. The DSO trace in Figure 13 shows that the pulse duration realized in practice is around 270 ps. This suggests such a circuit could be used as the basis for a PD emulator.

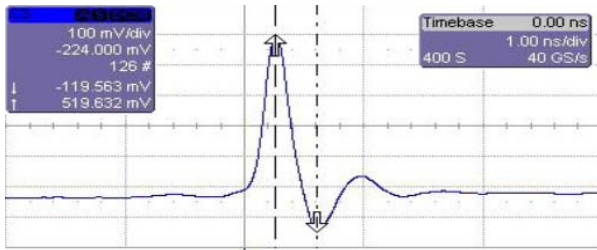


Fig. 13. Impulse generator output.

V. CONCLUSIONS

The principles of a low-cost self-calibrating radiometric PD WSN for real-time power system condition monitoring have been described in detail. Such a WSN could be a significant component in the future smart grid. Selected core components of the WSN radiometer (antenna, radiometer sensor and pulse generator) have been prototyped in a simplified form and their basic functionality has been demonstrated. This preliminary work suggests that a PD radiometer of the type proposed can be implemented at a sufficiently low cost to allow widespread deployment in the power system with a sensor density sufficient to localize a source of PD. Funding is currently being sought to develop a practical prototype network.

VI. REFERENCES

- [1] Moore, P J, Portugues I and Glover I A: RF-based partial discharge early warning system for air insulated substations, IEEE Power Engineering Society General Meeting Transactions, Boston, USA, August 2003.
- [2] Portugues, I, Moore, P J and Glover, I A: Characterisation of radio frequency interference from high voltage electricity supply equipment, Proc. 12th IEE International Conference on Antennas and Propagation, vol. 2, pp. 820 – 823, Exeter, UK, April 2003.
- [3] Moore P J, Portugues I and Glover I A: Remote diagnosis of overhead line insulation defects, Proc. IEEE Power Engineering Society General Meeting, (PES 04), Denver, USA, June 2004.
- [4] Moore P J, Portugues I and Glover I A: Radiometric location of partial discharge sources on energised high-voltage plant, IEEE Trans. in Power Delivery, vol. 20, no. 3, pp. 2264-2272, July 2005.
- [5] Moore P J, Portugues I E and Glover I A: Partial discharge investigation of a power transformer using wireless wideband radio frequency measurements, Power Engineering Letters, IEEE Trans. on Power Delivery, vol. 21, no. 1, pp. 528 – 530, January 2006.
- [6] Hampton, B: UHF diagnostics for gas insulated substations, Proceedings of ISH99, London, August 1999.
- [7] Farahani, S.: ZigBee Wireless Network and Transceivers. 1. ed. 30 corporate drive, suite 400, burlington, MA 01803, USA: Newnes, 2008. ISBN 978-0-7506-8393-7.
- [8] Glover, I A, Grant, P M: Digital Communications, 3rd ed., Pearson, 2009. In Press.
- [9] Souza Neto, J.M.R.; Silva, J.J.C.; Cavalcanti, T.C.M.; Rodrigues, D.P.; da Rocha Neto, J.S.; Glover, I.A.; , "Propagation measurements and modeling for monitoring and tracking in animal husbandry applications," Instrumentation and Measurement Technology Conference (I2MTC), 2010 IEEE , vol., no., pp.1181-1185, 3-6 May 2010. doi: 10.1109/I2MTC.2010.5488068
- [10] Stutzman, W.L. & Thiele, G.A., "Antenna Theory and Design", 1st Ed., 1981, pp. 274.
- [11] Antenna Magus 2.4.0.; Information Report from Antenna Magus Software: Diskone Antenna. : 5 April 2011.
- [12] PoPtronix, "Discone VHF - UHF Antenna", Eletronix Handbook, 1997.Biographies

- [13] Lee, J.S.; Nguyen, C.; , "Uniplanar picosecond pulse generator using step-recovery diode," Electronics Letters , vol.37, no.8, pp.504-506, 12 Apr 2001 doi: 10.1049/el:20010350 URL: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=919987&isnumber=19885>

VII. BIOGRAPHIES

José Maurício Ramos de Souza Neto was born in Campina Grande - PB, Brazil in 1984. He was graduated in electrical engineering from Federal University of Campina Grande, in 2008, he received his master's degree in electrical engineering, and currently he is a PHD student at the same university. Most of his research interests include electronic instrumentation and sensors, microcomputer-based laboratory automation and applications of wireless sensor network.

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José Sérgio da Rocha Neto was born in 1952, in Sapé-PB-Brazil, and received his electrical engineering degree from the Federal University of Paraíba, Campina Grande, in 1978. In March 1982, he received his master's degree in electrical engineering at the Federal University of Paraíba, and his doctoral degree in November 1994 in electrical engineering at the Federal University of Paraíba. He worked as an assistant professor at the State University of Paraíba (UEPB) from 1980 to 1981, and as professor at the State University of Santa Catarina, Joinville-SC-Brazil from 1981 to 1994. Since February 1994, he is associate professor at the faculty of the Electrical Engineering Department of the Federal University of Campina Grande - PB - Brazil. His research interests include electronic instrumentation and sensors, microcomputer-based laboratory automation and applications of wireless sensor network.

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