Partial Discharge Location using Unsynchronized Radiometer Network for Condition Monitoring in HV Substations – A Proposed Approach

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Abstract. A location estimation system for online Partial Discharge (PD) detection is proposed as a low-cost approach to real-time condition monitoring, asset management and operation optimization in future smart grid. Some early progress in the development of subsystems (specifically the antenna, radiometer device, PD emulator and PD generator) for a proof-of-principle prototype system is described. The proposed PD Wireless Sensor Network (WSN) uses a novel approach to PD location which obviates the need for synchronization between sensors thereby improving scalability.

1. Introduction
Partial discharge 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.

Many PD sensors for monitoring the insulation integrity of HV electrical equipment are now available commercially. Sensors which require contact with HV conductors bridge the insulation of the power system and require plant to be taken out of service for installation, maintenance or reconfiguration. Sensors such as HFCTs and TEVs rely on near-field inductive, or surface-wave, coupling and therefore require (at least) one sensor for each item of plant to be monitored. 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 (typically ~ 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 receiver antenna position and receiver frequency band are varied.

Recently, a free-standing technology has been developed which allows PD to be detected and located at a distance [1]. 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. This not only obviates the need to take HV plant out of service for installation and reconfiguration but can provide wide area coverage from a single sensor.

The location method used in this technology is based on time-difference-of-arrival measurements of the PD signal at three or more spatially separated points requiring sophisticated receivers. An alternative technology for detection of PD in substations using a simple (and therefore cheap) unsynchronized (and therefore scalable) network of radiometers is proposed by the authors. In this paper we report progress in the development of this novel approach to PD detection and location using a WSN.

2. Vision
The vision is of a network of low-cost PD radiometers distributed throughout the power system 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 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 m$^2$ 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.

3. 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 WSN technology such as ZigBee or WirelessHart. 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 [2].

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 to (relatively) 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. (PD sources will be local to those radiometers with elevated temperatures.) The localization of PD sources will be refined, however, by inverting the transmission-loss law of the PD signal modeled by:

\[ P_R = \frac{k}{r^n} \]

where \( P_R \) is received power, \( r \) is range from the source of radiation, \( k \) is a constant that depends on system’s parameters (radiated power, antenna gains, radiometer bandwidth etc), and \( n \) is a path-loss index. If the value of \( n \) is independent of range equation (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 [3]. 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 [4]) to give an estimate of the ratio of distances from a PD source to any two radiometers. A location for a PD source can therefore made if the source is detected by three or more radiometers. In practice this location estimate will be subject to error determined, principally, by the spatial and path-orientation variability of the transmission-loss index. If the spatial- and orientation-variation in transmission-loss index were known, however, an initial location based on an assumed transmission-loss law (e.g. one 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 as necessary.

To facilitate the iterative 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 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.

The location algorithm outlined above 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
(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 a proposed radiometer architecture.

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.

4. Some Early Progress
The radiometer WSN concept described above is fairly well-advanced but progress towards realization is at an early stage. A proof-of-principle, elementary, radiometer and a PD generator for system validation have been developed, however.

4.1. Radiometer
The diskcone antenna [5] has been selected for the proof-of-principle system. (In a production version the antenna is more likely be a microstrip patch design – possible of a bow-tie antenna – and will thus be much smaller and lighter than that described here.) The diskcone antenna is a monopole variation of the biconical antenna. It is low-gain, omnidirectional, linearly-polarised and has wide bandwidth. It is also an unbalanced structure and therefore does not require a balun for a coaxial feed. Figure 2 shows a schematic diagram of the diskcone antenna.

![Diagram of proposed radiometer architecture.](image-url)
The geometry of the antenna can be related to the lowest (cut-off) frequency, $f_c$, of its design band [6] 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 $D_d$ (disc diameter) and $H$ (cone length) 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 50 $\Omega$, $\theta_h = 30^\circ$. (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 $\theta_h$.) This antenna was simulated using design software and 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 and improvement was obtained with a cone flare angle of 20 degrees. The lower frequency edge of the 10 dB window was thereby reduced to 227 MHz. (The high frequency edge of the window was increased to 1050 MHz.) The prototype antenna was constructed from aluminium sheet (thickness 0.82 mm). The measured return-loss and input impedance of the antenna are shown in Figure 3. (The measured results are, somewhat surprisingly, better than the simulated results.)
A demonstration of the antenna’s PD detection capability has been undertaken using a test cell PD generator. The PD generator is described in Subsection 4.2. The antenna was located 1.2 m from the generator and a spectrum analyzer was used to observe the power spectrum of the received signal. The spectrum analyzer IF band used in the measurement was 10 - 500 MHz and the sweep speed was 1.3724 GHz/s. An example of the noise spectrum is shown in Figure 4.

Further, and more rigorous, characterization of the antenna is required but these early result are encouraging. The noise floor in this simple test is at least 24 dB below the maximum signal level in the spectrum. Assuming the signal decays with distance at 6 dB/octave (corresponding to free-space propagation) this implies a range of \(1.2 \times 2^{(24/6)} = 19.2\) m before the signal reaches the noise floor. A practical system probably requires a range closer to 30 m if the density of radiometer sensors required to cover an entire substation is not to be prohibitively high. These early (and elementary) results are nevertheless encouraging.

The antenna described above has been interfaced to an RF power detector (Linear Technology - LT5538) and microcontroller (Analog Devices – AduC841). Figure 5 shows the schematic diagram of
the RF Filtering and Electronics block, the output of this circuit is connected to the microcontroller analog to digital converter which manage the power information and transmit it using a ZigBee transceiver.

![Prototype radiometer circuit](image1)

**Figure 5** Prototype radiometer circuit.

The prototype radiometer is shown in Figure 6. A discharge generator has been used to demonstrate the plausibility of a radiometer based on these components.

![Simplified radiometer prototype](image2)

**Figure 6.** Simplified radiometer prototype.

Consideration has been given to the realization of the PD emulator that would be used for transmission-loss calibration in the iterative location algorithm. The core of the emulator is a low-cost short-duration pulse generator. The pulse duration realized is comparable with those pulses that occur in PD.

The emulator uses the power system waveform to synchronize emulated PD pulses and the power system cycle. (This is not necessary for the calibration of path loss but is a facility incorporated to allow the laboratory emulation of PD for other purposes.) It comprises two subsystems; a monostable to generate pulses and a high-pass filter to shorten the pulse – the degree of shortening determined by the monostable pulse rise time. Using this approach emulated PD pulses with variable amplitude and rate (from 390 kHz to 2.42 MHz) can be generated. The system is managed by the same microcontroller used for data acquisition, Figure 7, which drives a set of analog switches to set up the
pulse parameters. The emulated PD is increased in power using a 12 dB RF amplifier and then radiated via a whip antenna.

Figure 7. PD emulation.

Figure 8 shows an emulated PD pulse.

Figure 8. Emulated PD pulse.

4.2. PD cell
An artificial PD cell has been developed to assess the detection sensitivity and location accuracy available from the prototype PD WSN during development. It will also be used to validate the effectiveness of the PD WSN after deployment and assess its location accuracy.

Artificial PD cells contain electrodes connected to a high potential. Electrodes of different shapes can be used to reproduce different kind of PD including corona, surface discharge and discharge in internal insulation voids. The space between the electrodes is occupied by the particular insulation of interest, e.g. oil, SF6, or solid dielectric [7, 8, 9, 10, 11, 12, 13].
The cell is of a conventional design and therefore requires a high voltage (HV) supply. For the work reported here the HV transformer in Federal University of Campina Grande (UF CG) High Voltage Laboratory was used. The final version of the PD generator is required to be portable and to operate from low-voltage batteries. It will therefore incorporate voltage step-up circuitry.

The PD generator applies an electric field to an insulator containing a well-specified imperfection. Comsol Multiphysics was used to simulate the field intensity inside a cylindrical insulation void as part of the cell design process. An acrylic cylinder with an external diameter of 45 mm and an internal diameter of 32 mm was adopted as the basic cell housing and a 60 Hz sinusoidal voltage of 10 kV rms was applied between a pair of parallel circular electrodes. The radius of the electrodes is 20 mm. The simulation results predicted an electric field-strength inside the insulation void of 120 kV/cm; sufficient to cause PD.

The prototype PD cell was constructed from an acrylic tube incorporating plane (i.e. flat) HV electrodes, Figure 9. The electrodes are parallel and circular with a radius of 20 mm and a thickness of 2 mm. The edges of the electrodes are rounded to avoid the enhanced electric field strength that would occur close to a sharp edge. Two nylon screws are used to set the electrode separation.

The test piece, emulating a region of defective insulation is placed in the gap between the electrodes. The results reported here are for a single cylindrical cavity in a block of insulation with plane parallel boundaries. The orientation of the cavity is such that its axis of symmetry is perpendicular both to the plane surfaces of the insulation and to the plane surfaces of the electrodes. The test piece was constructed by compressing three to five insulating plates in a layered sandwich between the two electrodes. The insulation defect is realized by pre-drilling a hole through one layer in the middle of the sandwich. The space around the test object and electrodes was filled with transformer oil to avoid surface discharges and minimize corona. Several different types of insulation defects have been emulated, each test piece being subjected to a 60 Hz voltage between 10 and 20 kV rms. Test results using two emulated defects are presented here. Defect 1 is a cavity with diameter of 2 mm and length 1.6 mm. Defect 2 is a cavity with diameter 1 mm and length 1.6 mm. The test results, comprising apparent charge \( (Q) \) plotted against power system phase \( (\phi) \) obtained using the LDS-6 commercial PD monitoring and diagnosis system manufactured by the Doble Lemke Group®., are shown in Figure 10.
5. Conclusions
The principles of a proposed low-cost, self-calibrating, radiometric PD WSN using a network of free-standing radiometers for real-time power system condition monitoring, asset management and operational optimization have been described. Such a WSN would be a significant component in the future smart grid. Early progress in the development of components for the system has been presented. The core components of the WSN (antenna, radiometer sensor and pulse emulator) have been prototyped in a simplified form and their basic functionality has been demonstrated. A PD cell for validation of the PD WSN has also been described. It seems likely from this preliminary work that a PD radiometer network of the type proposed could be implemented at a sufficiently low cost to allow widespread deployment in the power system with a sensor density sufficient to localize sources of PD. Funding is currently being sought to develop a practical prototype network for deployment in a real scenario.

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