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A Novel Ring-Shaped Fractal Antenna for Partial Discharge Detection

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***Abstract*— This paper presents the development and application of a novel ring-shaped hybrid fractal antenna to the detection of partial discharge in inverter-fed low voltage drives. Partial discharge is known both as the source and indication of degradation in the winding insulation that is subjected to repetitive impulse voltage with short rise-time (high dv/dt) from PWM-controlled inverters. The partial discharge causes erosion of insulation thin magnet wire which results in premature failure and affects the reliability of low voltage electrical machines. The hybrid fractal antenna presented in this paper exhibits a wide bandwidth which covers the frequency spectrum (~0.3-3GHz)and features a ring-shape geometry which enables it to be embedded within the a machine end-winding and have ideal directivity in all direction across the cross-section.**

Keywords—Electrical machine insulation, end-winding, hybrid Hilbert fractal antenna, partial discharge (PD)

I. Introduction

Inverter-fed drives are widely used in transportation system which includes aeronautics, electric vehicles, and ships where reliability and availability are important requirements [1], [2]. It is well known that fast switching of power electronics converters using solid-state MOSFETs or IGBTs-based switches with pulse width modulation (PWM), can result in significant electrical stress in the machine windings. The short rise-time (dv/dt) from these switches, combined with wave propagation phenomena in the cables and machines can induce transient over-voltages at the motor terminals. The short rise-time voltage surges in these PWM-controlled inverters are linked to fast-front voltage wave which travels from an inverter to a motor terminal, through a cable. A reflection wave is generated from this fast-front voltage due to mismatch in impedance between the cable and the motor. This reflected wave then rebounds back to the inverter end, inducing another wave to be reflected from the mismatch in impedance, between the cable and the inverter. The second reflected wave increases the wave of the original voltage, which causes an overshoot at the leading edge of the voltage wave. The resultant effect of this process manifests in the overvoltage at the motor terminals, with amplitude which could be more than the double of the dc-link voltage. The stator winding insulation system is eventually impacted by these voltage surges and thermal stresses, leading to accelerated ageing and degradation, eventually resulting in premature stator winding failure. These induced over-voltages at the motor terminal can have amplitudes reaching twice the dc-link voltage. Although the effect of short rise-time and switching frequencies on PDIV has been recently shown to be insignificant, their combination with other electrical stressor such as voltage can lead to deterioration of machine insulation[3], [4]. Overvoltages can result in partial discharge (PD) which is an unwarranted phenomenon in stator winding insulation system [1], [5]–[7]. Although PD is common in medium-voltage (>1kVrms) and high-voltage machines, with insulation designed to withstand continuous PD activity, it should be avoided in low-voltage machines.

PD events occur when the insulation experiences voltage levels higher than the partial discharge inception voltage (PDIV). For low voltage machines, known as Type I machines (rated voltage ≤ 700Vrms and generally random wound) [8], the consequence of PD is particularly damaging as they are not expected to withstand PD activity due to the susceptibility of their thin

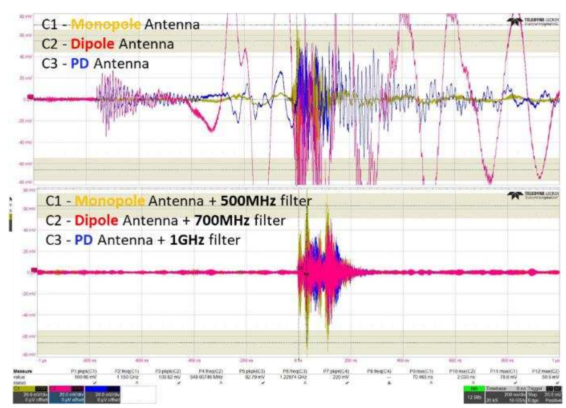


Figure 1: Signals captured by three antennas following a PD event. Unfiltered (top) and filtered (bottom).

organic insulation layers to puncture as a result of PD[9]. Any occurrence of PD on Type I machines can escalate rapidly, leading to insulation failure and complete machine breakdown.

With the increased use of fast switching power converters based on wide band-gap devices such as SiC and GaN, and the fast adoption of motor drives in new applications with high reliability demands, such as automotive and more-electric aircrafts, the condition monitoring of machines is gaining increased interest. It is therefore of great industrial interest to develop reliable and non-invasive PD detection methods for online condition monitoring of inverter-fed machines [10], [11].This paper presents the design of a novel fractal antenna suitable for online PD detection in inverter-fed machines [12].

II. PD DETECTION

PD monitoring is routinely performed in grid connected (50-60Hz) medium and high-voltage transformers, switchgear and machines and many sensors and systems are commercially available. The most commonly used systems use sensors based on high-bandwidth current transducers, Rogowski coils, coupling capacitors and antenna-based solutions.

However, the effectiveness of these solutions for PD detection in inverter-fed machines is hindered by the presence of significant noise resulting from the commutation of PWM converters which obscures PD signals, the existence of simultaneous PD sources and the shielding effect of machines cases and cables which makes the use of external sensors problematic [13]. By way of example, Fig. 1, shows the signals captured by three off-the-shelf antennas following a PD event in a machine resulting from the switching in a SiC converter. It is evident the importance of adequate bandwidth and band-pass filtering to isolate the signal of interest from the background noise.

It is of great practical interest to develop a solution for online monitoring of PD in machines which is in proximity to the windings, while minimizing its invasiveness. A number of antennas have been applied recently to the detection of PD in inverter-fed drives. PD tests under impulsive voltages were conducted using an electric monopole with center band of 1GHz in [14]. An Archimedes spiral antenna with 0.5-2GHz bandwidth was proposed for offline PD detection in [15]. A non-intrusive sensor, realized with the combination of a stripped coaxial cable connected to SMA jack and high-pass filter, was proposed in [12].

To design and develop sensors for PD online measurement in random-wound Type I machines fed by PWM inverters, it is essential to understand the type of signal and its spectral characteristics, and there is need to ascertain that (1) the bandwidth which the PD signal will occupy, (2) the radiation pattern which will characterize the directivity of the antenna, and (3) the scattering parameters (also known as S_{11}) which is the metric for the antenna efficiency [16]. The sensor for PD detection under impulsive voltage should have a large bandwidth from 0.5GHz to 2GHz and a high pass filter is required to improve interference rejection. Fig. 2 shows the time and frequency domain characteristic of a typical PD

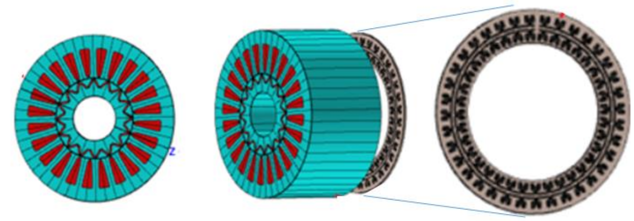


Figure 2: Concept for PD sensor integration in the end cap of an electric machine

signal, showing spectral content in the 500MHz-2GHz range. As can be seen from the literature, most sensors used for PD detection are general purpose antennas that were not originally designed for measuring PD signals in electrical machines fed by fast switching inverters. Besides electromagnetic performance limitations, their physical design might also hinder their integration in an online electric machine monitoring system. A sensor for PD detection in random-wound Type I machines, which are expected to be exposed to sustained rotor vibration and harsh operating conditions, should be embedded in the end-winding without any mechanical infringement between the rotor and stator. Since the sensitivity of an electromagnetic sensor to detect PD is affected by its position and distance with respect to the stator core[17], and PD pulses are accompanied by propagation of electromagnetic waves, it would be beneficial to install the sensor in close proximity to the windings so as to mitigate the attenuation of PD signals which may due to inverse square law ($1/r^2$). Considering that the slots are arranged in a circular configuration, the geometry of the PD sensor should align with the configuration of the slot to obtain maximum directivity. Also, to improve the SNR of the captured PD signal, the thickness of the sensor structure needs to be carefully chosen to ensure that the machine frame is not obstructing the sensor due to Faraday cage effect.

A sensor that simultaneously meets all these criteria has not been found in the literature. This paper therefore proposes a novel hybrid fractal sensor with UHF spectrum bandwidth which can be easily embedded in the end-winding of inverter-fed Type-I electrical machine as shown in the drawing in Fig. 3.

III. SENSOR DESIGN

The UHF sensors used for PD detection in PWM-driven electrical machines are normally installed outside of the stator winding due to geometrical constraint. In both Type I and Type II electrical machines, the sensors are sometimes installed at the motor terminals to detect the current pulses created by PD events[18]–[20]. However, the pulses measured through this method are dominated by noises and similar pulses from other sources such as electrostatic precipitators, power systems harmonics, etc which obscure the PD signals and inhibit the

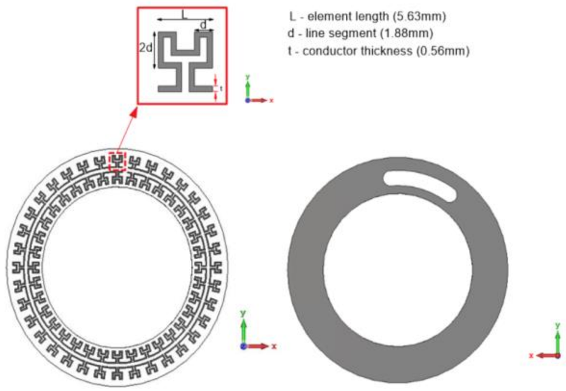


Fig. 3 Geometry of the proposed Fractal sensor (left) and reflection plane (right)

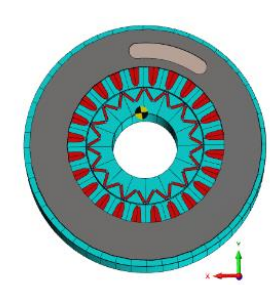


Fig. 4 Geometry of the proposed Fractal sensor (left) and reflection plane (right)

effectiveness of the detection. Additionally, there is also the effect of inverse square law which leads to increased attenuation of PD signals with increasing distance of the sensors from the discharge site, thereby affecting the sensor's sensitivity and reliability of the measurement.

Various schemes have been devised to mitigate the challenge posed by noises from external sources which obscure PD signals and reported in the literature. A method to reduce the effect of electromagnetic interference from neighboring sources was implemented using a twin-antenna sensor which suppresses the disturbance from PWM solid-state switches using a filter was introduced in [21]. However, since the noise content that dominate PD pulse and its amplitude during a PD measurement is a function of floor noise, electromagnetic interference from surrounding equipment and commutation from PWM-driven switching devices, the application of filters may lead to inadvertent discrimination of PD spectral contents that are below the filter cut-off frequency, resulting into inaccurate measurement.

A PD monitoring system using a non-intrusive sensor positioned close to power cable was introduced in [20] to detect PD in a twisted pair sample. Two numerical signal processing techniques were then employed to classify and separate the acquired signals based on their features. However, these methods are cumbersome and requires heavy computation.

Bearing these in mind, a simple and low-cost hybrid fractal sensor was conceived primarily to be retrofitted to the end-winding of random-wound insulation system used by Type-I low voltage machines. The aim was to develop a novel sensor that fits within the geometry of the random-wound insulation system which will exhibit wide bandwidth that covers the frequency spectrum of PD in PWM-controlled inverter-fed drives, and is less sensitive to interference. The comprises of dual 36-element fractal structures which form a dipole. Its ring-shape geometry encircles the end-winding to have directivity to detect PD signal in all directions and as well as avoid mechanical contact during drive operation as shown in figure 4.

The sensor has been designed and simulated using CST Microwave Studio. It is well known that the bandwidth of an antenna is determined by its characteristic length and how well the geometrical configuration and available volume within a structure are utilized[22]. In view of the constraint of geometry of a random-wound insulation system, it is difficult to achieve a wide bandwidth of PD signal with a typical Euclidean antenna. A unique fractal antenna that can efficiently utilize the available space of the insulation geometry was thus selected for these two main reasons: 1) Fractals have no characteristic size and their bandwidth therefore is not constrained as in the case of Euclidean antennas. 2.) Fractals have irregular shapes which can be fitted into any geometry[23]. Also, Fractal antennas' sharp shapes, sudden bends and discontinuities contribute to the enhancement of their radiation and sensitivity[22]. Additionally, a fractal antenna can be easily printed on a rigid or flexible printed circuit board (PCB) and, therefore, can be very suited to the intended physical integration in a machine.

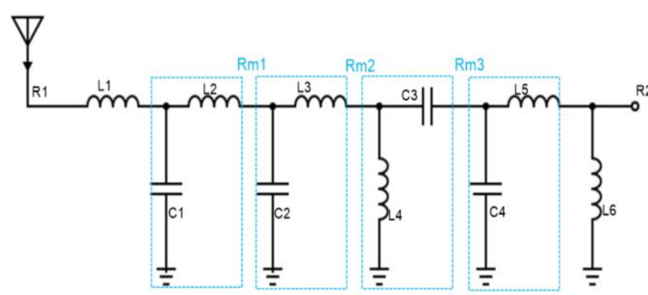


Figure 6:. 4-section interstage impedance matching network
Design parameters: L_1=5.6nH, C_1=0.3pF, L_2=22nH, C_2=0.7pF, L_3=22nH, L_4=33nH, C_3=2.7pF, C_4=1.8pF, L_5=8.2nH, L_6=68nH

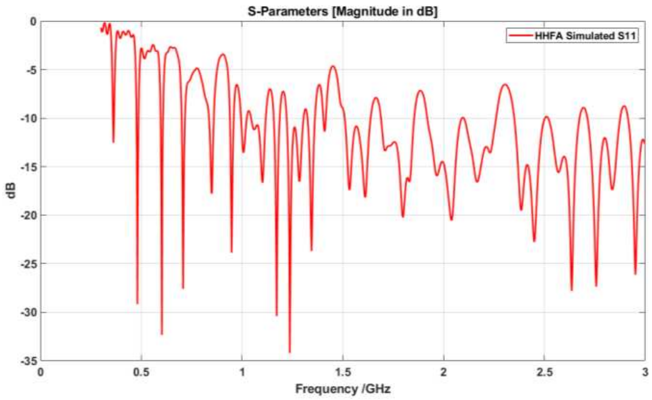
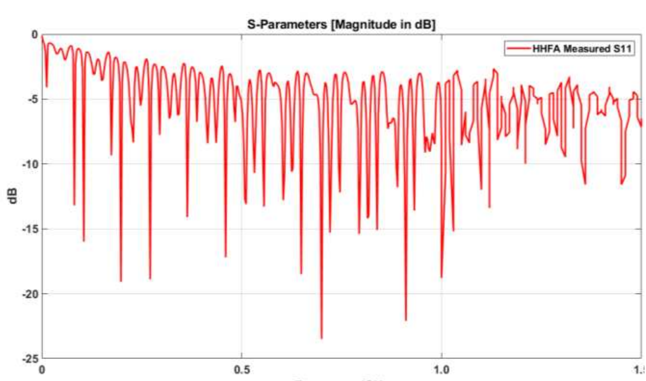


Figure 5: Simulated reflection coefficient S_{11}

The proposed sensor, shown in Fig. 3, contains dual 36-element fractal structures which are spaced apart by 10 degrees and configured as a dipole. The dimensions are as follows: Outer diameter: 59mm, Inner diameter: 40mm, Thickness of substrate (FR4 lossy). The structure was simulated with the Frequency Domain Solver of CST Microwave Studio, which is based on the finite element method (FEM). It transforms Maxwell's equations into frequency domain by assuming time-harmonic dependence of the fields and the excitation. The discretization of the geometry was performed using tetrahedral meshing which is automatically generated by CST Microwave Studio. Apart from the geometrical consideration, one of the aims of the designing this sensor was to achieve wide bandwidth based on the S_{11} parameter which is lower than -10dB which is equivalent to voltage standing wave ratio (VSWR) of less than 2.0. The diameters of the dual 36-element fractals are 95.25mm and 98.88mm respectively. The first resonant frequency obtained was 0.45GHz and the working bandwidth extends to 2GHz, as demonstrated by the reflection coefficient S_{11} shown in Fig. 5.

IV. DESIGN OF MATCHING NETWORK

To ensure a minimum reflection and maximum power transfer between HHFA and a receiver to be used for PD monitoring, an impedance matching network is required. As fractals antennas generally have higher input impedance due to their perimeter length and reduced space requirement, the HHFA was optimized with an input impedance of 200Ω which is different from the 50Ω used by the load (the ultra-wide working band cable). Hence, a matching network had to be designed to interface the HHFA with the load.



Methods for designing matching networks include BALUN, Smith chart, analytic solutions, single- or double-stub tuning, quarter-wave transformer, T and π-networks and others which can be found in [22], [24]–[26]

The Smith chart, which is the simplest of them, gives a geometrical representation of a load in terms of scattering parameters by moving the source towards the center of the Smith chart. However, its computational accuracy is low as there is need for visual interpolation between the chart grid circles [26]. This is impracticable for a multi-resonant ultra-wide bandwidth antenna like HHFA.

A widespread method to implement impedance matching network is the lumped element L-section which matches a load to a source using two reactive elements (inductors and capacitors). But a simple L-section network only has two possible configurations which makes it limited and infeasible for frequencies up to 1GHz[24], [25]. Thus, it is inadequate for HHFA.

To overcome this limitation in L-section networks and obtain a wide bandwidth which extends beyond 1GHz frequency, a cascade of L-section network can be used to form an interstage network topology to improve its bandwidth[27].

Accordingly, a cascaded 4-section lumped element was designed to match the impedance of HHFA with the 50Ω load as shown in Figure 6. Each of the sections was designed to match the impedance to another one. The C1-L2 matches R1 from HHFA to Rm1, the C2-L3 matches Rm1 to Rm2, the L4-C3 matches Rm2 to Rm3, and C4-L5 matches Rm3 to R2. Both L1 and L6 are used for improving the bandwidth.

The relationship between the sections is given by:

$$\frac{R_1}{R_{m1}} = \frac{R_{m1}}{R_{m2}} = \frac{R_{m2}}{R_{m3}}$$

The bandwidth of a lumped element matching network can be determined as:

$$\Delta f = \frac{f_o}{Q_L} \qquad (1)$$

Where F_o is the center frequency and Q_L is the load quality factor.

$$Q_L = \sqrt{\frac{R_{m3}}{R_2} - 1}$$

The value of Q_L was calculated and optimized with AWR microwave software to obtain wide bandwidth that covers the

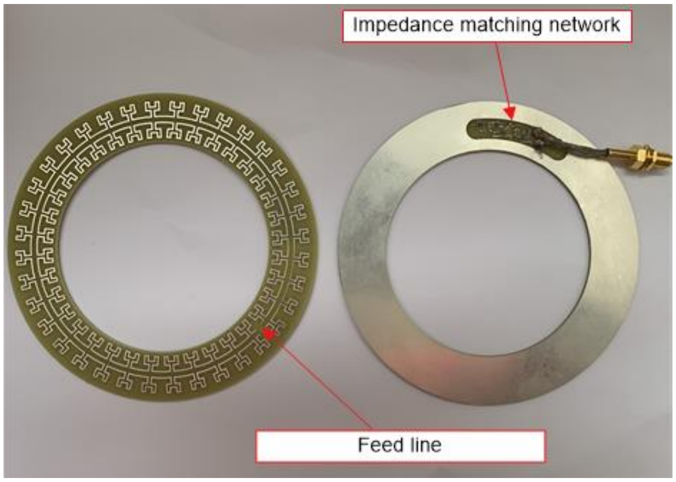


Figure 7: Fabricated prototype of dual 36-element hybrid fractal antenna (left) and the back reflection plane (right)

expected spectrum of PD. The design parameters are shown in figure 6.

The fabricated prototype of HHFA and its measured reflection coefficient are shown in figure7 and figure 8 respectively.

V. PD TESTS, COMPARISON RESULTSOF SENSORS AND RESULTS

After a HHFA prototype was fabricated, a series of PD events was simulated using a twisted pair of magnet enamel wires with the experimental setup shown in figure 9 at the Electrical Machines and Drives (EMD) laboratory, the University of Sheffield.

The aim was to ascertain the feasibility of embedding a sensor at the end-windings of a motor insulation in close proximity to PD event site. A commercial PD pulse generator (Schleich MTC2 multipurpose winding analyzer) with adjustable voltage control was used to generate PD pulses across the twisted pair wire. Because the PD mechanism in random-wound insulation system is dependent on how the wires in the stator slots are placed in the electrical machine, a twisted pair of enamel wires can be used to simulate random-wound insulation system [28].

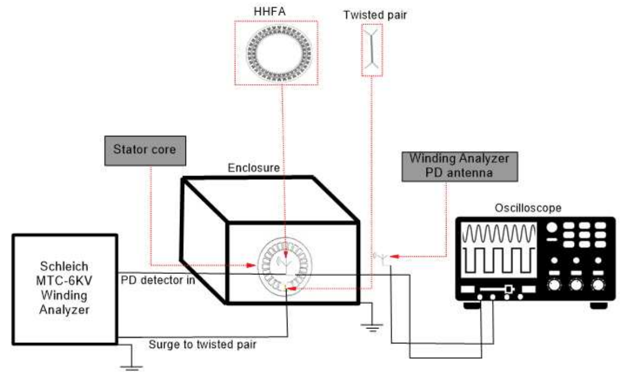


Figure 9: PD monitoring experimental setup

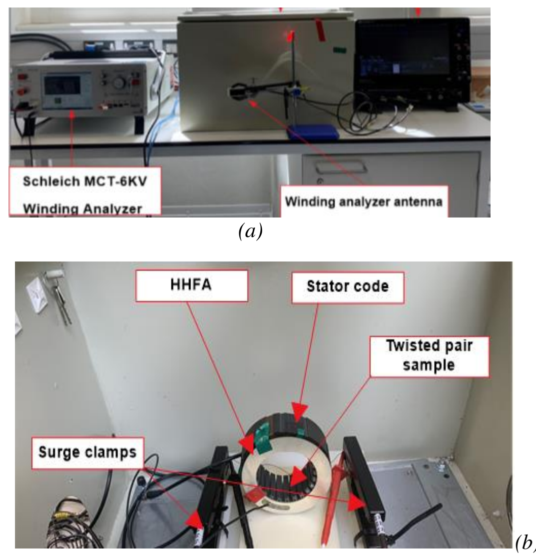


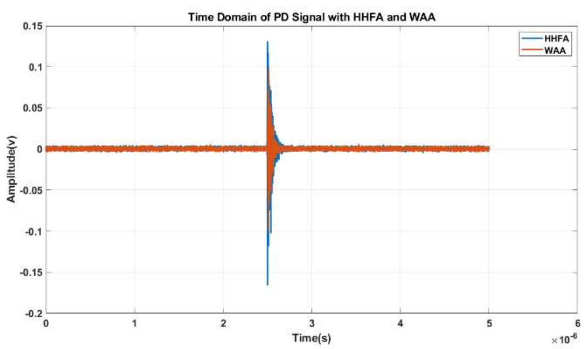
Figure 10: Arrangement of equipment for experiment: Setup showing pulse generator and enclosure (a), Integration of HHFA to end-winding inside enclosure (b)

The twisted pair sample was inserted inside a stator core slot in the enclosure (figure 10a) to simulate the end-winding configuration of a motor. The ring-shape geometry of HHFA enables it to be retrofitted to the motor end-winding without any infringement to any mechanical part as can be seen in figure 10b. An off-the-shelf winding analyzer antenna (WAA) was placed outside of the enclosure to monitor the PD events. The PD signals were captured using Teledyne Lecroy WavePro 404HD-MS oscilloscope to compare both HHFA and WAA at 10GS/s sampling rate. A differential probe was used to record the voltage across the twisted pair. The experiments were carried out at room temperature.

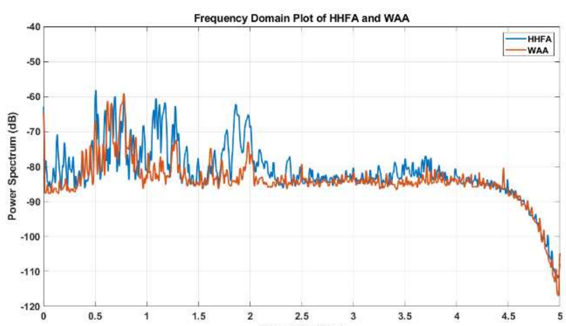
The results of the PD tests clearly show that the HHFA outperforms the WAA in terms of bandwidth and spectral sensitivity to PD pulses by significant margin. The first test was carried out using a 500MHz filter connected to both HHFA and WAA and a PD event was triggered with PD pulse generator at PDIV 1071Vp-p. From the result figure 11a, it can be seen from the time domain signal that HHFA has better reception in terms of amplitude compared to WAA. The frequency domain (figure 11b) of the same signal shows that HHFA is able to capture and reveal more spectral content of the PD pulse signal better than the WAA.

Another a PD event was triggered at PDIV 1108Vp-p. This time around, no filter was connected to either HHFA and WAA. The time domain result (figure 11c) shows that the WAA has higher amplitude compared to the HHFA. However, the spectrum (figure 11d) of the same PD pulse signal shows that HHFA captures more spectral content than the WAA. The higher amplitude in figure 11c is as a result of floor noise and electromagnetic interference from external sources. This also confirms the relative noise immunity of the HHFA which is as a result of the inherent filtering of the interstage matching network topology which incorporates a cascade three low-pass filters and a high-pass filter.

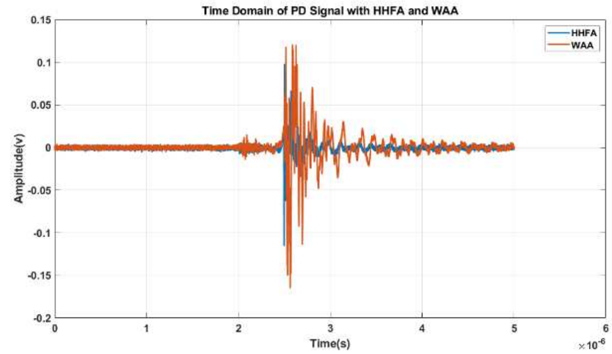
The multi-resonant characteristic of HHFA clearly aids its radiation and spectral detection capability. And unlike the Euclidean geometry-based sensors which cannot retrofitted to the end-winding of a live electrical machine, fractals can be designed to fit into any insulation geometry and is ideal for online condition monitoring of PD.



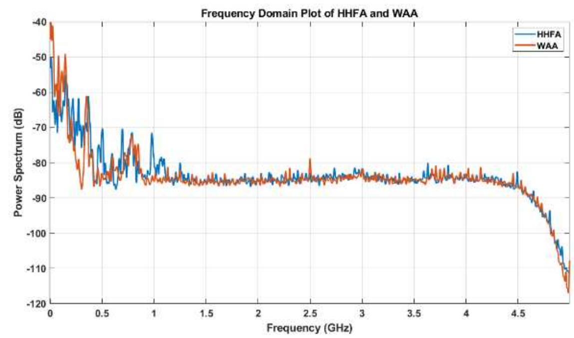
(a)



(b)



(c)



(d)

Figure 11: Experimental results

VI. CONCLUSIONS

A low-cost hybrid Hilbert fractal antenna has been presented for detection of partial discharge in electrical machine insulation system. It has a bandwidth that covers the UHF spectrum and contains dual 36-element fractal structures which are spaced apart by 10 degrees and configured as a dipole. The dimensions are as follows: outer diameter: 118mm, inner diameter: 80mm, thickness of substrate (FR4 lossy).

For the first time in the literature, a sensor which can be embedded in the end-winding of an electrical machine without any mechanical infringement between the stator and the rotor has been designed, simulated and experimentally validated. The sensor's ring shape, which facilitates its integration to the end winding of a machine, ensures its proximity to the site of PD events, thus improving the effectiveness of detection and appropriate diagnosis. Thanks to the four section 50ohms impedance matching circuit, the sensor can inherently filter out most of the floor noise and effectively capture the spectral content of the PD signals. More tests will be carried out with inverter-driven motors in the future.

ACKNOWLEDGEMENT

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