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Proceedings Paper:
Ogundiran, Y.L. and Griffo, A. (2023) A novel modified archimedes spiral antenna for partial discharge detection in inverter-fed electrical machines. In: 2023 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD) Proceedings. 2023 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), 13-14 Apr 2023, Newcastle upon Tyne, United Kingdom. Institute of Electrical and Electronics Engineers (IEEE). ISBN: 9781665486941. ISSN: 2694-0264. EISSN: 2380-856X.

https://doi.org/10.1109/wemdcd55819.2023.10110949

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A Novel Modified Archimedes Spiral Antenna for Partial Discharge Detection in Inverter-Fed Electrical Machines

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Abstract—**This paper proposes a modified Archimedes Spiral antenna (MASA) for detecting partial discharge (PD) in pulse-width modulation- (PWM) controlled inverter-fed electrical machines. The occurrence of PD is both a source and indication of insulation degradation in electrical machines. With the widespread electrification of transportation and many reliability critical applications, PD phenomenon remains a big challenge as it deteriorates the insulation system and can lead to premature failure of an electrical machine. Online condition monitoring using embedded sensors to detect PD in the insulation system has been suggested in the literature but has been difficult to implement due to geometrical constraints and bandwidth limitation of existing sensors. The proposed MASA overcomes these challenges. The design is based on the modification of polar coordinates equation of Archimedes spiral and its operation demonstrates how the geometrical constraint which inhibits other sensors can be overcome by physically integrating it within the end-winding of a machine. With its ultra-wide bandwidth (0.3 – 2 GHz), it is capable of effectively capturing the expected spectrum of PD in inverter-fed electrical machines, which is verified experimentally. Another novelty of the proposed sensor is its inherent ability to discriminate between commutation disturbance and PD pulses without the need for an external high-pass filter, making the solution suitable for condition monitoring and PD detection in inverter-fed electrical machine in service.**

Keywords— Electrical machine insulation, inverters, power electronics, machine end-winding, modified Archimedes spiral (MASA), partial discharge (PD).

I. INTRODUCTION

The use of inverter-fed electric drives has become widespread in transportation, such as aerospace, electric vehicles and ship propulsion, as well as other reliability critical applications. The need for increased efficiency and improved power density has been driving the trend to use fast switching wide bandgap (WBG) devices such as SiC and GaN MOSFETs whose voltage rise times are a few tens of nanoseconds [1]. New voltage architectures featuring DC-link voltages of 800 V and 500 V are being proposed for new generations of electric vehicles (EV) and more-electric aircrafts (MEA), respectively. However, despite the many advantages of pulse-width-modulation (PWM) controlled power electronics converters, the faster rise times and higher voltages induce excessive voltage stress and switching transients in electric drives have been identified to be detrimental to the lifetime of the insulation and the overall reliability of the system.

The fast-switching operation of the WBG devices excites wave propagation and reflection across the cables which can give rise to overvoltages at motors' terminal and non-uniform voltage distribution across the windings and insulation of the machine [2]. These overvoltages can induce partial discharge when the voltage level across the insulation exceeds the partial discharge inception voltage (PDIV), which is particularly detrimental to random-wound low voltage Type I machines (rated voltage ⩽ 700 Vrms.) [3]. For Type II machines which use medium- and high-voltages, the occurrence of PD is permitted up to a certain degree as they use inorganic epoxy mica stator winding for their insulation. But considering the susceptibility of the thin organic magnet wires of random-wound Type I machines to puncture, any occurrence of PD can escalate rapidly and lead to premature insulation failure and complete machine breakdown [1], [4]. Since there is a correlation between the impulsive voltage waveforms from a PWM-controlled WBG devices and PD events, which is detrimental to the machine insulation, it is essential to have a PD monitoring system in reliability critical applications. The development of non-invasive electromagnetic sensor for online insulation monitoring which can instantly detect the occurrence of PD is of great industrial importance. For periodic online tests and scheduling of replacement of machines affected by PD, it has been reported that it is advantageous to have a permanent sensor embedded in a machine at the time of manufacturing [5]–[7].

There are several PD monitoring solutions in grid-connected transformers, gas insulated switchgears, substations, and electrical machines. Sensors widely used in these PD monitoring systems are based on coupling capacitors, Rogowski coils, high-bandwidth current transducers, optical and antenna-based solutions [8]. However, for PWM-controlled inverter-fed electrical machines with significant commutation noise from the switching of the WBG devices, these sensors are inadequate for PD detection [9]. As the occurrence of PD happens from a few nanoseconds to tens of nanoseconds, the Fourier transform of the time series signal generates a spectrum that lies between kilohertz and gigahertz range. This makes the use antennas with ultrawide bandwidth attractive. A plethora of antennas have proposed for PD detection in inverter-fed electric machines in the literature. An antenna probe having 0.1-100 MHz bandwidth was introduced in [10]. A comparison analysis to investigate the sensitivity of PD to proximity of antenna was carried out using 1.0-3.0 GHz Horn Antenna and a 1.5-2.0 GHz Patch Antenna in [11]. A similar comparison was carried out in [12], [13] using a patch antenna and loop sensor on a twisted pair embedded inside a stator core. The electromagnetic wave generated by PD was analyzed using patch antenna in [14]. A non-invasive sensor made of stripped coaxial cable connected to a sub-miniature version A (SMA) jack and high-pass filter was proposed in [15]. There are others that are based on Hilbert fractal antenna [16], [17], Vivaldi antenna and optical sensors [18]–[20]. However, apart from these sensors not originally developed for PD detection as they were adapted from other applications, they are geometrically constrained to be used as embedded sensors in an electrical machine in service. And that is why most of them are required to be installed at the terminals of machine to detect the current pulses [8], [21]–[23]. This approach, unfortunately, leads to the detected signal being contaminated by the commutation noise from the switching devices. Moreover, inverse square law affects the detected PD signal, causing rapid attenuation to the signal strength as it increasingly travels from discharge site inside the windings to the motor terminals and leading to poor signal to noise ratio (SNR). This situation always requires the use of external high-pass filters or the application of complicated and computationally expensive signal processing algorithms. This approach is evidently problematic.

To address these challenges, it is expedient to have a non-invasive sensor which can be simultaneously insensitive to commutation noise and overcome the geometrical constraints of existing sensors that inhibit them from being used as embedded sensors in electrical machines in service. The only sensor that meets these requirements in the literature was introduced by authors in [24] based on a hybrid of Hilbert fractal curves. However, the sensor's geometry does not have any analytical definition. The design is based on arbitrary iteration and simulation which will be complicated to replicate. In this article paper, a novel sensor based on Archimedes spiral geometry is presented. Although some Archimedes spiral antennas have already been proposed for PD detection [9], [25], [26], they are all general purpose antennas which are inadequate for online detection and cannot be embedded in the end-winding of the electrical machines due to geometrical constraints. A modified Archimedes spiral antenna (MASA) which is specifically developed for PD detection is proposed in this paper. It will be demonstrated that simple modification of parameters of the polar coordinates of an Archimedes spiral can increase its perimeter and therefore its bandwidth and can facilitate its geometry to be physically integrated to the end-winding of an electrical machine and thus make it suitable for online PD detection.

II. PD DETECTION

Compared to other grid connected (50-60 Hz) electrical equipment, such as high-voltage transformers and gas insulated switchgear (GIS), PD monitoring in such systems is implemented using high-bandwidth current transducers, Rogowski coils coupling capacitors, optical- and antenna-based solutions. However, the effectiveness and applicability of these solutions are hindered by the commutation noise emanating from PWM-controlled machine, as well as radio noise, airborne noise, etc, from other neighbouring sources, which severely limit the use of external sensors [8]. As an illustration, Fig. 1 shows signals obtained by an external sensor to capture PD events in a machine in service. Given the ringing emanating from the commutation operation of the inverter as seen in the top plot, the necessity for adequate bandwidth and band-pass filtering to isolate the signal of interest from the background noise is evident. The disturbances from the switching devices and neighbouring sources need to be rejected using high-pass filter with an appropriate cut-off frequency [8].

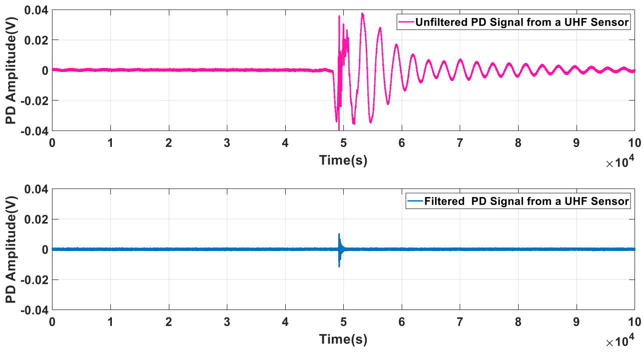
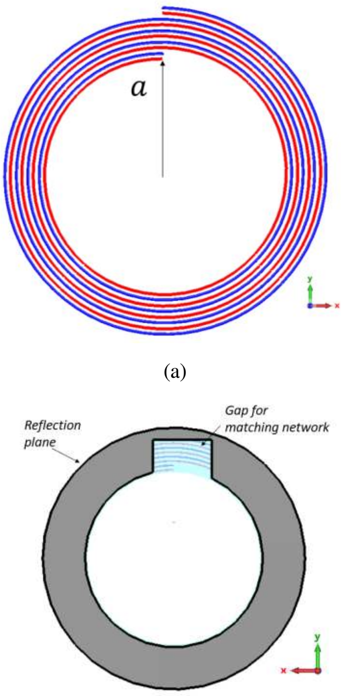


Fig. 1. Example of noisy PD signal captured with UHF sensor.

To design an effective sensor for PD monitoring in any application, the spectral properties and the signal type need to be understood. The sensor's radiation pattern, which will characterize its directivity, and the scattering parameters must be ascertained. For PWM-controlled inverter-fed electrical machines, the sensor should have ultra-wide bandwidth with at least 0.5 – 2 GHz [27]. Since proximity of a sensor to the stator core affects its sensitivity PD pulses which are accompanied by electromagnetic waves, its geometry should be non-invasive to facilitate a physical integration to the machine's end-winding to guarantee a proximity to the discharge site of the machine [28]. Not only will the geometry prevent the sensor from having any mechanical infringement on the rotor, it will enable the sensor to obtain maximum directivity to capture PD signals which are propagated as electromagnetic waves. Additionally, the sensor's proximity to stator winding will ensure improved SNR. Another advantage of embedding the sensor in the end-winding is that the machine casing can serve as a Faraday cage and minimize commutation disturbance from the switching operation of the inverter and electromagnetic interference from other neighbouring sources. The concept of embedding a sensor based on Archimedes spiral-based sensor to the end-winding of PWM-controlled inverter-fed electrical machines is illustrated in Fig. 3. The details of the design are presented in Section III.



(a)

(b)

Fig. 2. (a) Geometry of the proposed MASA, (b) reflection plane.

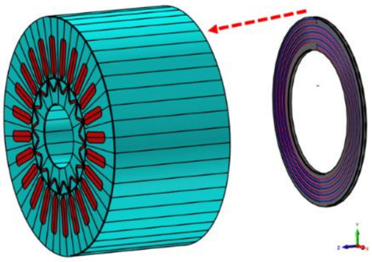


Fig. 3. Concept of integrating a sensor to machine's end-winding.

III. Sensor Design

As the occurrence of PD happens in tens of nanoseconds, the Fourier transform of the time series signal generates a spectrum that lies between kilohertz and gigahertz range. Hence PD sensors based on VHF and UHF are preferable, especially in applications with rapid rise-time such as WBG-based switching converters [8]. However, due to geometrical constraint, most of the sensors are installed at motor terminals to capture PD pulses [21].but the region is contaminated by radio noise, airborne noise and commutation noise.

The modified Archimedes spiral antenna (MASA) was accordingly conceived to be physically integrated to the end-winding of a representative random-wound insulation system which is usually found in Type-I low voltage machines. The goal was to develop a novel UHF sensor that can be embedded to the cylindrical geometry in the slot region of the random-wound insulation and have a sufficient bandwidth to cover the frequency spectrum of partial discharge that is manifested in PWM-controlled inverter-fed machines [9]. It comprises of two complementary spiral arms which form a dipole. It is engineered to have a ring-shape geometry which facilitates its integration to the end-winding without any infringement to the mechanical moving parts of the motor. The ring-shape geometry enables proximity to the site of PD to ensure that the sensor has capacitive coupling to the end-winding and therefore has better sensitivity. These features are missing in existing state-of-the-art. And, additionally, as the bandwidth of antennas is affected by how efficiently they utilize available space within a sphere, no Euclidean-based sensor which can be embedded inside a machine in service has been developed yet. But with MASA, it can be demonstrated that, by modifying the parameters of the polar coordinates of an Archimedes spiral, its structure can be made to align the stator-rotor geometry of the machine. This modification can lead better space utilization, perimeter extension and therefore higher bandwidth, i.e., 0.3 – 2 GHz in the case of MASA. Recall that the theoretical fundamental limit of an electrically small antenna is a function of the Chu limit which is given that the Q-factor is proportional to the reciprocal of a volume of a sphere in which it is enclosed, and is expressed as follows [29], [30]:

$$\mathrm{Q} = \frac{1}{k^3a^3} + \frac{1}{ka} \approx \frac{1}{k^3a^3} \tag{1}$$

where, $k = 2\pi/\lambda$ is the wavenumber and a is the sphere radius that encloses the volume. The bandwidth of an antenna is related to the Q by[31]:

$$\frac{\Delta f}{f_0} = \frac{1}{Q} \tag{2}$$

where, f_0 is center frequency and Δf is the bandwidth Accordingly, to obtain the required geometry and Δf for the proposed sensor, each of the spiral arms was determined using the well-known polar coordinates equation:

$$r = a + b\theta \tag{3}$$

where, a is the inner radius which can be modified to move the centre-point of the spiral arm outward from the origin to enable the structure form a ring-shaped geometry and align with the slot region of machine stator, while the progress factor b controls the distance between the loops, and θ is the angle of rotation of the spiral. The progress factor b can also be determined by

$$b = \frac{p}{2\pi} \tag{4}$$

where p is the sum of spiral arm width and gap of the spiral. For the representative permanent magnet synchronous motor with slot region which has 80mm inner diameter and 118mm outer diameter, respectively, the parameter of geometry of the two-arm spiral MASA is as follows: Inner spiral, Sl (in red), $a_1 = 40mm$ and $b_1 = 4$; Outer spiral, S2(in blue), $a_2 = 42mm$ and $b = b_2$. The spiral structure was designed on a low-cost FR4 substrate with permittivity ε_r= 4.4, loss tangent tanδ = 0.02, and substrate thickness = 1.5 mm. The substrate ring-shape dimensions are as follows: outer diameter: 118mm, inner diameter: 78mm which enables it to align to the motor slot region without any mechanical infringement on the rotor. The sensor has been designed and simulated using CST Microwave Studio, which is based on the finite element method (FEM) that transforms Maxwell's equations into frequency domain by assuming time-harmonic dependence of the fields and the excitation. The geometry was discretized using tetrahedral meshing generated by CST Microwave Studio. Additionally, unlike the traditional Archimedes spiral antenna (ASA) that requires either a rectangular or a circular cavity at the back, another novelty of proposed MASA is the introduction of reflection plane at the back of the substrate which enhances its bandwidth. This also enables it to overcome the geometrical constraint of traditional ASA with a cavity which prevents it from being physically embedded in the end-winding of the machine insulation and therefore makes it impossible for it to be used for online condition monitoring in machine in service. The effect on the MASA bandwidth, the result of scattering parameter lower than -10dB, is shown in Fig. 4.

IV. Design of Matching Network

To maximize the power transfer and minimize reflection between MASA and the receiver that will be used for the detection of the PD, an impedance matching system is required. In traditional ASA, a balanced-unbalanced converter (Balun) is usually preferred [25], [32]. However, designing

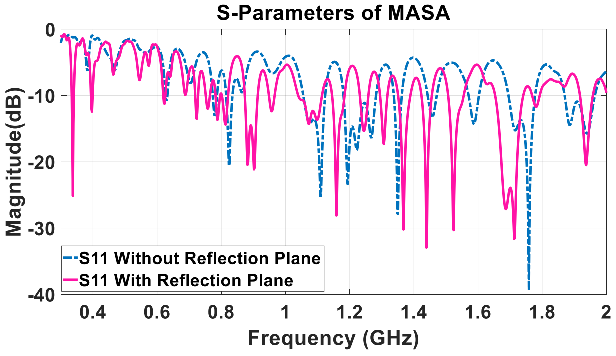


Fig. 4. Scattering parameter of the proposed sensor.

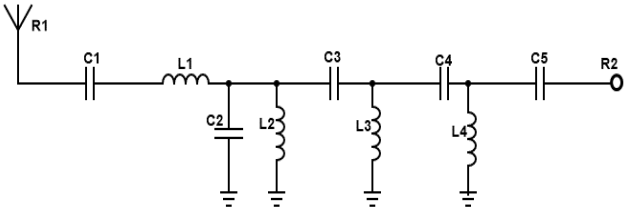


Fig. 5. Four-section interstage impedance network showing connection between MASA(R1) and 50 Ω coaxial cable (R2). Design parameters: C1 = 2 pF, C2 =0.3 pF , C3 = 2.7 pF, C4 = 3.3 pF , C5 = 4.7 pF , L1 = 5.6 nH , L2 = 39 nH, L3 = 30 nH, L4 =27 nH.

Fig. 6. A fabricated prototype of MASA.

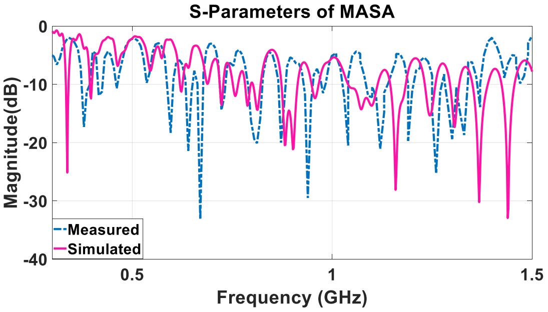


Fig. 7. Measured and simulated result of MASA.

a Balun to match the ultrawide bandwidth of MASA will require a bigger profile which could make the sensor bulkier and unsuitable to be embedded in the end-winding of an electrical machine [33]. But it has been reported in [24], [28] that a cascade of lumped element L-section which forms an interstage network topology can be used for bandwidth ≤ 2 GHz and can be easily integrated within the profile of the sensor's PCB. Accordingly, a four- stage lumped element L-section with reactance cancellation was designed to match the 50 Ω impedance of the receiver as showed in Fig. 5. Here, the impedance of each LC section is matched with the next section. The relationship can be found in [34].

V. EXPERIMENTS AND RESULTS

To validate the performance and effectiveness of MASA, a prototype, shown in Fig. 6, was fabricated and measurement was carried out using Siglent SVA1015X vector network analyzer with 9 kHz to 1.5 GHz bandwidth. The measurement of scattering parameters agrees with the simulation, and it confirms the presence is multiple resonances in the region of interest between 0.3 and 1.5 GHz reflection coefficient <−10 dB is multiple resonances in the region of interest between 0.3 and 1.5 GHz as depicted in Fig. 7. which should enable the sensor to be used for the intended purpose of PD detection.

After measuring the scattering parameters of MASA, to ascertain its feasibility to detect PD, a test was carried out using Schleich MTC2 multipurpose winding analyzer to generate a PD surge voltage across an impregnated twisted pair of 0.5mm connected to two electrodes. The MASA was placed in close proximity to the end of the twisted pair to emulate the end-winding of a random-wound low voltage Type I electrical machine. A ramp of surge voltage, shown in Fig. 8a, was applied to incept PD at the instance of the applied voltage exceeding the PDIV of the twisted pair. As can be seen from the plot, the voltage ramp (in orange) is accompanied by two oscillations (in blue) as captured by MASA: 1.) a low magnitude oscillation which is closely aligned with the switching instance of the ramp voltage; and 2.) a high magnitude oscillation which is slightly delayed after the switching instance of the applied ramp voltage. These two oscillations are magnified in Fig.8b and Fig.8c for better illustration and visualization. A Fourier transform of the oscillations can be seen in Fig.8d and Fig.8e, respectively, which evidently indicates that the high magnitude oscillation,

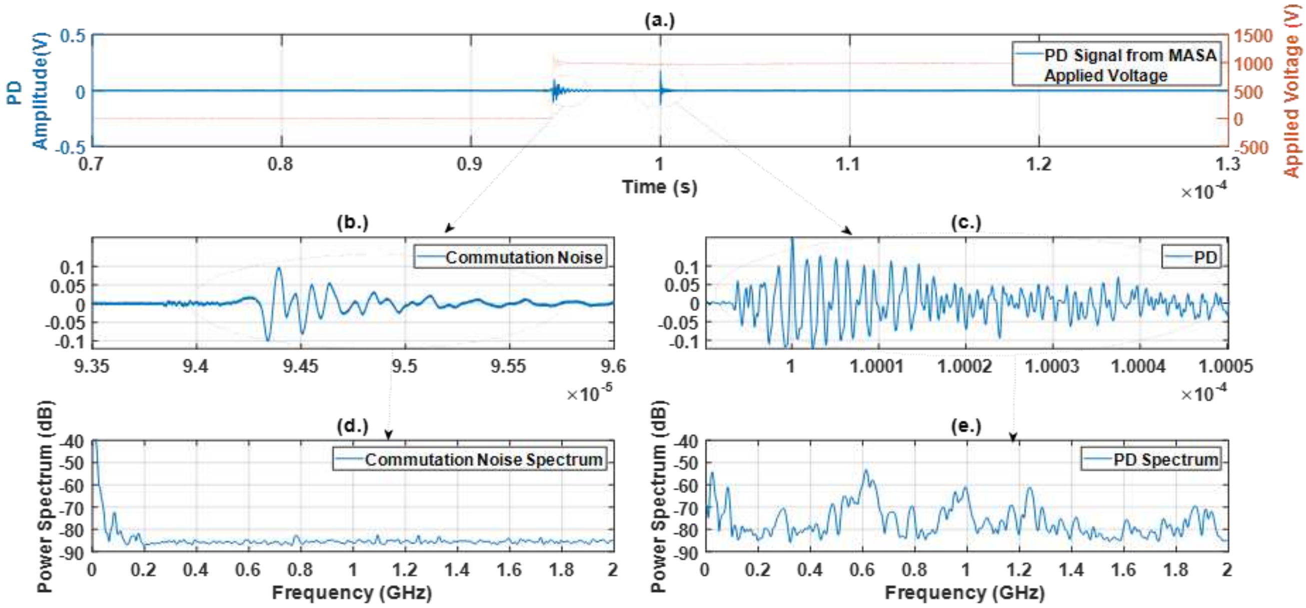


Fig. 8. Measured and simulated result of MASA.

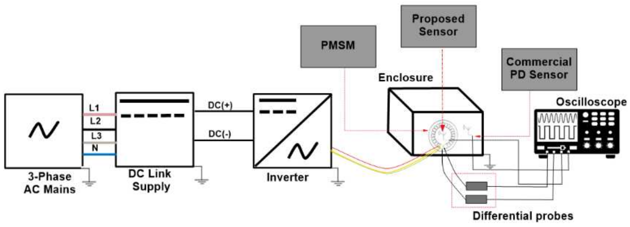


Fig. 9. Test setup of inverter-fed electric drive.

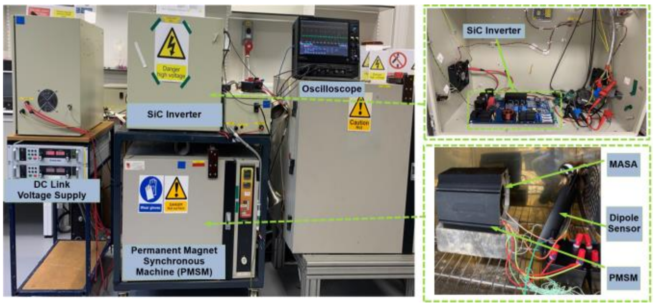


Fig. 10. Proposed Arrangement of equipment for PD detection in inverter-fed electrical machine.

which spans across 0.5 – 2 GHz, bears the spectral characteristics expected of a PD while the low magnitude oscillation is disturbance from harmonics and switching operation which are characterized by low frequency. This test tends to prove that the MASA can effectively discriminate between disturbance and PD, which is facilitated by the inherent filtering capability of the interstage impedance matching network of MASA.

To further ascertain the efficacy of MASA in an electrical machine in service, it was embedded to the end-winding of the sample of an aged random-wound motor that was fed with impulsive voltages from a SiC PWM-controlled inverter. The experimental setup and its arrangement are own in Fig. 9 and Fig. 10. The supplied DC link voltage was gradually increased to exceed the PDIV of the aged sample which had been previously determined using a Schleich MTC2 multipurpose winding analyzer. For comparative analysis, an on-the-shelf dipole antenna with the scattering parameters profile in Fig. 11 was placed at the motor terminal of the motor. Together with MASA which was embedded at the end-winding, both sensors were connected to two different channels on a Teledyne Lecroy WavePro 404HD-MS oscilloscope with 4 GHz bandwidth and sampled at 10 GS/s with the display set to 2 ms/div. for time domain visualization. A differential probe was connected to the inverter terminal to monitor and display the voltage waveforms on the oscilloscope. To capture and record the signal in the event of occurrence of PD in the winding insulation of the machine, a simple peak detection was implemented by setting the trigger of the acquisition device to 200 mV on the channel through which MASA sensor was connected. A 700 V dc bus voltage was then fed to the SiC inverter switching at 20 kHz PWM frequency which was connected to the motor terminals. As can be seen in the results in Fig. 12a, the time domain plot of the signal obtained with the commercial dipole sensor is dominated by ringing and commutation disturbance from the switching of the WBG which overlapped with the PD, making it indistinguishable and completely hidden within the disturbance. On the other hand, it can be observed in this same PD event, but captured with the MASA sensor, shown in Fig. 12b, in which the commutation disturbance, indicated as low magnitude oscillation, was clearly discriminated from the PD which was the high magnitude oscillation. The events highlighted in blue are PD coming from the three phases of the machine while those highlighted in magenta are commutation noise, clearly demonstrating the superiority of the MASA for online condition monitoring and PD detection compared to on-the-shelf sensor that would require an external high-pass filter. This experiment also proves that installing a sensor at the motor terminal or along power cable, a region dominated by commutation disturbance and electromagnetic interference from neighbouring sources, is problematic for PD detection. Moreover, since RF signals cannot be propagated through a metallic enclosure according to Faraday's law, the casing and enclosure of an electrical machine will inhibit the propagation of PD whenever it occurs within the stator winding from being effectively detected by external sensors in practical applications.

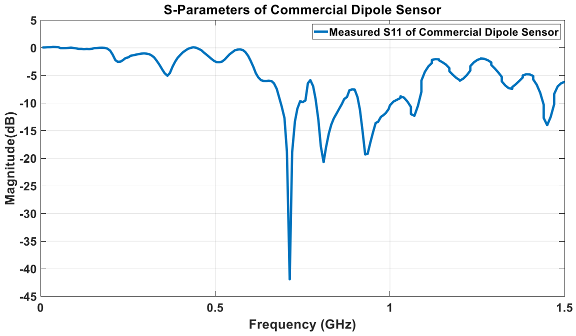


Fig. 11. Plot of scattering parameters of commercial dipole sensor.

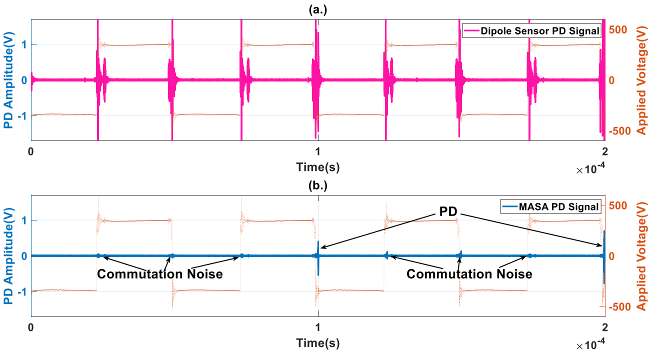


Fig. 12. . Plot of time-domain of recorded PD events.

VI. CONCLUSION

A novel modified Archimedes spiral antenna designed for PD detection in PWM-controlled inverter-fed low voltage drives has been presented. The design and principle of the proposed PD sensor demonstrates how the geometrical constraint and bandwidth limitation of existing sensors can be overcome by the modification parameters of polar coordinates equation of Archimedes spiral. Compared with an on-the-shelf dipole sensor that requires an external high-pass filter and which cannot be retrofitted in the end-winding of a machine in service due to geometrical constraint, the proposed MASA shows superiority in terms of low profile geometry that enables its physical integration to the end-winding of a machine, and its inherent filtering capability which is facilitated by the interstage impedance network discriminates between commutation disturbance and PD pulses. The system offers a low-cost solution for PD detection in inverter-fed electrical machines for industrial and reliability critical applications.

ACKNOWLEDGEMENT

This work was supported in part by Nigeria's Petroleum Technology Development Fund (PTDF), in part by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/S00081X/1, and in part by the European Commission under Clean Sky Programme under Grant 101008082.

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