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Model Based-Testing of Spatial and Time Domain Artificial Intelligence Smart Antenna for Ultra-High Frequency Electric Discharge Detection in Digital Power Substations

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Abstract—This paper presents a fifth-generation (5G) wireless smart antenna for performing both power substation communication (in space domain beam-steering) and electrostatic discharge (in time domain Ultra-high Frequency "UHF" impulse) detection. The same smart antenna used to communicate with other wireless antennas in the switchyard, as well as with the control room, is utilized to cyclically gather data from power apparatus, busbars, and switches where electrostatic discharge (ESD) may occur. The ESD poses a major threat to electrical safety and lifetime of the apparatus as well as the stability of the power system. The same smart antenna on which beam rotation in space-domain is designed by implementing an artificial neural network (ANN) is also trained in time-domain to identify any of the received signals matching the ultra-high frequency band electrostatic discharge pulses that may be superimposed on the power frequency electric current. The proposed system of electrostatic discharge detection is tested for electrostatic pulses empirically simulated and represented in a trigonometric form for the training of the Perceptron Neural model. The working of the system is demonstrated for electrostatic discharge pulses with rising times of the order of one nanosecond. The artificial intelligence system driving the 5G smart antenna performs the dual roles of beam steering for 5G wireless communication (operating in the space domain) and for picking up any ESD generated UHF pulses from any one of the apparatus or nearby lightning leaders (operating in the time domain).

1. INTRODUCTION

The substations carry out crucial tasks in power generation, transmission, and distribution. Therefore, to maintain the performance and reliability of the system, substation fault monitoring must be done speedily, accurately, and effectively. Over the past years, many researchers have successfully examined methods to improve the fault monitoring system for conventional substations. However, there is still room for improvement as many of the conventional substations are converted into digital substations using smart antennas for switchyard communication and control. Going digital means that the protection, measurement, and control units are digitized.

1.1. Motivation

The digital power substation [1] and the use of smart antennas [2–5] inside the substation open new techniques to be used for the detecting and identifying the location of ESD inside and close to the substation [6–12]. One of the two commonly used techniques used to detect and locate the ESD has

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been the Time Difference of Arrival Techniques (TDOA) where a minimum of three antennas are used to obtain the arrival of the UHF signals to three antennas. Then using the distance as the time of arrival divided by the velocity of light, circles are drawn around each antenna to get the intersection point, the point of ESD origin. The second method is the well-known Angle of Arrival (AoA) technique. The AoA with a single antenna requires distance measurement technique to get the accurate location of the source of ESD. Otherwise, the AoA may need a minimum of two antennas for detection and location [6, 11].

Smart antennas may be used to survey the substation cyclically using narrow steerable antenna beams and are ideal for the location of ESD in a substation switchyard power apparatus such as power transformers, switches, or busbars, as well as approaching lightning leader or lightning flash. With smart antennas, using just one adaptive array antenna and the ability to rotate the beam around the substation, it is possible to locate the ESD location accurately [9]. Smart antennas are part of the wireless communication systems inside the substation, and without extra cost, may be used for ESD diagnostics. One major reason for not using ESD detection and localization systems inside the substation is the extra cost involved [8]. However, in this method, we are proposing the communication system using ESD detection without any extra hardware required. It only involves a scanning algorithm that goes over the UHF signals captured by the smart antenna. This additional algorithm searches for the presence of ESD electromagnetic pulses (ESD_EMP) at UHF, in the 5G communication band.

Figure 1 shows the three levels of digital substation. The the protection data exchange system is between the protection and bay level, including data on the switchyard power apparatus ESD_EMP, which is picked up by the smart antenna in the switchyard. The exchange of instantaneous data from the electronic current transformer and electronic voltage transformers is between the bay and process level. Control data exchange takes place between the control room and bay level, as well as the process and bay levels. Through the wireless system, the data are exchanged using the smart antenna installed at each point of data acquisition for eventual transmission to the control room. The size of the process level switchyard may be 100 m × 100 m, within which the placement of wireless antennas enables communication within the switchyard, as well between the switchyard and the substation control room. The control room is within a distance of 25 m from the switchyard. The control room will have its wireless, smart antenna receiving data from the switchyard antennas. The smart antennas used for 5G communication between the switchyard and the bay level are also used to pick up ESD_EMP, thus playing the dual roles of communication and ESD detection for preventive action data acquisition [13].

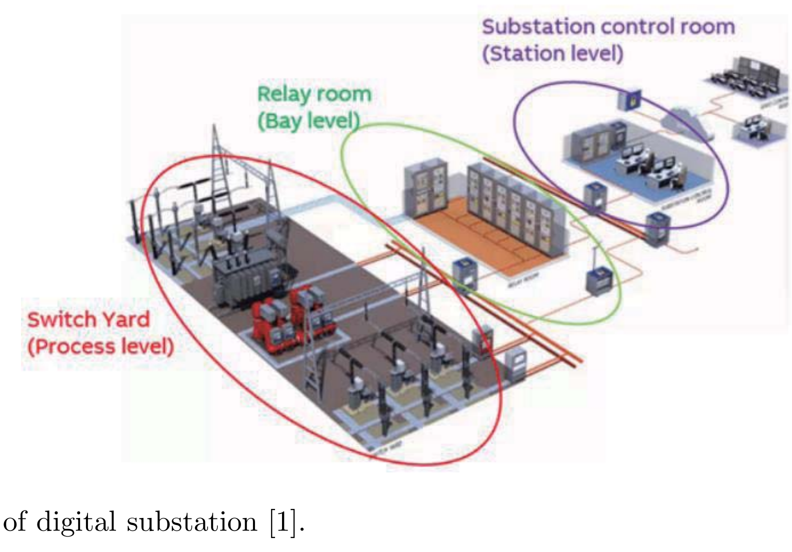

Figure 1. Layout of digital substation [1].

Modern digital electronic sensors, replacing the conventional sensors, use direct digital communication to process switchyard electrical state and to initiate control and protective actions. The use of copper wires connected point-to-point to the Current Transformers (CTs) or Potential Transformers (PTs) is replaced by electronic voltage/current transformers (EVT and ECT), fibre optics cable, and wireless smart antenna systems to minimize the exposure to high voltage electricity and the risk of damage to the equipment [14]. Nevertheless, having this substation equipment digitized, including sensor data, communications, and sensor signal processing, the substation is still exposed to the risk of potential hazards such as ESD in high voltage apparatus and busbars. Therefore, pre-breakdown and pre-fault monitoring is still needed to detect the existence of ESD in the substations, which may lead to a complete breakdown of the system [15].

1.2. Contribution

With the use of the proposed smart antenna based on ESD localization, the extra hardware cost is zero. The technique as presented in this paper needs a communication smart antenna to make a controlled survey of the entire substation area, primarily for data communication purposes [15]. The same smart antennas are used for detecting the electric discharge generated pulse (ESD_EMP). Here, the pulse is generated using an empirical formula and tested for detection in the time domain, by the communication smart antenna. The pulsed UHF ESDs radiations (ESD_EMP) are picked up by the smart antenna beam when it points towards the power apparatus or area of the substation where ESD is present. There are two Perceptron software codes. The first one is used to point the smart antenna beam towards specific spots of the substation where the survey should be carried out periodically, in the space domain. The second Perceptron code, in the time domain, searches for the ESD pulse waveform on the signals picked up by the smart antenna. The pulse can be from another wireless transmitter inside the substation (sinusoidal signal in the microwave frequency) or ESD pulse in the microwave frequency spectrum.

This smart antenna acts like a sensor that can be steered isotopically and filter out (suppress) or maximize signals which differ by 5° or 0.0873 radians of the signal direction-of-arrival (DOA), simultaneously [3]. Having these abilities as a sensor, it can detect and localize the abnormal radiated electromagnetic activities in the substation using the ESD_EMP and DOA. It is thus a promising preventive approach to improve fault monitoring of grid components and avoid substation electric breakdown. Generally, the ESD indicates the presence of cracks, voids or other insulation degradation within the electrical equipment that can lead to equipment failure, accidents, and electric breakdown of the power grid. For instance, when an open circuit occurs at a power transformer, the inductive circuit can cause hazardous conditions. Depending on the load, the high voltage on the secondary side may lead to ESD in the form of flashovers and arcing, which put the substation or personnel at risk, and the stability of electrical equipment could be disturbed. The most common ESDs are Electric Corona Discharge and Electric Sparks/arcs. These discharges usually occur on the overhead high voltage power transmission lines and also inside the substations. Based on the antenna characteristics and background noise for detection, the frequency spectrums of corona and arc are widely distributed across a range of 150 KHz–400 MHz but share the same frequency band of 150 KHz–10 MHz [6, 7].

The work reported herein may be extended to aircraft and ESD in the presence of thunderclouds. Despite the rapid advances in the design and development of a variety of safety and security systems, aircraft safety systems, which are mission-critical, have not advanced at the same rate as, for instance, safety systems for land-based motor vehicles. A crucial need in aircraft safety systems is for the detection, and early warning and localization of electrostatic discharge (ESD, including lightning occurrences) ahead on the flight path to enable the aircraft to avoid electrically threatening regions. The existing weather radar system mounted inside the radomes of the aircraft is mostly used to detect the density of clouds ahead of aircraft, to indicate to pilots the nature of the weather ahead of the flight path but not the specific location of ESD [16].

We present a novel two-step approach towards this end. First, the ESD radiated electromagnetic fields are captured by a smart antenna in a digital substation. Second, the captured signals are processed using ANN to localize the ESD activity. These radiated fields may be due to ED within the substation or nearby leader and return stroke lightning discharges. With the angle of arrival known, a trained ANN that acts on the time domain ESD_EMP also seeks to locate the distance region ahead where the ESD activity has occurred. Here, the artificial neural network (ANN) is trained to identify the unique patterns of radiated electric field-time characteristics from the near field ESD radiation. The ANN training depends on these time-domain characteristics of the measured electromagnetic fields. For the first time, this paper presents a spatial and time-domain Perceptron ANN that may be used for communication and ESD detection in an electric power substation.

2. MODELLING OF SMART ANTENNA

In order to keep the antenna light and simple in design and installation, we use dipole wire antennas arranged in an array. We assume that the dipole antenna matches the microwave ESD generated radiated electromagnetic pulses (ESD_EMP). The beam is steered by a microcontroller with a clock frequency of the order of 1 GHz.

2.1. An Array Antenna to Search and Identify ESD

For a two-element array antenna in receiving mode with one of the two elements containing a digital beam steering (beamforming) weight (w) [17], our task is to scan the region around the substation, in the plane that is parallel to the earth surface. The total output from the two-element array antenna is given by

$$E_T = w_1 E_1 + w_2 E_2 \tag{1}$$

where E_1 and E_2 are the electric fields picked up by the two antenna elements, with the received signal of the second element multiplied by the electronic weight, w. For an ESD occurring at a distance R from the apparatus and at an azimuth angle θ, the dipoles pick up electric fields of

$$E_1 = \mu_0 j\eta \frac{kIh}{4\pi R} e^{-jkR} \sin\theta \tag{2}$$

$$E_2 = \mu_{0\theta} j\eta \frac{kIh}{4\pi R} e^{-jkR} \sin\theta \left(e^{jkd\sin\theta\cos\varphi}\right); \tag{3}$$

where η is the free space intrinsic impedance; h is the length of the antenna (for half-wavelength dipole, $h = \lambda/2$, and wave number $k = 2\pi/\lambda$); and I is the current flowing along with the ESD, whether partial discharge leaders or arcs. Therefore, the total electric field picked up by the array antenna is as defined in Equation (1) where the weights w_1 and w_2 are determined by the Perceptron which is trained based on the specific location of each apparatus and must cyclically keep under observation. The rotating antenna beam captures the maximum ESD_EMP in the direction of $\theta = \theta_d$ and $\varphi = \varphi_d$ where $(\theta_d \varphi_d)$ angles indicate the direction of the ESD. The best moment of capturing the ESD activity is when the antenna beam is pointed directly towards the apparatus, or the location, where ESD is generated, when $AF_m = 2$. Since the ESD-EMP has the rise times of the order of a sub-nanosecond (1 GHz) to microsecond (1 MHz), the sampling frequency of the signals received by the array antenna will be in the microwave spectrum for nano-second radiation from ESD. For the antenna beam to enable sampling of received signals at every 30° (the segment angle used in the fourth generation wireless communication systems), the microprocessor (depending on the clock frequency) should change w_1, w_2 values to ensure that the beam rotates, searching for ESD and samples ESD at 2 GHz. One further step is to use a single beam smart antenna instead of two symmetrical beams generated by the linear array antenna because two symmetrical beams require a reflector to fold one of the beams over. Thus, we can use the nonlinear three-element smart antenna which is capable of generating a single, steerable beam [5, 18].

2.2. ESD Radiated Electric Field Pattern

In addition to training the Perceptron ANN to steer the beam towards different fixed locations of the substation, the same Perceptron ANN is trained to analyze the time domain characteristics of the ESD-EMP to look for pulses superimposed on the electric current of the power line, substation busbar, transformer terminals, or circuit breaker terminals. The ESD_EMP model is used to train the Perceptron ANN for ESD_EMP signal recognition. The current of ESD could be modelled as a sum of the four exponential terms given by,

$$I(t) = \begin{cases} 0 & \text{when } t < 0 \\ \sum_{n=1}^{4} I_n e^{-f_n t} & \text{when } t > 0 \end{cases} \tag{4}$$

Table 1. Parameters in the basic model of return stroke.

n	Current I_n kA	Damping frequency, f_n GHz	Time Constant $\tau_n = 1/f_n$ ns
1	-29	3	0.333
2	23	2.5	0.400
3	5	4	0.167
4	1	9.5	0.105

where I_n is the amplitude of individual term, and f_n is the natural damping frequency of the current. Table 1 specifies the values of I_n and f_n. Also, the return stroke current is modelled in such a way to satisfy the following conditions,

$$I(t)|_{t=0} = 0 \quad \text{and} \quad \left.\frac{dI(t)}{dt}\right|_{t=0} = 0 \tag{5}$$

Considering the ESD as a vertical dipole of length L, the ESD_EMP electrical field components at a distance r could be expressed in the spherical coordinate system as,

$$E_r = 2\eta \frac{L\cos\theta}{4\pi} \sum_{n=1}^{4} k_n^2 \left(\frac{1}{(k_n r)^2} + \frac{1}{(k_n r)^3}\right) I_n e^{-f_n t} \tag{6}$$

$$E_\theta = \eta \frac{L\sin\theta}{4\pi} \sum_{n=1}^{4} k_n^2 \left(\frac{1}{k_n r} + \frac{1}{(k_n r)^2} + \frac{1}{(k_n r)^3}\right) I_n e^{-f_n t} \tag{7}$$

where $k_n = j\sqrt{\mu_0 \varepsilon_0} f_n$ and $\eta = \sqrt{\frac{\mu_0}{\varepsilon_0}}$. Hence, the resultant ESD_EMP electrical filed can be expressed as

$$\mathbf{E} = E_r \hat{\mathbf{r}} + E_\theta \hat{\theta} \tag{8}$$

Thus, the amplitude of the resultant field is

$$|\mathbf{E}| = \sqrt{|E_r|^2 + |E_\theta|^2} \tag{9}$$

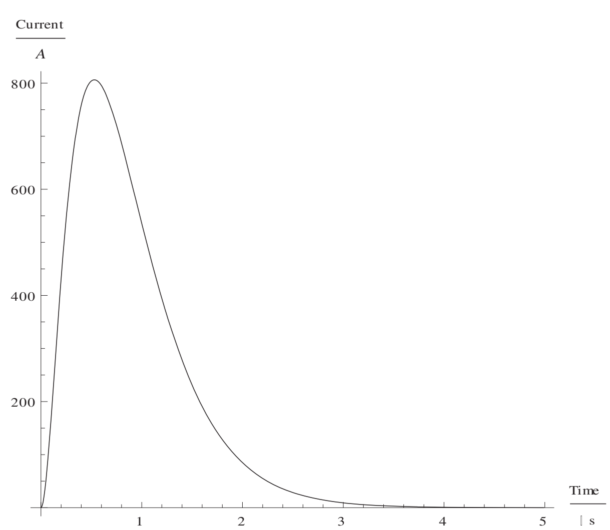

Figure 2. ESD current.

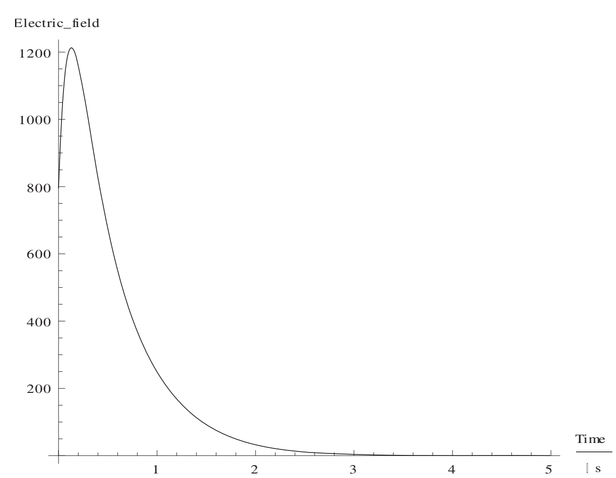

Figure 3. Electrical field 20 m from the ESD source.

The resultant electric field is the outcome of dipole (electrostatic) static charges, the direct current in the dipole (magneto-static), and the time-varying current in the dipole (radiation). Thus, different contributions predominate the resultant field component at different distances. Consequently, the presented approach in this paper attempts to use the ESD_EMP wave shape to identify the presence of ESD. Figure 2 shows the model of ESD current variation with the time whereas Figures 3 to 5 show that the amplitude of the field varies with time to the respective distances. Observing the patterns, it is clear that there is a notable deviation in patterns with respect to the distance from the ESD. However in the work reported herein, we do not consider the distance estimation, reported elsewhere.

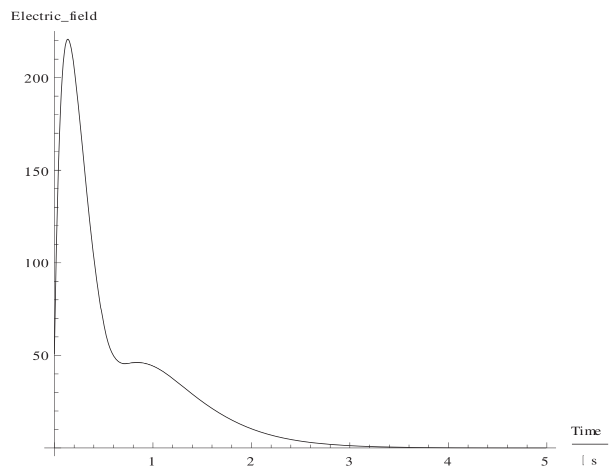

Figure 4. Electrical field 50 m from the ESD source.

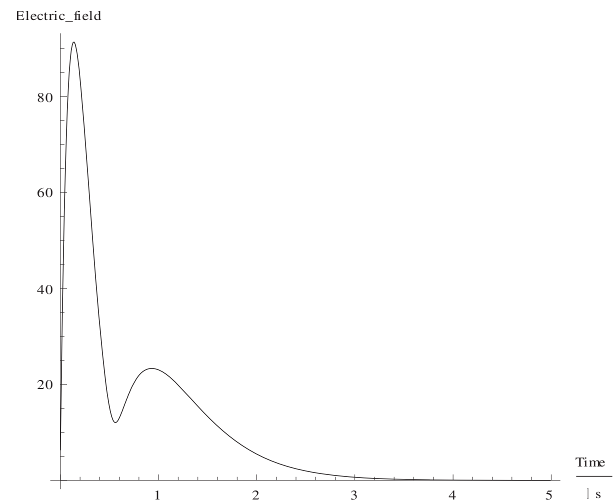

Figure 5. Electrical field 100 m from the ESD source.

2.3. Application of the Perceptron ANN for UHF ESD Detection

An ANN is a numerical structure which comprises interconnected artificial neurons, in a substantially small scale, and works like that of a natural neural system or brain. An ANN can gain from information either in a managed or unsupervised way and can be utilized as a part of assignments, for example, arrangement, relapse, grouping, and many more from there. The human brain gets signals from sensors, for example, the eye, ear, and touch. These signals are then processed by the brain. In ANN, the sensors might be genuine image sensors (camera), sound sensors (microphone), or capacitive touch sensors which are the inputs to the ANN. Figure 6 simplifies the concept of applying the Perceptron ANN training algorithm for UHF ESD Detection based on a 2-element array antenna to form the smart antenna. On account of the Smart Model Based Testing as proposed in this paper, the inputs are normally transmitted signals from transmitting antennas [17]. The input signals are processed mathematically, for example by multiplying each input signal by a number (weight w) and phase-shifting the signal (complex weights, b), at that point sum up the input signals and place the sum at the output as a transfer function that will yield the final output signals. On account of the human brain, the final output signals might be activating signs to the muscles, for example, to move the human body for activity.

For smart antennas, the final output signals might be to divert the beamforming towards the desired users. An ANN is structured of a substantial number of highly interconnected processing elements called Artificial Neurons organized in layers. The weights (w) and biases (b) are known as Adjustable Scalar Parameters (also known as hyperparameters) of the neuron. The parameters can be adjusted to meet the desired behaviour as part of the network training process. ANN is preferable in many applications as it has fast convergence and is adaptive to any complex changes. The hyperparameters, which are the learning rate (step size) and the bias of the perceptron, control the effect of weights updating and

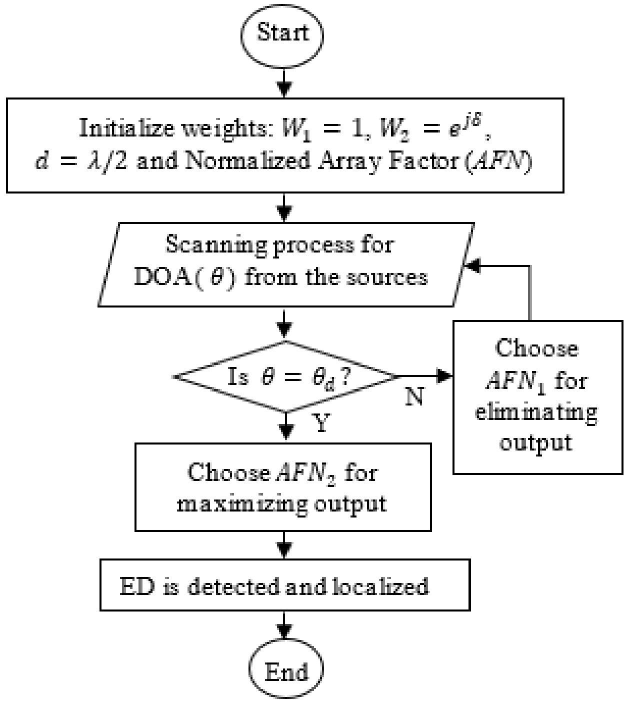

Figure 6. The flowchart of the simultaneous scan.

the convergence rate of the perceptron. Therefore, selecting the initial values for these hyperparameters is crucial. However, this Perceptron ANN algorithm has some limitations. These include some series of sufficient trainings to obtain the optimum Perceptron hyperparameters if one needs to apply more than the 2-element array antenna to meet the desired behaviour. This algorithm is designed to detect, localize, and identify the EMP but not to classify the EMP signal.

In this paper, the Perceptron ANN is incorporated with a linear array antenna to form a smart antenna. The linear structure of array antenna is used due to its low complexity, and it can perform beamforming in a single plane within the angular sector. This smart antenna can simultaneously scan and detect any abnormal activity of electrical Partial Discharges (PD) in a power substation based on the Direction of Angle (DOA) of the electromagnetic (ESD_EMP) source. Two conditions are considered in this investigation, i.e., to eliminate the interferer signals (signal from undesired direction) and to maximize the desired signal (from the desired direction). The MATLAB Coding is programmed according to the flowchart shown in Figure 6 for the ANN training algorithm [3, 9]. The scanning process is simultaneously performed by taking some initial parameters setting and calculation to represent the ideal condition of an indoor or outdoor substation [5, 19].

In this work, the investigation is focused on the ESD_EMP detection and localization. The Electromagnetic Pulse (Ep) is used to represent the ESD_EMP for simulation purpose. The radiation pattern of the desired output signals of Figures 3 to 5 may be detected by a time-domain frame represented by a *sinc* function in the time-domain. The beam is steered by a Perceptron ANN trained to different locations, where the power apparatus is present by another spatial-domain using *sinc* function. The radiation pattern of the desired output signal, $y_d = sinc\,(\varphi - \varphi_m)$ with a series of DOA, randomly selected at $\varphi_m = 45°$, $120°, and 300°$ is visualized, and the effect of each delay of DOAs induced in the signal is observed. The similarity of the desired output waveforms in space and time-domain makes the technique efficient and demands minimal computational complexity. This similarity shows the same ANN used in Smart Antenna (SA) spatial-beam optimization and Ep detection.

Consider that ESD_EMP originates at the power transformer in an indoor substation carrying the power frequency sinusoidal current. This ESD_EMP will be superimposed on the sinusoidal current as shown in Figure 7. The power frequency current is $i(t) = I\sin(\omega t)$ with a frequency $f = 50\,\text{Hz}$,

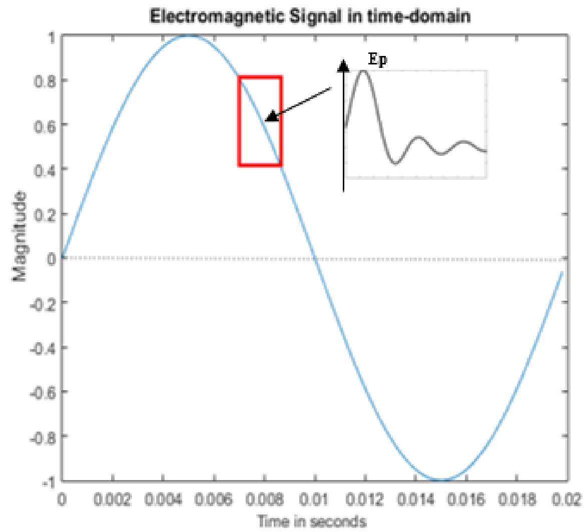

Figure 7. An EM signal generated in time-domain.

and the period is $T = 0.02\,\mathrm{s}$. The impulse is produced by the ESD superimposed on the 50 Hz power frequency. Since the spectrum of the UHF ESD impulse is the signal that will be captured by the UHF smart antenna, the antenna will naturally filter out the power frequency component, thus giving the time domain UHF impulse to the Perceptron to process and detect the presence of the UHF impulse.

Assuming that an event of ESD current radiating pulse *Ep* happens within the boxed region in Figure 7, an ultra-high frequency ESD phenomenon lasts over a few nanoseconds. The smart antenna is placed with respect to the power transformer say at $DOA = 45°$. Hence, *Ep* is represented by $Ep(t) = sinc\,(\varphi(t) - pi/4)$ for θ between 0° and 360°. We use the ED_EMP detection frame that is *sinc* function in the time-domain which will seek in the UHF band for pulses similar to Figures 3 to 5 in the time-domain. The ESD_EMP pulse represents the initial oscillating pulses followed by the major leader pulse and then the dying away of the major pulse. Assume that generated *Ep* has a rise time of 1 ns. Therefore, *Ep* spectrum reaches about 1 GHz received by the Smart Antenna.

The capability of this antenna to allow detection up to 1 GHz spectral line from the ESD_EMP with a rise time 1 ns depends on the training of the time-domain Perceptron ANN. The time-domain is trained to handle pulses up to 3 GHz. ESD emits UHF ranging from 300 MHz to 3 GHz [3–12] and 0.6 GHz to 6 GHz [7]. The ESD in the 300 MHz–3 GHz band is preferable for the UHF detection or sensing methods due to the low level of noise in this spectrum band compared to lower frequency bands [8]. The Perceptron ANN training is in time-domain for signal identification of ESD_EMP time-domain waveform.

3. RESULTS AND DISCUSSION

In Figure 8, the smart antenna single beam is shown being rotated by the Perceptron ANN over any desired direction inside the substation switchyard. It is for communication and picking up ESD_EMP from power apparatus positioned in specific angular positions towards which the antenna beam may be cyclically rotated by pre-trained weights to observe the ESD activities [5]. As observed, the beam is focused in the specified DOA. The ANN Perceptron is trained in the space domain to rotate the beam to focus on each location of the power apparatus or substation section over each scanning cycle. Thus, the antenna knows the condition of the particular apparatus or substation section that it is looking in each scan. In Figure 8, we assume that there are three specific locations of apparatus that the smart antenna should focus on to pick up any UHF emissions.

Figure 9 shows the Perceptron ANN generated beam focused towards a spatial location of 45° and the simultaneous time-domain search to match received signal with the time-domain pulse for ESD_EMP detection. The waveforms show that there is a similarity of the waveforms in space-domain (the beam

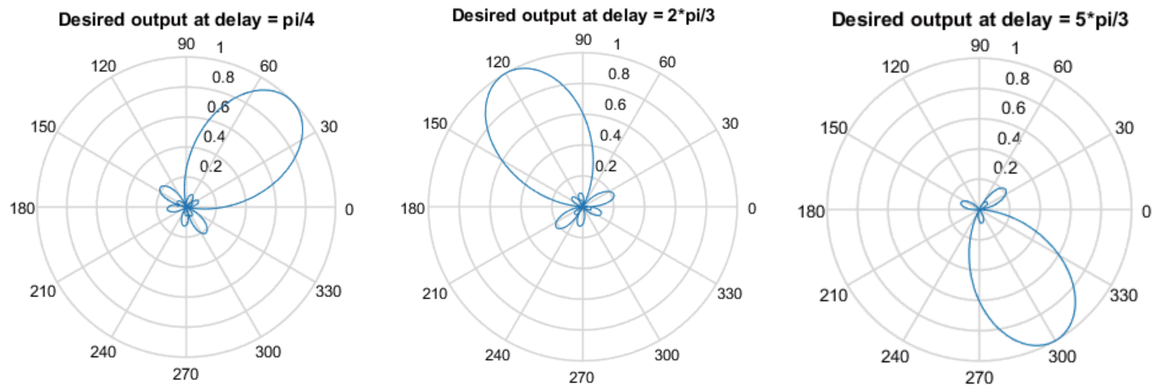

Figure 8. The y_d at DOA of 45°, 120° and 300°.

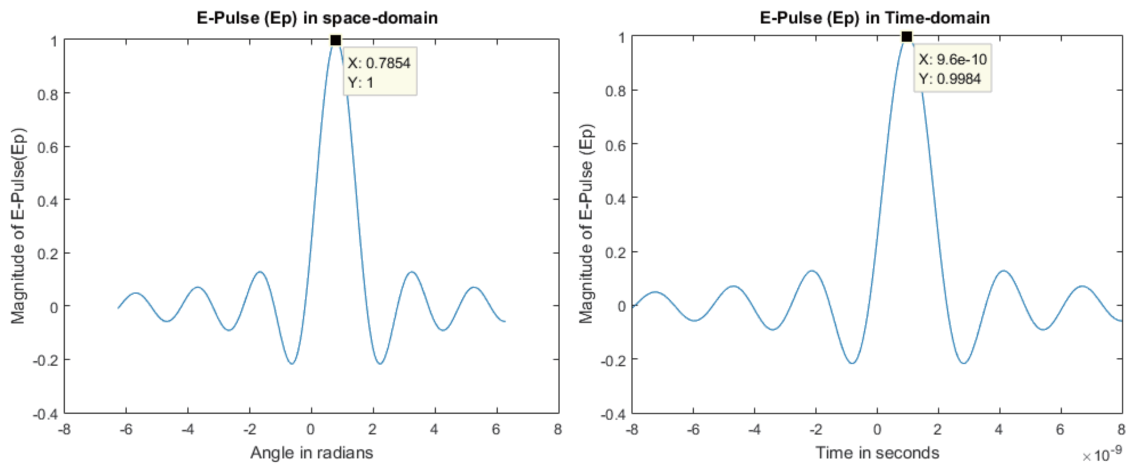

Figure 9. The waveforms of *Ep* generated at 125 MHz.

pointing towards a power apparatus at 45°) and time-domain (a UHF ESD current generated ESD_EMP superimposed on power frequency current). The maximum peak of *Ep* in space-domain is denoted as θ_m, representing the delay angle of DOA. The maximum peak at time-domain is denoted as *Ep*.

Figure 9 shows the spatial antenna beam and time-domain pulse picked up in the band encompassing 125 MHz at $DOA = 45°$. In the space-domain of the antenna beam, the maximum magnitude, $y = 1$, is observed at an angle of 0.7854 rad while in time-domain pulse, the peak magnitude $y = 0.9984$ shows peak time, $t_p = 9.6e^{-10}$ s. Thus, at the peak time of 0.96 ns, the frequency allowed into antenna receiver is 1.04 GHz. As observed, for the 1 ns peakESD_EMP, the error is 4%. Therefore, the accuracy for ESD_EMP signal detection and localization is at 96%.

In space domain, the antenna beam peaks in the direction of the substation apparatus that it is pointing towards, and the beams in other directions shown by the side lobes are small enough to filter out any UHF arriving from any other parts of the substation. Hence the antenna may detect ESD even when there is more than one apparatus that has partial discharges or arcs. The time domain shape in Figure 9 is the impulse signal for which the time domain processing of the ANN Perceptron is seeking. When the output of the Perceptron shows zero error, which is a match between the signal and the setting of the time domain Perceptron, an ESD presence is registered, as shown in Figure 10.

A further investigation is carried out to evaluate the accuracy of the smart antenna detection based on a sample of ESD_EMP in the range of 10 KHz–400 MHz. Figure 10 shows the comparison between the detected *Ep* and the targeted *Ep*. The average percentage error is 3.84% giving a detection accuracy

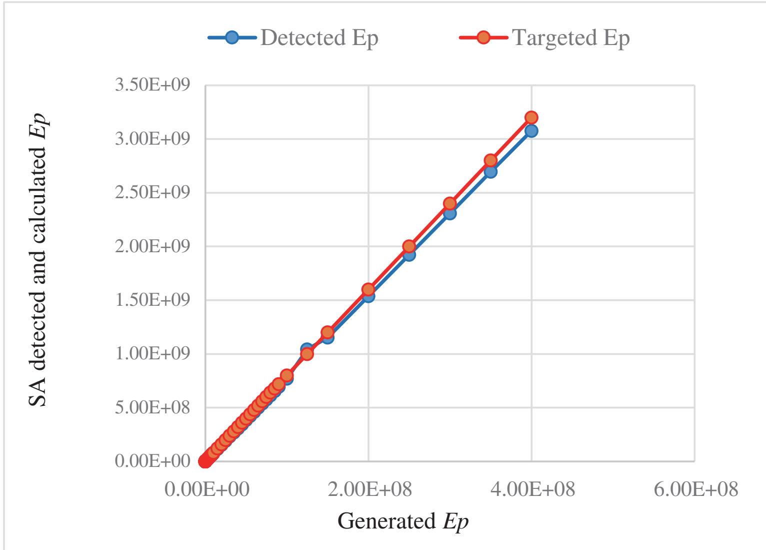

Figure 10. The comparison of detected and targeted *Ep*.

at 96.16%. The Smart Antenna is capable of detecting ESD_EMP within the ultrasonic frequency band of 20 KHz–100 KHz at a detection range of 154 KHz–769 KHz and *Ep* frequency of 150 KHz–400 MHz at the detection range of 1.15 MHz–3.08 GHz. The work shall be further explored for real-time UHF ESD-EMP measurements and spatial layout of both digital substations and remote power installations using distributed generation systems [20].

4. CONCLUSIONS

The paper has explored the possibility of implementing and training the same Perceptron ANN algorithm for beamforming (in space) for a wireless communication system within a digital substation, while it is also trained and used (in the time-domain) for the detection of EMP radiated by electric breakdown phenomena in the vicinity of the substation. The EMP detection algorithm uses the training waveform, for space domain beamforming, also in the time-domain to scan the signals picked up by the smart antenna when it is pointed towards specific electric power apparatus such as the transformer or switchgear. The Perceptron ANN model is not only a powerful tool for wireless communication within the switchyard and between the switchyard and control room, but also an accurate tool for detecting EMP in the UHF band in which the electric gas discharges associated with electric breakdown radiating signals with little interference.

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