Ground Based Inspection for Overhead Transmission Line Sag

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***Abstract*—Upscaling of the energy network represents a challenge on the resilience of the electricity network and grid to ensure that there is electricity available to meet demand. Cost-effective maintenance of high power electrical lines are of critical importance and overhead linesmen face several safety concerns during inspection of catenary lines which include working in remote areas, at height and facing adverse weather conditions. Whilst some technological advancements have been made via robotic sensing and in-situ sensing systems, these proposed solutions are inadequate for hazardous weather conditions and still include risks to workers. This article presents preliminary results obtained using a Frequency Modulated Continuous Wave (FMCW) radar sensing employed as an alternative solution for the measurement of sag in high power transmission lines. The results indicate that the FMCW radar sensor can detect multiple overhead lines within a single scan and the relevant overhead line sag. Results when compared against a laser distance meter provide an average accuracy of 95.5%.**

Keywords—Catenary Line, FMCW radar, microwave sensing, power line sag, pylon maintenance.

I. Introduction

In 2020, the UK government released a ten-point plan for a green industrial revolution with the aims to decarbonize the energy sector. The key aims of the plan include the upscaling of four subsectors within the energy sector for offshore wind, low carbon hydrogen, nuclear power and zero emissions vehicles, all targeted to reduce greenhouse gases reaching the atmosphere [1], [2]. Decarbonization of energy supplies will involve a substantial shift of previously non-electric energy demand onto the electricity network.

Beyond decarbonization, the upscaling of the energy sector also represents a challenge on the resilience of the electricity networks and grid which ensures there is electricity available to meet the demand. Overhead transmission lines are located widely around the world and used to transmit electrical energy across large distances. These lines consist of several electrical cables suspended overhead by pylons. In England and Wales, there are over 90,000 pylons and 7,000 kilometers of high-voltage overhead lines to inspect and maintain [3]. Safety concerns for overhead line technicians during inspection include accessing remote areas, facing adverse weather conditions and working at height [3].

Overhead transmission lines are rated to specific standards such as IEEE standard 524-2016 which outlines commonly used mechanisms for protective grounding, different components and mechanisms for creating sag in overhead line wires as per the tension requirements of the conductors [4]. However, a problem encountered in catenary lines includes the change in the amount of sagging often resulting in line breaks and loss of energy efficiency. This can be due to climatic and seasonal changes where the cables stretch due to warmer temperatures, shrink due to colder temperatures or formation of ice during winter contributing to further sag of the line [5]. Often these scenarios occur in remote areas where the climate is more hazardous and severe, resulting in engineers having to travel large distances to inspect overhead lines in difficult areas.

Determination of the precise and reliable amount of sag amount is either measured on-site by overhead linesmen or calculated theoretically if tension of the lines, span length, height of the lines at both ends and elevation of the pylons are known [5]. Measurements require working at height, which can be prohibited in the presence of dynamic weather conditions such as fog or snow which generate low visibility of the lines.

This research article investigates Frequency Modulated Continuous Wave (FMCW) radar sensing for the detection and measurement of overhead transmission line sag from the ground. Positive results from this work could potentially alleviate the need for overhead linesmen to work from height during these types of inspection. The key contributions in this paper are as follows: A Proof-of-Concept (PoC) test designed to establish whether the transmission cable presents a suitable contrast against the sky for a FMCW sensor operating in the K-band. This was conducted on two sets of overhead cables that cross paths over each other. The second investigation evaluates the use of FMCW radar for measurement of the range of overhead lines along the length of the catenary line and therefore detection of the line sag.

The paper is structured as follows: Section II provides a short literature review related to two commercial solutions that are been trialed. Methodology concerning the two investigations is described in Section III. Results and Discussion are provided in Section IV followed by preliminary conclusions in Section V.

II. Related Work

A couple of commercial solutions are currently on trial. The OTT Hydromet is a UK based company which provides water and weather applications solutions with the aim to protect lives, infrastructure and the environment. In December 2020, three meteorological stations and cameras were installed on separate pylons susceptible to ice formations during winter. The trial aimed to predict ice formation through remote visual monitoring of the overhead lines and to send automated warnings to the network operator. The solution consisted of a monitoring weather sensor system that includes camera, humidity, temperature, air pressure, wind direction wind speed and radiation, a data logger, 4G communications, solar panel and battery. A challenge in the system includes how to supply power to the device within remote areas. This was achieved via the solar panel and battery which can operate during short dark days [6]. A disadvantage of this approach is the potential of low visibility due to snow or fog which would limit the efficacy of the visual camera.

A hanging power line inspection robot is the second solution presented whereby the ROSETLineBot is moved along a transmission line via an actuator wheel. Position change was calculated via two consecutive cumulative trapezoidal numerical integration of the acceleration measured by an inertial measuring unit (IMU). The data was then filtered with a 0.9 cosine tapered window ratio and detrended to compensate for the sensor shift. The laboratory results from a fairly sizeable rig extending to approximately 2.5m in height and 13.7m in length achieved less than 2% error against the measured sag [5]. To be cost-effective, this approach requires the robot to transition beyond a insulator at each pylon. Human intervention is also needed to deploy the robot on a catenary line.

In summary, the approaches discussed are diverse and offer some benefits depending on the need of the network operator. However, both require an overhead linesman to be deployed to work at height. There are also sufficient risks which exist especially in the hazardous conditions which these sensing devices/robots are deployed in. E.g., Human deployment of robots in dynamic weather and at height. Opportunities still exist for a sensing device that can be positioned as part of the infrastructure or from the ground and can accurately monitor the overhead line sag in a range of adverse weather conditions.

III. Methodology

A. Measurement of Overhead Line Heights

The 275kV overhead transmission lines were initially measured using a Mileseey laser distance meter (serial number A200957904) capable of measuring a maximum range of 120 m with measuring accuracy of $\pm$ 2.0 mm. Measurements of overhead line heights at the STD-D type pylons were carried out by pointing the laser rangefinder at the bottom of the relevant line insulator. As identified within Table I and Fig. 1, the overhead lines between pylons 3 and 4 are at increased heights compared to pylons 1 and 2.

B. FMCW Radar Setup

The FMCW radar sensor is a compact, lightweight, low power sensing device which can be integrated as part of an existing infrastructure or deployed as a handheld device. The radar setup used in this study is shown in Fig. 2 where the radar utilizes 1,500 MHz frequency sweep from 24-25.5 GHz. The horn antenna is connected to the electronics via a standard waveguide. The FMCW electronics is connected to the laptop via a serial port cable and is powered via laptop USB which has a buck booster to provide the required voltage from the USB port. The laptop runs the MATLAB script continuously and records the data received from the FMCW radar sensor. Further details about the characterization of the standard gain horn antenna and FMCW theory can be found in [7], [8].

C. Proof-of-Concept (PoC) Investigation

The objective of the PoC investigation was to identify if the FMCW radar sensor can detect and measure the height of the overhead transmission lines when positioned underneath on the ground. The FMCW radar sensor was positioned at a location approximately midway underneath the length of the overhead cable (between pylons 1 and 2) as represented schematically in Fig. 3. To assess the efficacy of the radar under adversarial

TABLE I. Average range from the laser rangefinder to the insulator for each overhead transmission line. See fig. 1 for the naming convention of each overhead line.

Pylon	*Overhead Line*	*Range (m)*	*Elevation above sea Level (m)*
1	R3	16.578	123.578
	R2	19.935	126.935
	R1	24.221	131.221
	B1	26.524	133.524
2	R3	14.358	120.358
	R2	18.276	124.276
	R1	22.164	128.164
	B1	25.727	131.727
3	O3	38.042	146.042
	O2	45.804	153.804
	O1	53.487	161.487
	K1	X[a]	X[a]
4	O3	37.494	150.494
	O2	44.133	157.133
	O1	103.567	216.567
	K1	X[a]	X[a]

[a] Unable to obtain a measurement for cable heights as it was too difficult to aim the laser range finder at the target consistently as it was too high.

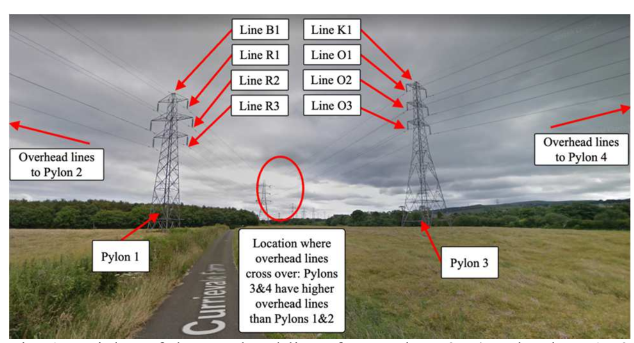

Fig. 1. Heights of the overhead lines from pylons 3&4 and pylons 1&2 carried out by laser range measurements.

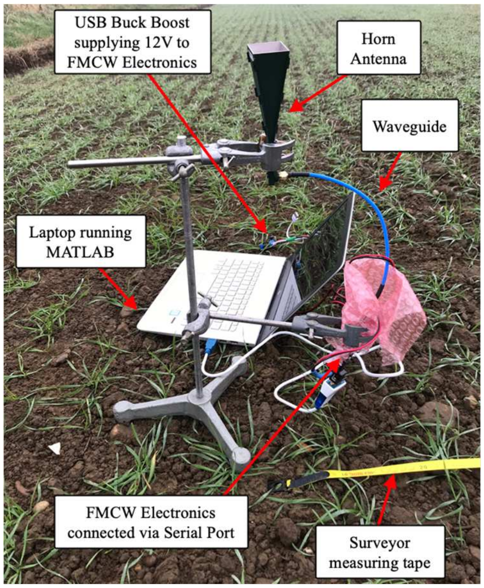

Fig. 2. FMCW Radar sensor setup alongside other equipment used including clamp stand, laptop and surveyor measuring tape.

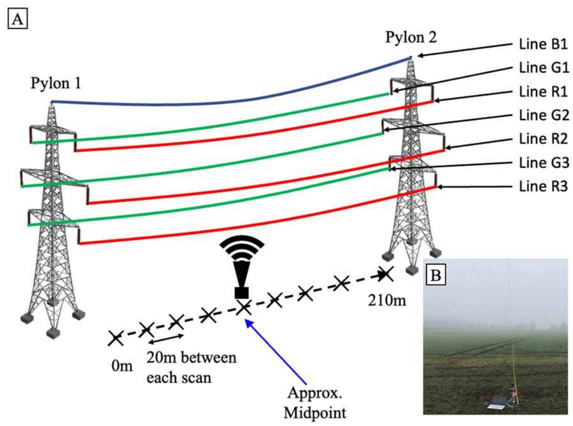

Fig. 3. A- Diagram of the experimental setup highlighting the FMCW sensor positioned between pylons 1 and 2. B- FMCW radar setup between pylons 1 and 2 displaying misty weather conditions.

weather conditions such as misty weather, the FMCW radar system was also positioned directly underneath cables R1, R2 and R3 as shown in Fig. 3B.

When repeating the investigation for the overhead lines between pylons 3 and 4, the exact same approach was taken where the FMCW radar sensor was positioned at the approximate midpoint. These overhead lines were labelled O3, O2, O1 and K1. The aim was to assess if the radar sensor can detect the significantly increased heights in these lines and compare against these obtained for pylons 1 and 2.

D. *Identification of Overhead Line Sag*

Results were collected on the second day of the investigation however, the weather conditions remained foggy as displayed in Fig. 3B. The radar sensor was positioned at distances along the overhead line from pylon 1 to pylon 2 in 20 m intervals as displayed within Fig. 3. At least eight consecutive scans were carried out to ensure accurate and consistent scans.

IV. Discussion and Results

A. *Proof of Concept Investigation*

Fig. 4 displays the converted Return Signal Amplitude (RSA) received at the FMCW radar using the Fast Fourier Transform (FFT). Each peak within this graph represents a detected overhead transmission line where the BIN number represents the time of flight from the radar to cable, hence, resulting in a distance measurement. For results labeled 'Test 1', the overhead lines R3, R2, R1 and B1 can be distinguished when compared against the sky baseline recorded. For the results within 'Test 2', overhead lines O3, O2 and O1 can be detected when compared against the sky baseline. In addition, these results verify that the overhead lines from pylons 3 and 4 are at higher heights than pylons 1 and 2.

The peak at 500 BINs is a characteristic of the antenna as this is also visible in the sky baseline, hence an annotation labelled indistinguishable for where K1 would be expected. For the other overhead lines, there are distinguishable deviations from the sky baseline indicating the detection of the overhead lines.

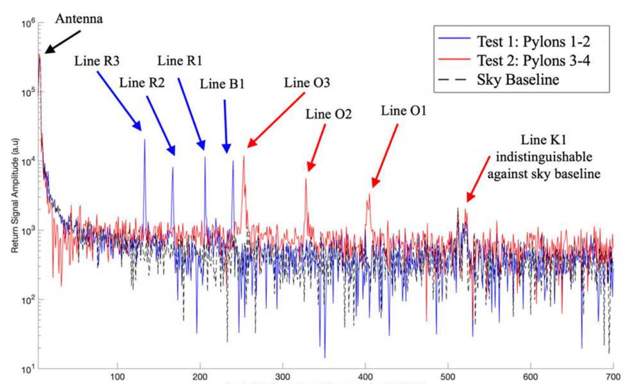

Fig. 4. FFT displaying the RSA for Pylons 1-2 and Pylons 3-4 displaying the detection of each cable and distance from the radar to the overhead line.

TABLE II. Range from the FMCW radar to the detected overhead lines as displayed in Fig. 5.

Distance along overhead line (m)	Range from Radar to Overhead Line (m)			
	G3	***G2***	***G1***	***B1***
0	17.888	21.586	25.482	29.180
20	17.188	20.786	24.683	28.280
40	16.589	20.086	24.083	27.581
60	15.589	19.087	22.984	26.382
80	14.390	17.888	21.785	25.083
100	13.291	16.788	20.586	23.884
120	12.891	16.389	20.186	23.484
140	13.091	16.589	20.486	23.684
160	14.190	17.688	21.485	24.783
178[a]	14.890	18.487	22.285	25.682
200	15.290	18.887	22.584	26.082
210	14.990	18.587	22.285	25.882

[a.] 178m due to a stream at 180m which was not appropriate to position FMCW radar.

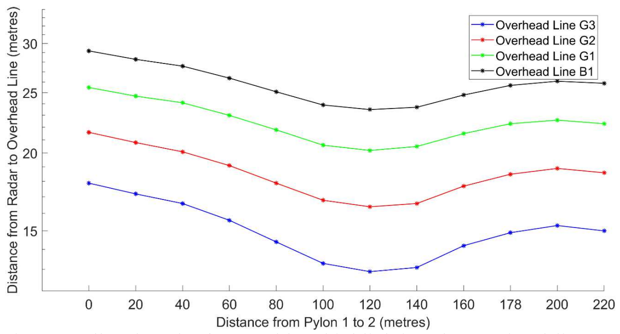

Fig. 5. Collated peaks from Table I highlighting the overhead line sag between Pylons 1 to 2.

TABLE III. RANGE TO OVERHEAD TRANSMISSION LINE FOR FMCW RADAR SENSOR AND LASER DISTANCE METER

Distance along overhead line (m)	Method of measurement	Range to Overhead Transmission Line (m)			
		G3	***G2***	***G1***	***B1***
0	Laser Range Meter	16.578	19.935	24.221	26.524
0	FMCW Radar	17.888	21.586	25.482	29.180
210	Laser Range Meter	14.358	18.276	22.164	25.727
210	FMCW Radar	14.990	18.587	22.285	25.882

TABLE IV. ACCURACY COMPARED AGAINST THE LASER DISTANCE METER AS A PERCENTAGE

Distance along overhead line (m)	Accuracy (%)			
	G3	***G2***	***G1***	***B1***
0	92.68	92.35	95.10	90.90
210	95.78	98.33	99.46	99.40

B. *Identification of Overhead Line Sag*

For each scan at a distance along the overhead transmission line, the FMCW radar sensor receives the RSA and converts this data into a FFT. As identified previously within Fig. 4, each peak within this graph represents a detected overhead transmission line where the BIN number represents the time of flight from the radar to cable, hence, resulting in a distance measurement.

These peaks were then recorded and converted into range using equation 1 and are displayed within Fig. 5. The results from Table II were then plotted in Fig. 5 to identify the overhead line sag between pylons 3 and 4.

$$Range = \frac{BIN \times c}{2 \times BW} \tag{1}$$

The range equation used to calculate distances in Fig. 5 is provided in Equation (1) where, BIN represents the peak identified for the transmission line within the bandwidth in the frequency domain (see Fig. 4, x-axis), c is the speed of light and BW represents the bandwidth of the frequency at 1.5GHz.

Due to safety reasons and limitations within the laser distance meter, there are challenges in corroborating the overhead line heights of the sag between 20-200m. This is due to the cables being too thin to attain a reading on the laser distance meter. However, a comparison of the results for where the overhead lines connect to the insulator has been created within Table III and resulting accuracy as a percentage when the laser distance meter is compared against the FMCW Radar sensor in Table IV. These results indicate an average accuracy of 95.5% for utilizing the FMCW radar sensor as a range meter when comparing the results against the laser distance meter.

In addition, we can qualitatively verify that the FMCW radar sensor is effective at detecting the overhead line sag for Pylons 1-2 due to the point where the line sag being at the midpoint between the pylons. Identification of this is within Fig. 5 at 120m indicating the detection of the overhead line sag.

V. CONCLUSION

This article provides a solution to mitigate challenges in inspecting and maintaining overhead transmission lines. The solution minimizes engineers working at height and can operate irrespective of dynamic weather conditions. A brief evaluation of pilot projects within the state of the art has been presented discussing the advantages and disadvantages. A PoC investigation was presented evaluate that the FMCW radar sensor can identify and measure the height of overhead transmission lines. A second investigation was conducted to assess the detection of overhead line sag. Results verify detection of overhead line cables and indicate that multiple overhead lines can be detected within a single scan and the detection of overhead line sag. An average accuracy of 95.5% when compared against a laser rangefinder for measuring the height of the overhead lines.

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