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Weather-Driven Data Analytics for Asset Failure Prediction

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SUMMARY

Mechanical wear due to wind and environmental corrosion are the two main ageing mechanisms for overhead line systems. The combination of these effects accelerates the degradation of conductors and fittings and reduces their useful lifetime. Whilst corrosion reduces the mechanical strength and performance of conductors and fittings, wind-induced oscillations introduce high frequency stresses that cause fatigue and can lead to component damage or failure.

We present here the results of a novel methodology to quantify these mechanisms using Numerical Weather Prediction (NWP) data and mechanical vibration models, trained on available asset data for a large number of overhead line spans, provided by National Grid UK.

A high-resolution NWP model, combined with local downscaling tools, was used to generate weather variables and conditions (wind speed and direction, temperature, precipitation, icing) for every span over a period of 11 years. These outputs were then combined with our mechanical vibration model, to predict frequencies and amplitudes of oscillation experienced by the system throughout its lifetime. Finally, proprietary machine learning and statistical models were used to combine the simulated data with the available asset condition data, in order to provide a reliable classification of environment risks for asset failure prediction.

The model is currently being applied to over 3390 kilometres of overhead line routes across the UK in a variety of coastal, mountainous, rural and industrial environments.

This work was conducted in partnership with National Grid UK, as a part of OFGEM's Network Innovation Allowance (NIA) funded project: "Evaluation of Methodology for the Assessment of Wind Induced Conductor Oscillation Risks". National Grid provided all the Asset Integrity Data used in the project.

KEYWORDS

Overhead Lines, Asset Management, Aeolian Vibrations, Galloping, NWP, Data Analytics, Machine Learning, Statistical Modelling

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DATA

Asset Integrity Data

National Grid UK (NG hereafter) provided to Digital Engineering (DE) a collection of Asset Integrity Data for 15 overhead lines (OHL) covering the time period from 2005 to 2015 (both inclusive).

The collection includes quantitative and categorical data for each span along the selected routes, including: recorded instances of defects and failures at a component level (conductor, dampers, spacers, dowel pins, jumpers, hot joints); categorical evidence of galloping (1 if observed, 0 otherwise); mechanical characteristics of both towers and spans (height, length, conductor type, diameter, linear density and tensile strength, bundle multiplicity); and geographical coordinates (Easting, Northing, tower base elevation ASL).

The data cover 3444 spans, for a total of 1161 km of length across England and Wales, and encompasses a wide range of geographical and weather environments.

The recorded instances of defects and failures did not include the date of reporting, and were only recorded as totals per span.

Weather Data

High resolution weather data were generated for the 11 years of interest using DE downscaling model, based on the WRF-ARW regional model [1].

Downscaling was done using a two-way nested grid to 9 km resolution, completely covering the landmasses of Great Britain and Ireland and the surrounding sea, as well as a subsequent one-way refinement to 3 km along each route.

The global reanalysis chosen as input for the WRF model is the NCEP Climate Forecast System (CFSR/CFS2 [2]); the downscaling model was run with a configuration that matched the parametrization of the NCEP model as closely as possible, to ensure consistency and continuity across all refinements.

For each span, time-series of all required weather variables were extracted at its mid-point and at the elevation above ground level (AGL) of the earth-wire, interpolating each variable between the four closest surrounding grid points of the 3km downscaling. Whenever a value of elevation AGL wasn't available from the data, a default of 50 m was used instead.

A further refinement was then applied to wind speeds to take into account the effect of local elevation and terrain, adopting the linear correction outlined in the ISO British Standards [3].

METHODOLOGY AND RESULTS

Turbulence

Due to the heavy computing requirements of calculating turbulence at each span location by means of a full CFD model, DE devised a simplified methodology to quickly calculate reliable turbulence values at each given point.

This methodology makes use of the OS Terrain 50 database [4] and the EEA CORINE Land Cover Database [5] to estimate the wind flow within 4 km of the location considered, and calculates a linear approximation of the expected value of turbulence at the required point from 16 directions.

The results of this method are in good agreement with the more accurate values obtained from high-resolution CFD, as confirmed through a comparison with CFD simulations for a number of sites across the UK. This comparison produces a scatter between CFD and linear model of 7.5% with a correlation coefficient of 0.86, based on 9 sites.

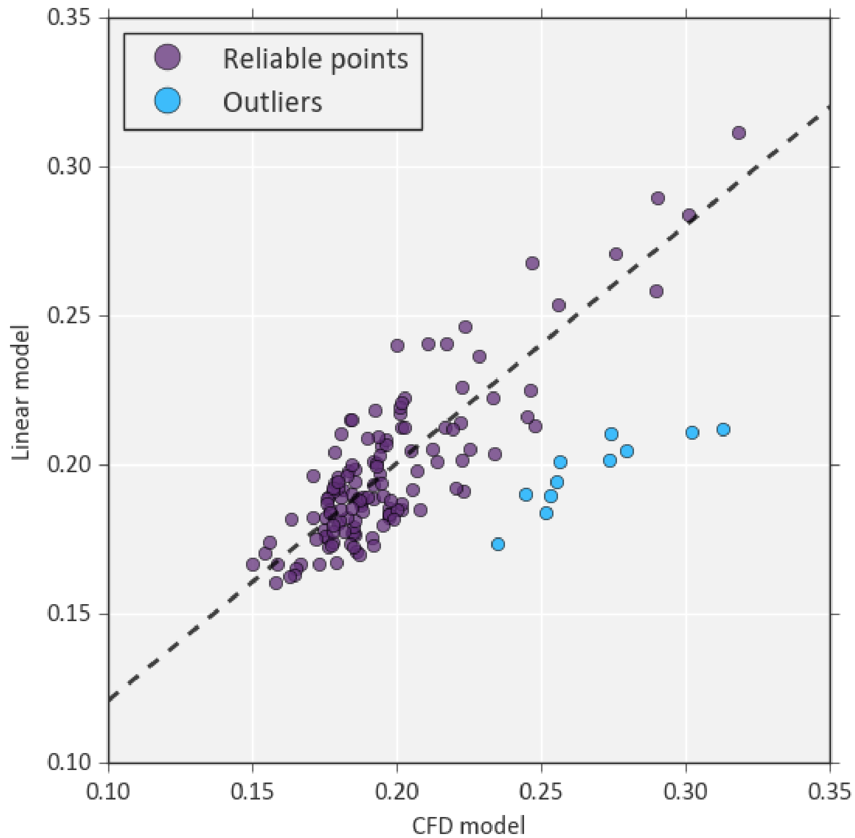

Fig. 1: Comparison of DE's linear model of turbulence and CFD. Blue points are classified as outliers to the distribution, and are found to all be sites of higher complexity. The solid line represents a linear fit to the reliable data (purple points).

Aeolian Vibration Model

Aeolian vibrations are low-amplitude, high-frequency oscillations induced by vortex shedding on a conductor; they constitute the major source of fatigue and failure on conductors and elements connected to them. The modelling of vortex shedding, and its consequences on conductor wires, has been addressed in a large number of works and publications (e.g. Blevins 1990 [6]; Williamson & Govardhan 2004 [7]).

We developed our own model of vortex shedding-induced Aeolian vibrations, based on high-resolution NWP simulations. The model combines the outputs of the NWP simulations at the span's mid-point, height and angle to the wind, with the spans' mechanical characteristics (length, linear density, diameter, tension), in order to calculate the resonant frequencies along the wire, given the laminar component of wind flow found at each time step of the simulation. This in turn is used to calculate the total number of oscillation cycles experienced by the wire, which is then ultimately converted to energy dissipated along the wire. Further refinements were also calculated, with particular emphasis on the scaling factor due to conductor bundle multiplicity, which is known to affect the spans' aerodynamic properties (cf. e.g. Shan 1997 [8]); these factors were obtained by means of clustering algorithms trained on the classification data provided by NG.

The yearly average of total dissipated energy, adequately corrected for all factors and normalized, is then used as a numerical measure of the risk of damage for each span.

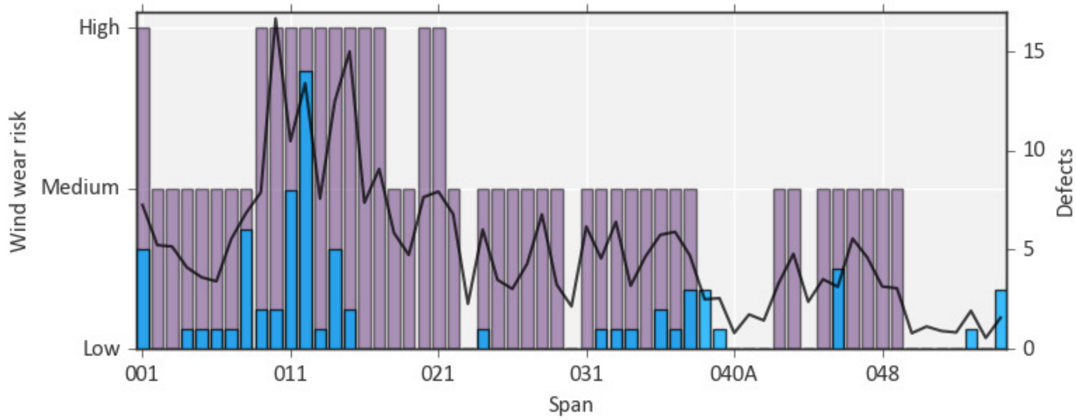

Fig. 2: Application of the Aeolian vibration model to an OHL route. The blue bars show the cumulative number of recorded defects for each span. The purple bars show the level of risk (low, medium or high) due to wind exposure, and the solid line shows the output of the wear model. The most significant cluster of defects falls in the section of the route correctly identified as having the highest risk of failure.

The data were then subset in bands as a function of the model outputs, and in each band the average rate of damage per year was calculated from the number of observed failures and defects for each span. This shows a good level of correlation between weather wear value and failure rate per span per year, and demonstrates the reliability of DE's vibration model for predicting failure risk levels for OHL assets.

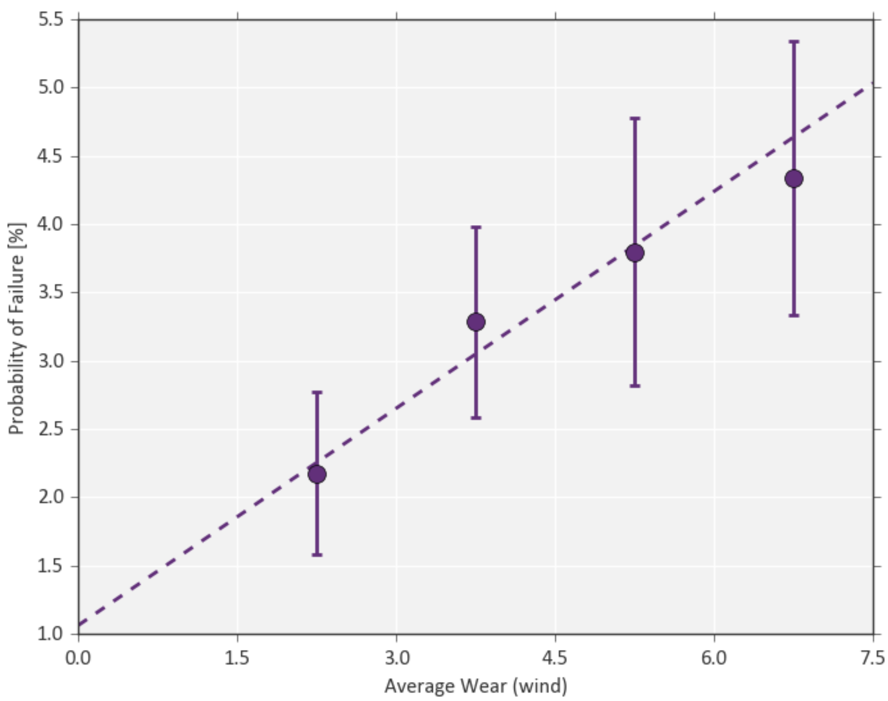

Fig. 3: Probability of failure as a function of weather wear. The purple points show the average observed rate of failure (and 1-sigma error) in a given bin of wind wear. The dashed line is a linear fit to the points.

Galloping

Galloping is a sudden, wide vertical displacement of a conductor (up to several meters in amplitude). It occurs when high wind speeds combined with an asymmetrical cross-section of the wire (usually due to ice accretion), which acts as an airfoil thus providing lift. These swings can lead to severe damage to conductors, fittings and towers, up to the complete collapse of the tower. The occurrence of galloping is therefore a complex function of wind speed and ice accretion on the conductors (cf. e.g. Lilien et al. 2006 [9]).

We modelled galloping by combining downscaled wind speeds from the NWP model, the angle between the span and the wind direction, and the presence of ice as highlighted by DE's in-house icing model (based on our downscaled NWP data and the Simple Model of ice accretion [10]). These input data were used to train a classification algorithm, which allowed us to identify the thresholds of wind speed (10 m/s), icing thickness (0.1 mm) and number of hours per year (28 hours) expected to yield an observable galloping event.

It must be noted that recorded occurrences of galloping on NG's network are so far based on anecdotal evidence (i.e. engineers witnessing an event, or evidence of major faults likely to be due to prolonged galloping);as such, spans where no galloping is recorded cannot be directly considered as true negatives, but simply as missing any record. Therefore, the classification model was configured to select the thresholds that would minimize the occurrence of false negatives.

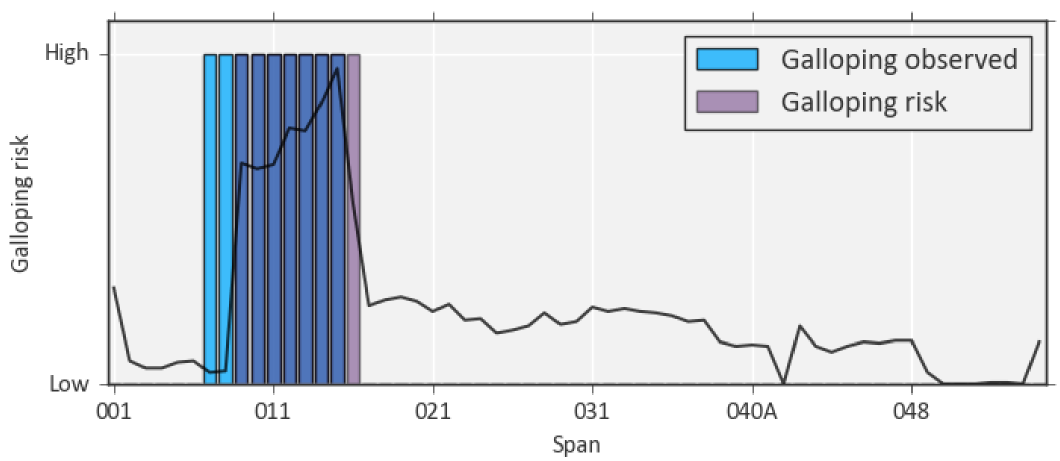

Fig. 4: Example of galloping classification applied to the same OHL route of Fig. 2. The blue bars identify the spans where galloping was observed; the purple bars show the spans where the model suggests high risks of galloping. The solid black line shows the galloping model output.

FUTURE WORK

DE is currently developing, in collaboration with NG, an integrated model of wind and corrosion wear for OHL assets. This model is based on the weather model described in this paper, coupled with DE's atmospheric corrosion model, based on a larger set of the same NWP data.

The corrosion model is based on an Artificial Neural Network (ANN) to link weather variables, concentration of pollutants, and atmospheric salinity, to derive a value of annual corrosion for several metals of relevance for OHL assets (carbon steel, aluminium, zinc, and copper).

The model was trained on data from the ICP-UNECE [11] and ISOCORRAG [12] campaigns, which include weather data and deposition rates of pollutants collected at 77 locations scattered across Europe for up to 15 years. The data are provided as yearly averages and include temperature, relative humidity, precipitation and time of wetness, plus deposition rates of sulphur dioxide and chlorides. Comparison of the model with observed data of corrosion shows a very good agreement, with a correlation of 0.95 and a standard deviation of 7.3 μm over two full orders of magnitude of corrosion values.

Application to NG's full network is under way and has already highlighted regions of interest along the routes examined, thus providing quantitative confirmation of the anecdotal information available until now.

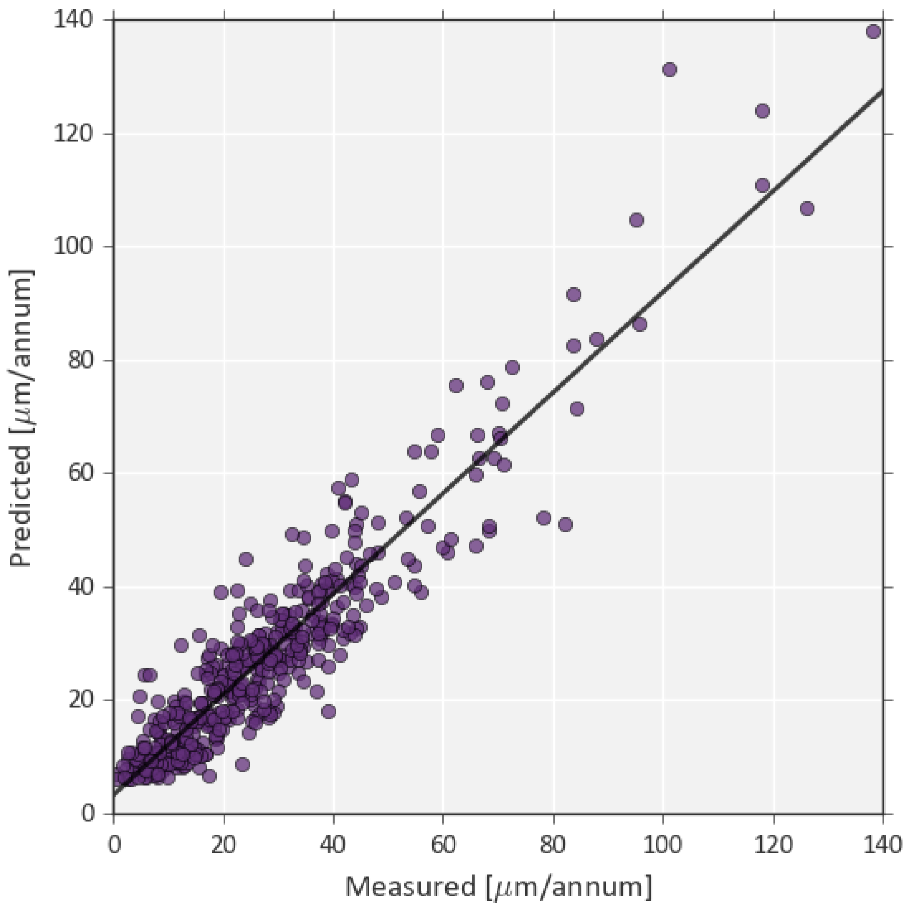

Fig. 5: Calibration of DE's atmospheric corrosion model vs. observed data from the ICP-UNECE and ISOCORRAG campaigns. The black solid line is a linear fit to the data.

BIBLIOGRAPHY

[1] W.C. Skamarock, J.B. Klemp, j. Dudhia, et al. 2008, "A Description of the Advanced Research WRF Version 3" (Tech. Note, NCAR/TN-475+STR)

[2] S. Saha, et al. 2010, "The NCEP Climate Forecast System Reanalysis" (American Meteorological Society, DOI: 10.1175/2010BAMS3001.1)

[3] BSI, 2015, "Overhead electrical lines exceeding 1 kV - Part 2-9: National Normative Aspects for Great Britain and Northern Ireland" (BS EN 50341-2-9 2015)

[4] https://www.ordnancesurvey.co.uk/business-and-government/products/terrain-50.html (Access date: 2017/08/31)

[5] https://www.eea.europa.eu/publications/COR0-landcover (Access date: 2017/08/31)

[6] R.D. Blevins, 1990, "Flow-Induced Vibration" (ISBN 10: 0442206518 / ISBN 13: 9780442206512)

[7] C.H.K. Williamson, R. Govardhan, 2004, "Vortex-Induced Vibrations" (Ann. Rev. Fluid Mech. 2004, 36:413-55, doi: 10.1146/annurev.fluid.36.050802.122128)

[8] L. Shan, 1997, "Wind tunnel study of drag coefficients of single and bundled conductors" (EPRI TR-108969, December 1997)

[9] J.-L. Lilien et al., 2006, "State of the art of conductor galloping" (EPRI RP 792, Task Force B2.11.06)

[10] K. Jones, 1998, "A simple model for freezing rain ice loads" (Atmospheric Research 1998, 46:87-97, DOI: 10.1016/S0169-8095(97)00053-7)

[11] UN/ECE International Cooperative Programme on Effects on Materials Including Historic and Cultural Monuments, Report n. 01: Technical Manual; Swedish Corrosion Institute: Stockholm, Sweden, 1988.

[12] D. Knotkova, K. Kreislova, S.W.J. Dean, 2010, "ISOCORRAG. International Atmospheric Exposure Program: Summary of Results" (ASTM:West Conshohocken, PA, USA, 2010)