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ELECTROMAGNETIC DESIGN & COMPARISON OF HIGH-POWER WIND TURBINE GENERATORS

DID YOU KNOW
Wind turbines generated 40% of UK electricity in December 2023, more than any other source including gas

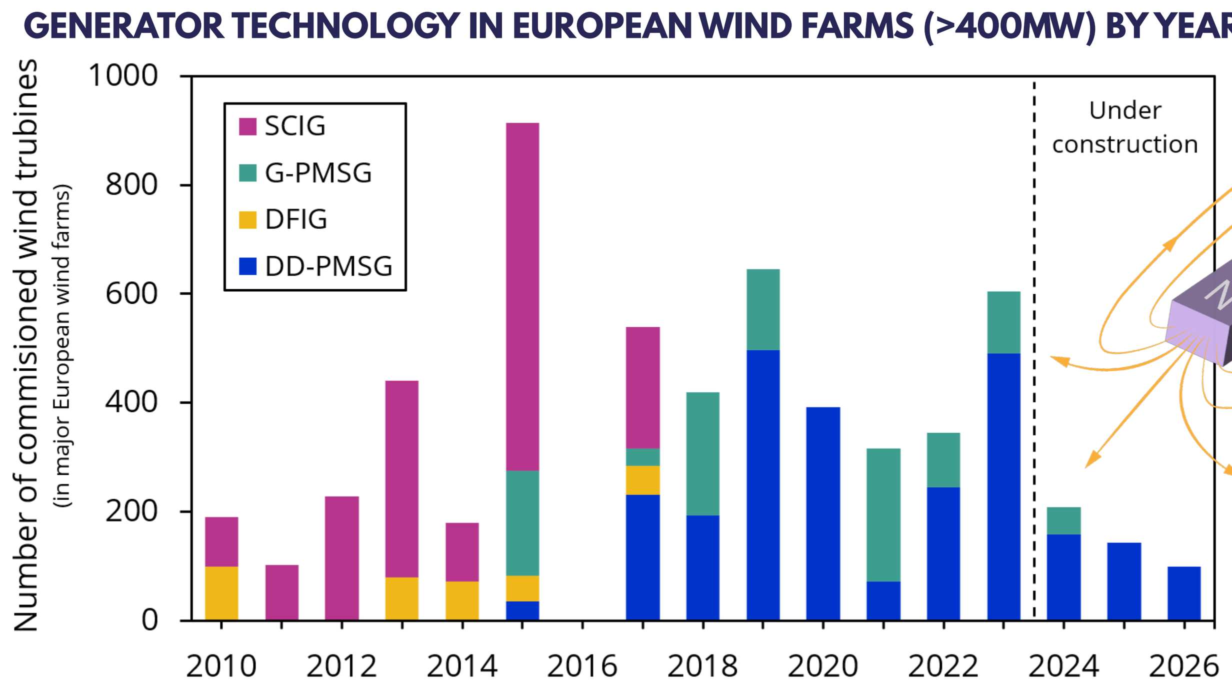
1) BIGGER, BETTER?

Wind turbines are a significant renewable energy resource which have increased in average rated power by ~380% since 2010.

As wind turbines move further offshore, and global challenges put pressure on sustainability and costs, it's crucial to maintain its low levelised cost of energy (LCOE). In the 2022 Contract for Difference (CfD) UK auctions, the agreed electricity generation price for offshore wind projects was £44/MWh, ~9 times cheaper than from gas [1].

The drive-train (with generator) is estimated to cost up to 25% of the total wind turbine capital cost and is also one of the most likely components to fail [2]. Therefore, design focus on this crucial component is paramount with new challenges for wind.

GENERATOR TECHNOLOGY IN EUROPEAN WIND FARMS (>400MW) BY YEAR



2) THE PMSG PROBLEM

Permanent magnet synchronous generator (PMSG) have been favoured for >6MW wind turbines since 2017.

However, **the PMSG technology has its drawbacks and risks,** so it might not be the most sustainable, efficient or cost effective solution across the board, such as in floating wind platforms and in developing markets.

Satellite view of the Bayan Obo rare-earth mineral mine, China Inner Mongolia Region. It produced 45% of global rare-earths in 2019 [3, 4].

The site has increased desertification. Cases of skeletal fluorosis & chronic arsenic toxicity are high locally, and 70,000 tons of radioactive thorium waste was detected in groundwater [5].

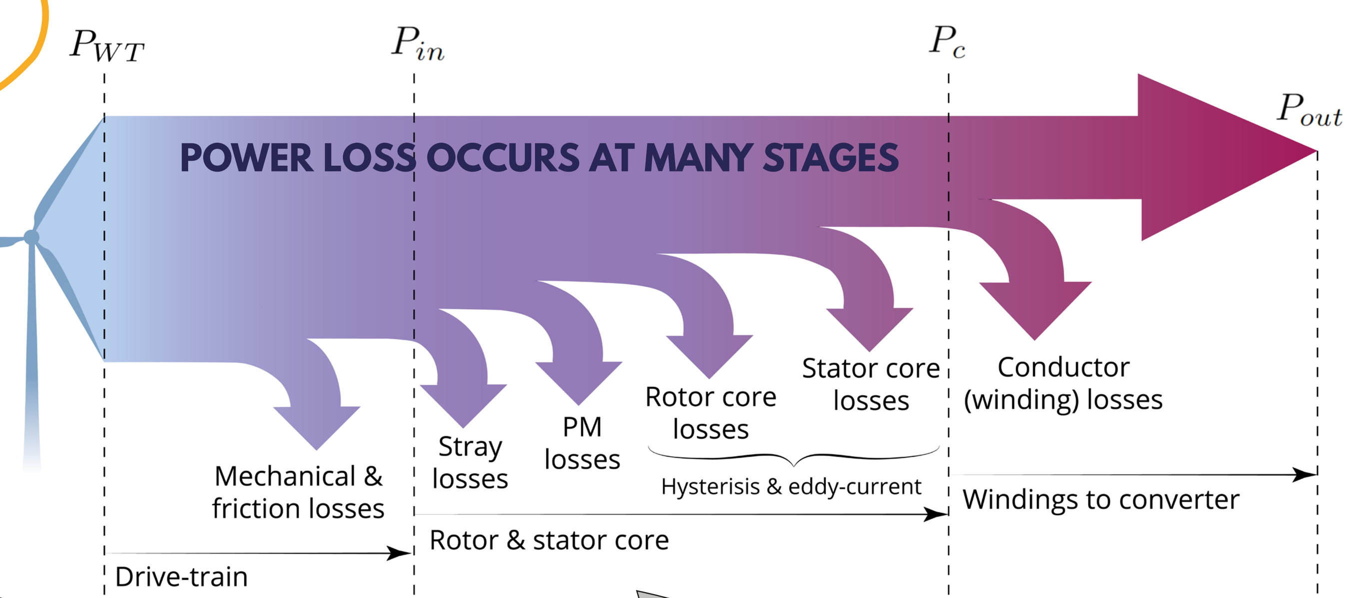
REVIEWING THE COMMERCIALLY PREFERRED GENERATOR

The Good
- High power density
- Gearbox not required
- Brush-less rotor

The Bad
- High capital cost
- Failure risk of fully-rated converter(s)
- Strict temperature limits
- High mass and radius when direct-drive

The Ugly
- Very high cost rare-earth, Neodymium Iron-Boron (NdFeB), permanent magnets which are environmentally, geopolitically and ethically problematic

DID YOU KNOW
The 14MW Haliade-X wind turbine is 3x the height of Durham Cathedral and could solely provide half of Durham City's residential electricity demand

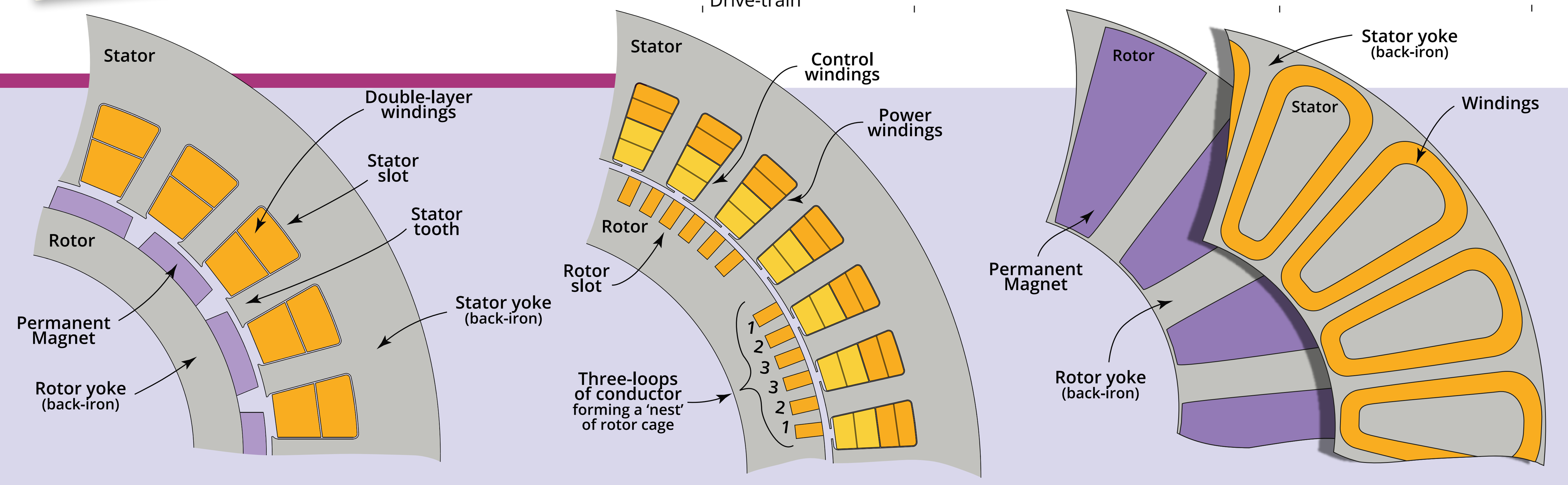


3) ALTERNATIVE GENERATORS

Alternative and unconventional types of generator demonstrate advantages for implementation in high power wind turbines, and could get around some of the aforementioned issues.

Two of the generators of interest and investigated as part of this research are the brushless doubly-fed induction generator (BDFIG) and variations of the axial-flux synchronous generator (AFSG).

These generators do not require rare-earth permanent magnets because the BDFIG is electrically excited and brushless (no brushes or slip rings), and the AFSG—and an adapted PMSG—have a different magnet design which uses flux-concentrating. This allows cheaper and sustainable ferrites to be utilised instead of NdFeB magnets. A challenge with unconventional designs is keeping the power density and efficiency competitive.



SURFACE MOUNTED PERMANENT MAGNET SYNCHRONOUS GENERATOR (SM-PMSG)

BRUSHLESS DOUBLY-FED INDUCTION GENERATOR (BDFIG)

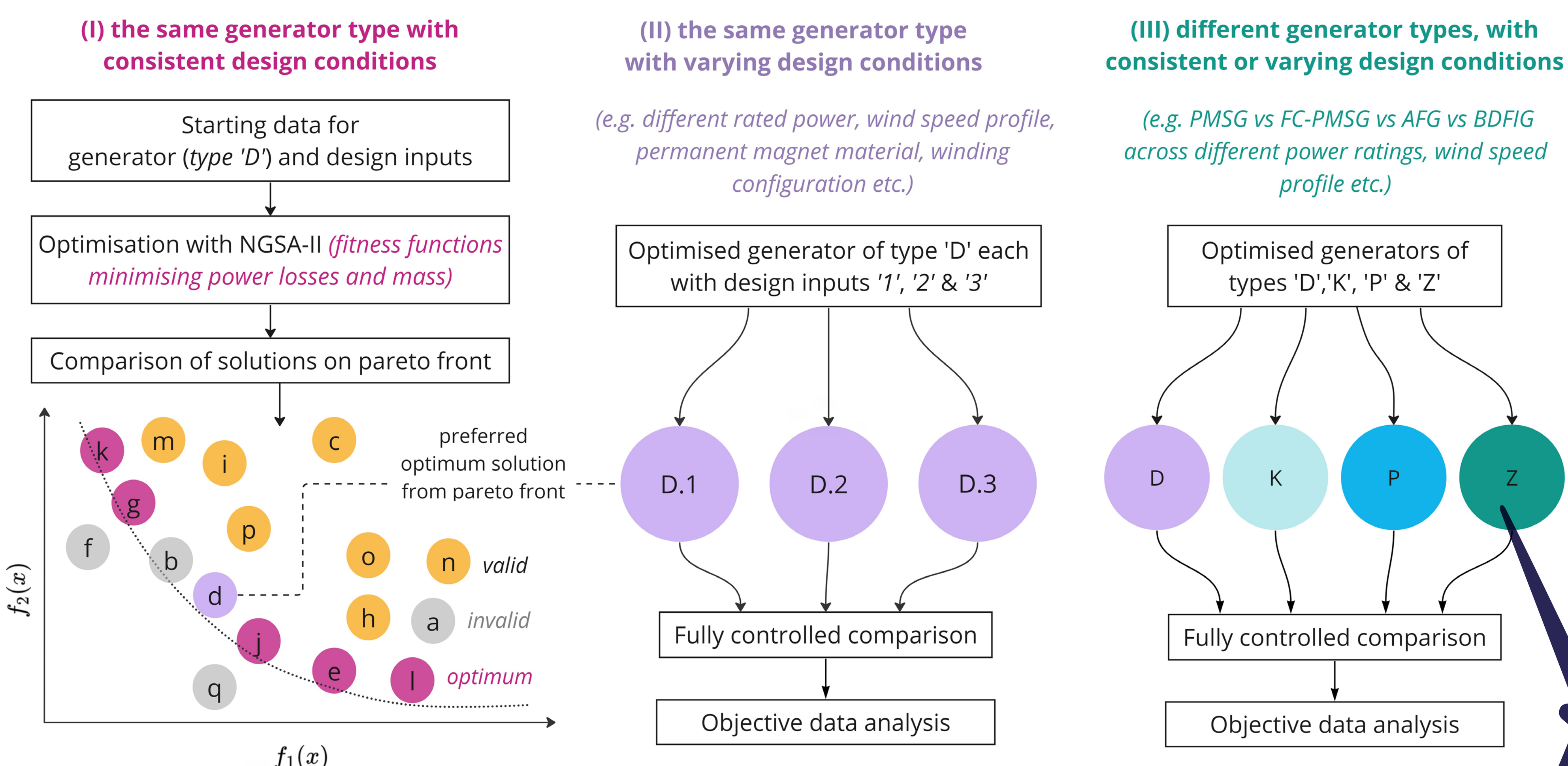
AXIAL-FLUX SYNCHRONOUS GENERATOR (AFSG)

4) THE METHOD MATTERS

There are limited quantitative generator comparison studies specific to wind turbines. **To allow for better-informed and time-efficient comparison of high-power wind turbine generators, an expansive design, optimisation and modelling platform has been developed.**

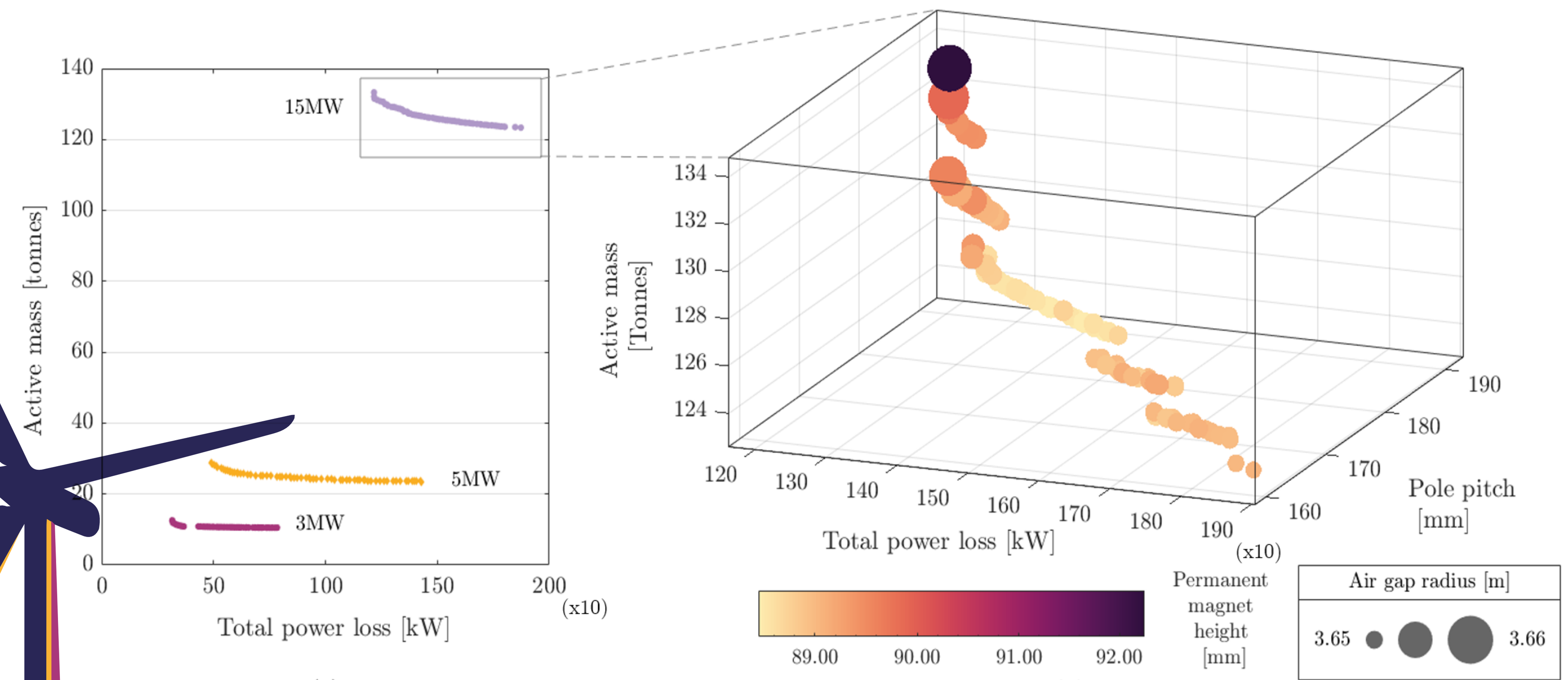
This approach objectively provides analytical insights and differences in electrical, magnetic and structural areas. It is also important for UK research and start-ups, given that **the vast majority of information about the design and operating parameters of commercial generators is restricted by manufacturers and operators.**

THE THREE MODES OF GENERATOR COMPARISON USED



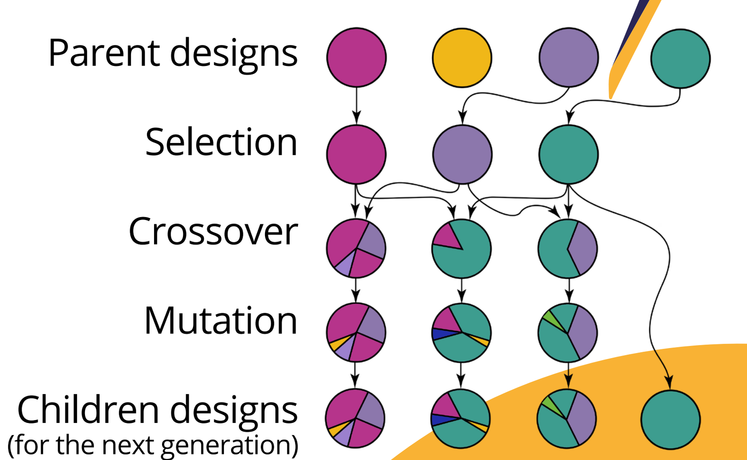
Exhaustive finite element analysis (FEA) software is not required but is used to automatically construct and scrutinise solutions. Results confirm that generator mass and performance does not scale linearly with rated power. This ties into a major challenge in the design of wind turbine generators >15MW, where magnetic steel saturation in the teeth occurs as it reaches its magnetic and current loading limits. Inequality constraint violations thus become far more prevalent, meaning more designs are infeasible, producing discontinuous pareto fronts.

ANALYSIS OF PERMANENT MAGNET GENERATORS WITH INCREASING RATED POWER

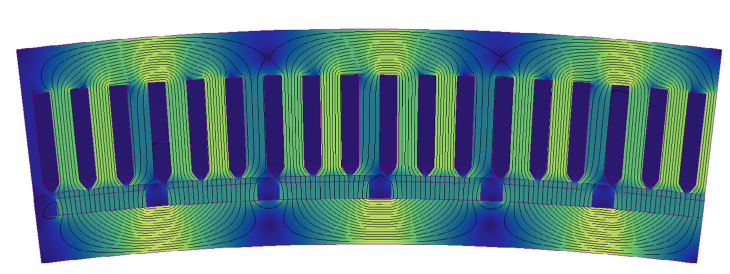


USING DARWIN'S THEORY OF EVOLUTION TO OPTIMISE GENERATORS

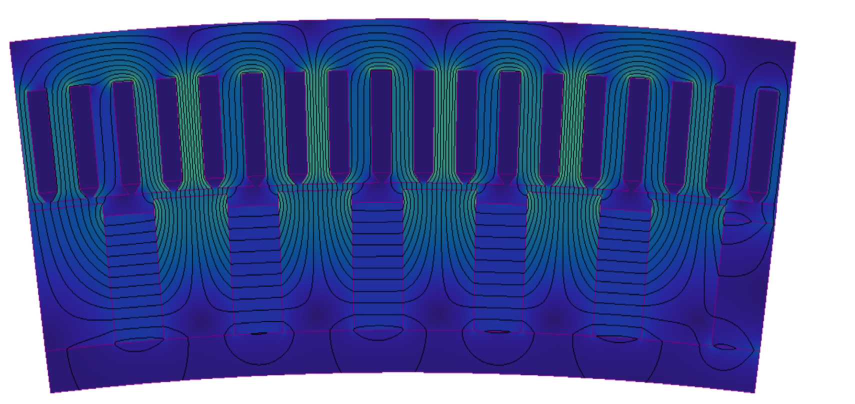
Generator design is a complex multi-physics problem with no perfect solution, so a number of crucial parameters, like air gap radius and current density, are guided as part of a constrained multi-objective optimisation problem. **The optimisation approach used is a type of genetic algorithm** (known as the NSGA-II) which is based on Darwin's Theory of Evolution, survival of the fittest.



MAGNETIC FLUX DENSITY PLOTS (USING FEA) TO REVIEW GENERATOR DESIGNS



PMSG with surface-mounted rare-earth NdFeB magnets (light green = stronger magnetic field, 0-2T)



PMSG with flux-concentrating ferrite (C11) magnets

WANT TO FIND OUT MORE ABOUT THE RESEARCH? DROP ME AN EMAIL OR MESSAGE ON LINKEDIN!

References:

[1] 'UK offshore wind 2023 round-up and 2024 outlook', ORE. Accessed: 3 Feb 2024. [Online]. Available: https://ore.catapult.org.uk/blog/uk-offshore-wind-2023-round-up-and-2024-outlook/

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