Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT

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SECTION 1: PROJECT DETAILS

Project Title	Enhanced Controllers to improve Wind Farm Efficiency
Lead Grantee (Organisation)	Trinity College Dublin
Lead Grantee (Name)	Breiffni Fitzgerald
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Report Submission Date	24/10/2023

	Name	Organisation
Project Partner(s)	Malabika Basu	TU Dublin
Collaborators		

Project Summary (max 500 words)

In this project we have created novel wind farm aerodynamic models and developed and experimentally tested new wind farm controllers that improve the efficiency of wind farms and account for turbulent effects in the wake.
The effects of rapidly changing wake aerodynamics due to turbulence has been considered in the wind farm models and controllers.
We have simulated, in real-time, the interaction of the controlled wind farms with the electrical grid and have demonstrated the improved performance of wind farms with our new technologies.
We have also studied the effects of our controllers on different O&M strategies for wind farms.

Traditionally the power output of each turbine in a wind farm is controlled independently. In this project our new controllers utilise hardware already installed on wind turbines (i.e. sensors, pitch controllers and PE devices) to enable individual turbines to cooperate with each and thus optimise the wind farm's overall performance.

A Model Predictive Control scheme was developed to optimise the performance of the wind farm.

Various wind turbine and wind farm scenarios and grid interactions were simulated and studied in a real time system.
The overall aims were to increase the efficiency/wind farm energy yield, to increase wind turbine availability and to investigate extended wind farm life due to enhanced O&M practices.

Keywords (min 3 and max 10)	Wind Farm, Wind Turbine, Control

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION	(max 10 pages)

2.1 Executive Summary

This project modelled, developed and experimentally tested novel wind farm controllers to improve the efficiency of the existing fleet of Irish wind farms accounting for turbulent effects in the wake. The effects of rapidly changing wake aerodynamics due to turbulence were considered in the wind farm models and controllers. The project simulated, in real-time, the interaction of the controlled wind farms with the Irish electrical grid and demonstrated increased wind farm energy yield from the existing fleet of Irish wind farms. The impact of the developed controllers on O&M strategies for wind farms were also be investigated.

This project simulated and studied various wind turbine and wind farm scenarios in a real time system. The new controllers were modelled and demonstrated using authentic wind farm data from real wind farms. The aim of the project was to increase the efficiency of Ireland's existing fleet of wind farms to obtain increased wind farm energy yield, increased wind turbine availability and longer wind farm life due to enhanced O&M practices.

2.2 Introduction to Project

Traditionally the power output of each turbine in a wind farm is controlled independently. In this project novel controllers will be developed utilising hardware already installed on the wind turbines (i.e., yaw controllers, pitch controllers, torque controllers and power electronic devices) and they will cooperate with each other to optimise the wind farm's overall performance rather than optimising each turbine's individual performance. A Model Predictive Control scheme will be developed to optimise the performance of the wind farm.

2.3 Project Objectives

This project's objectives targeted fundamental innovations in an area related to reliability and security of energy supply. This project built on the work that was pioneered by the project partners on aerodynamic and power electronic based controllers for wind turbines and wind farms. The scientific and technological objectives of the project were:

- To develop new (beyond state of the art) wind farm models considering turbulence models.
- To develop new wind farm controllers using a novel cooperative model predictive control algorithm.
- To develop a beyond state-of-the-art hybrid-model-data based O&M strategy for operational wind farms.
- To analyse the impact of the new controllers on wind farm O&M.
- To use real wind farm data and real-time simulation of the wind farms and the Irish grid to demonstrate increased energy yield and wind turbine availability due to the developed controllers.
- To disseminate the work widely and share data generated to encourage further studies and future collaborative research project at a national and international level.

Table 1 Summary of Project Objectives

No:	Objective Description:
1.	Develop novel wind farm models considering rapid distortion turbulence models and data from real wind farms

2.	Develop new wind farm controllers using a novel cooperative model predictive control algorithm considering wake effects and wind farm behaviour. Objective of controller is to increase wind farm electricity output.
3.	Simulate new controllers on real wind farms and compare results with standard wind farm controllers, refine controllers to achieve increased wind farm efficiency.
4.	Develop new hybrid-model-data based O&M strategy for operational wind farms and analyse the impact of the new controllers on wind farm O&M.
5.	Use real wind farm data and real-time simulation of the wind farms and the Irish grid to demonstrate increased energy yield and wind turbine availability due to the developed controllers.
6.	Disseminate the work widely and share data generated to encourage further studies and future collaborative research project at a national and international level.

The research activities in this project were grouped into four broad themes, corresponding to the four scientific work packages (WP2-WP5). The wind farm models and controllers were developed in WP2 and WP3 respectively. The impact of the controllers on O&M was assessed in WP4 and the controllers will be experimentally verified and tested in real-time simulations in WP5. WP1 focussed on project management and WP6 focussed on communicating the project results. Table 2 summarises the work packages.

Table 2 Work Packages

No.	Title
1	Project Management
2	Development of Wind Farm Models Including Rapidly Distorting Turbulent Wakes
3	Development of Cooperative Model Predictive Controller for Wind Farms
4	O&M Strategies for Wind Farms
5	Real-time Implementation and Demonstration of Wind Farm Controllers
6	Communication and Public Engagement

2.4 Summary of Key Findings/Outcomes

The innovations developed in each technical work package are outlined in this section.

WP2 - Development of wind farm models including rapidly distorting turbulent wakes.

- Innovation 1: Development of wind farm models for laminar flow

  A fully functional flow model with constant vorticity has been developed. Results from the model showing complex flow patterns in a wind farm are shown in Figure 1.

  Advantages of the laminar flow model:

  - Eliminates the need for modelling the complicated geometry of wind turbine blades and yet incorporates their effects to get a better approximation of the wind field and hence the power production.

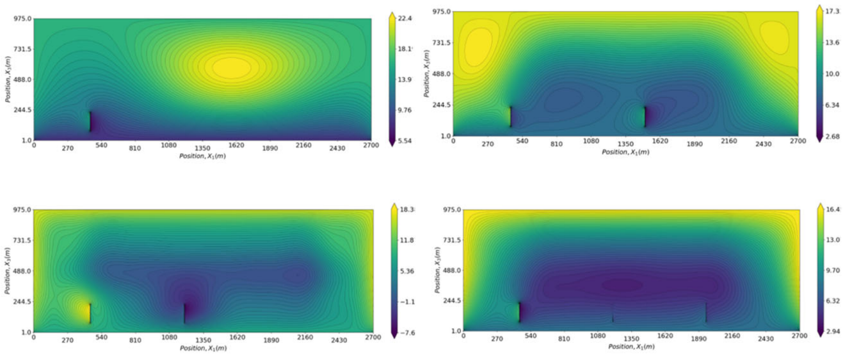

Figure 1 Laminar flow model results[1]

- Innovation 2: Development of parallel numerical algorithms for wind farm simulations.
  - Developed algorithms using Computational Fluid Dynamics (CFD) and Decomposed Immersed Interface Method (DIIM) coupled with existing analytical models to estimate the wind field in a wind farm.
  - Algorithms incorporate the advantage of parallel numerical algorithms & hence, can be used for multi-core simulation for large wind farms.

- Innovation 3: Development of wind farm models including turbulent wakes.
  - Incorporated turbulence into wind farm models, see simulation results in Figure 2. Considers steady flow only.

$$\frac{\partial V_j}{\partial t} + \underbrace{V_k \frac{\partial V_j}{\partial X_k}}_{\text{Advection}} = \underbrace{-\frac{1}{\rho}\cdot\frac{\partial P}{\partial X_j}}_{\text{Source}} + \underbrace{\nu \frac{\partial^2 V_j}{\partial X_k \partial X_k}}_{\text{Diffusion}} \quad \xrightarrow{\text{Linearized}} \quad \frac{\partial v_j'}{\partial t} + (1+\kappa)\left(\overline{V}_k \frac{\partial v_j'}{\partial X_k} + v_k' \frac{\partial \overline{V}_j}{\partial X_k}\right) = -\frac{1}{\rho}\cdot\frac{\partial p'}{\partial X_j} + \nu \frac{\partial^2 v_j'}{\partial X_k \partial X_k}$$

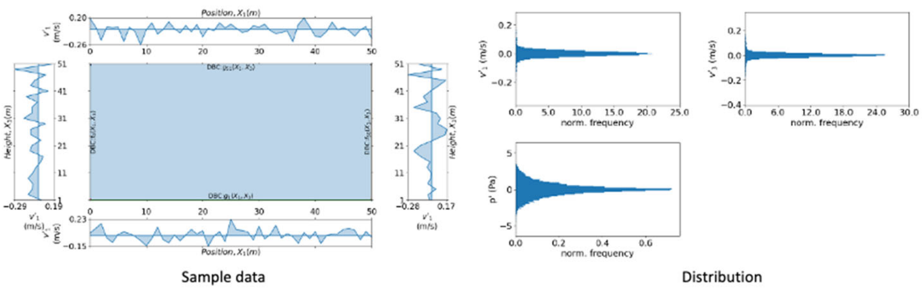

Figure 2 Turbulent Wind Farm simulation

<u>WP3 - Development of cooperative model predictive controller (MPC) for wind farms.</u>

- Innovation 4: Co-operative model predictive controller (MPC) developed for wind farms with advanced aerodynamic model.

  A comprehensive generalised inverter control scheme was developed which is applicable to renewable energy sources for grid-connected/standalone applications. Based on a generalised extrapolation technique, the selection of an optimised

[1] Basu, S. L., Soodhalter, K. M., Fitzgerald, B., & Basu, B. (2022). Flow in a large wind field with multiple actuators in the presence of constant vorticity. *Physics of Fluids*, *34*(10).

switching sequence has been applied to reduce the computational burden for calculating switching pattern. See Figure 3 for details.

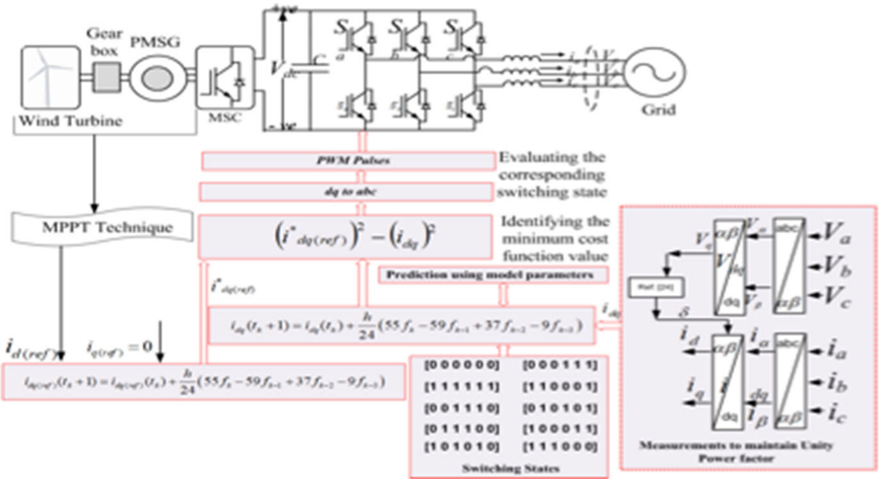

Figure 3 Cooperative MPC for wind farms

- Innovation 5: Co-operative model predictive controller with advanced aerodynamic wake model (including turbulence) implemented on wind farms and results compared with base controllers.

  Implementation of the proposed scheme up to four sample ahead proves to retain the desired quality of prediction. A comprehensive robustness test of the system under different situations such as load variation, computational delays and changes in parameters has been carried out, and further stability analysis has been performed.

WP4 - O&M Strategies for Wind Farms.

- Innovation 6: Development of Realtime experimental model compatible with OPAL_RT and impact assessment.

  OPAL-RT simulation model developed combining the wake effects and parameter uncertainty data into the developed MPC model.

- Innovation 7: Development of Condition Monitoring scheme for O&M of wind turbine generators.

  Hybrid Gaussian process regression and Fuzzy Inference System based approach developed for condition monitoring at the rotor side of a doubly fed induction generator[2]. See Figure 4 for fault classification.

[2] Zhang, S., Robinson, E., & Basu, M. (2022). Hybrid Gaussian process regression and Fuzzy Inference System based approach for condition monitoring at the rotor side of a doubly fed induction generator. Renewable Energy, 198, 936-946.

Performance evaluations under the hybrid approach (excluding drift faults)

Fault types	Accuracy	Dependability	Security	Response time
Healthy	100%	-	100%	-
Short circuit	99.74%	99.48%	-	12ms
Open switch in phase a	98.70%	97.40%	-	31ms
Open switch in phase b	98.96%	97.92%	-	28ms
Open switch in phase c	98.70%	97.40%	-	31ms
Rotor unbalance in phase a	98.45%	98.44%	-	22ms
Rotor unbalance in phase b	97.94%	97.92%	-	26ms
Rotor unbalance in phase c	98.19%	98.43%	-	25ms
Sensor fault in phase a	98.84%	98.44%	-	23ms
Sensor fault in phase b	98.45%	97.91%	-	27ms
Sensor fault in phase c	98.58%	98.09%	-	26ms

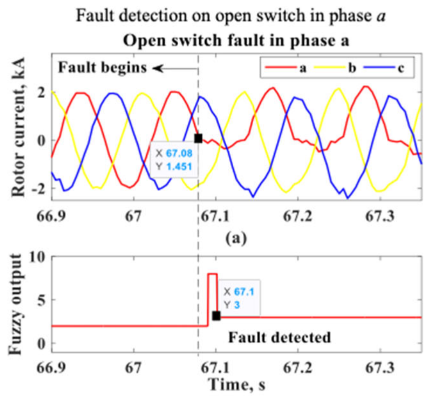

Figure 4 Condition monitoring approach

WP5 - Real-time Implementation and Demonstration of Controllers.

- Innovation 8: Development of Realtime simulator for wind farm model with controller.

The system was simulated using a Windows computer with 16GB of RAM and a 2.2GHz CPU on the MATLAB/Simulink platform. The complete list of parameters used in the simulation model is given in the Table 1.

Table 3 Parameters used in real-time simulation.

Column heading	Column heading two
3 phase Inverter	1*MW*
V_{DC}	700*V DC*
Grid Voltage	440*V AC*
Filter Inductance (L)	100*mH*
IGBT Voltage rating	1200*V*
IBGT Current rating	100*A*
Switching frequency	20*kHz*

The reference signal was perfectly tracked by the predicted signal at all the instances, and its results are shown in Figure 5.

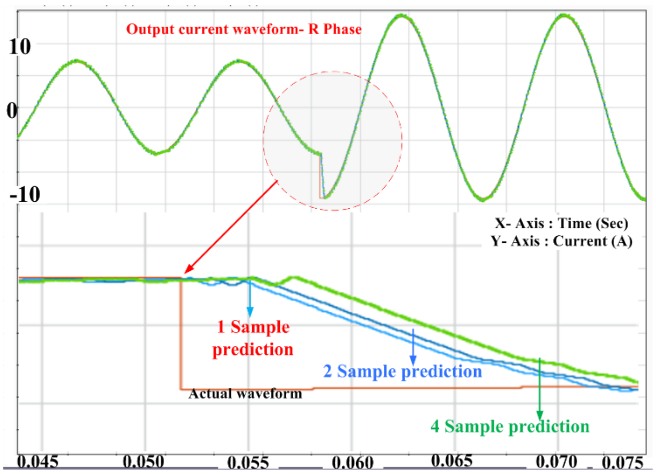

Figure 5 Simulation results of a three-phase inverter with 1, 2 and 4 sample prediction

- Innovation 9: Implementation and Demonstration of Realtime simulator for wind farm model with controller.

  The system has been tested and found to have satisfactory performance. In terms of closed-loop stability, the system is entirely stable until the control delay of 80 μS and four sample predictions. The conclusion is that the controller is so straightforward, efficient and quick enough to tackle real-life challenges.

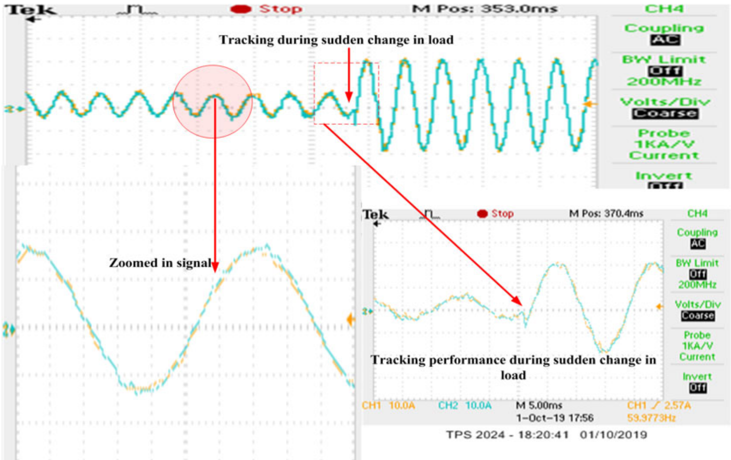

Figure 6 Real-time analysis of proposed scheme at sudden load changes and transient conditions.

2.5 Project Impact

Potential future impact for Irish energy sector and beyond

Irish wind farms will play a big role in helping Ireland to achieve its energy targets and limiting Ireland's exposure to the large costs associated with missed targets. The Irish energy sector will need to use innovative means to achieve its targets. The outputs of this project can contribute to achieving this:

This project has developed and experimentally tested novel wind farm controllers that improve the efficiency of wind farms. Using the controllers could increase the energy efficiency of Ireland's energy system and provides a low cost, sustainable option to reducing Ireland's exposure to costs from not meeting targets.

The models and control algorithms developed are available for industry/academia to use in an open source format. All papers describing the development of these models/algorithms are also free publicly available.

Sustainability of the work

The new controllers developed in this project utilise existing hardware that is already installed on wind turbines (sensors, PE devices). The project is therefore a sustainable and low-cost technology that can be readily applied to the existing fleet of Irish wind farms.

Security of supply

Ireland is heavily dependent on imported fossil fuels, a situation that the current conflict in Ukraine has highlighted. As such a large contributor to overall RES-E performance (>80%), any fleet-wide efficiency improvements to Irish wind farms will be significant, this project is this well placed to improve Ireland's energy security.

Potential for new research/wider partnerships established

The consortium is involved in several projects with an emphasis on onshore and offshore wind and integration of renewables to the grid. These projects include several international wind energy industry and research partners. This project has been a key enabling work and has led to other successful projects.

The research group at TCD has been funded by Science Foundation Ireland (SFI) under the Frontiers for the Future programme to develop new wind farm controllers using a data-driven approach. This new SFI project would not have been possible without the background work on wind farm modelling that took place in this project.

The TCD PI is now a Funded Investigator in SFI's new all-island, multidisciplinary energy research programme NexSys. NexSys will investigate new wind turbine and wind farm controllers for offshore wind. This is also logical follow in project from this project too.

Following work on this project the research team at TCD have been appointed by the International Energy Agency (IEA) to serve as Ireland's international experts on Wind Farm Control in IEA Wind Task 44. At Task 44, work from this project has been discussed with Dr Paul Fleming (NREL, USA) and Prof. Jan- Willem van Wingerden (TU Delft) and future collaborations are being planned. These partners are at the forefront of their fields and this project is a key enabling work that links the fields of aerodynamic control, structural dynamics, wind farm control and grid integration.

The project has therefore enhanced the project team's potential to participate in international consortia with world experts that would be competitively placed to wind large scale non-exchequer funding.

In May 2022 TCD was accepted to join the European Academy of Wind Energy (EAWE). This is a prestigious group of leading academic and research institutions involved in wind energy research. Work from this project was presented to EAWE as part of the application process.

This project has added to the R&D landscape in Ireland and has demonstrated our national capacity and capability to carry out internationally leading research in the wind energy field.

This project has enabled teams at TCD and TU Dublin to develop the critical mass required to carry out internationally leading research in wind energy.

2.6 Recommendations

The project, involving novel wind farm aerodynamic models and wind farm controllers, has several important implications, opportunities, and recommendations for Ireland:

<u>Implications:</u>

1. Improved Wind Farm Efficiency: The project's findings suggest that the new wind farm controllers and aerodynamic models can significantly enhance the efficiency and energy yield of wind farms. This can have important implications for Ireland's renewable energy goals, contributing to a more sustainable and greener energy mix.

2. Grid Integration: The real-time simulation of wind farm interactions with the electrical grid is a valuable aspect of the project. This information can help policymakers and grid operators in Ireland to plan and optimize the integration of wind energy into the national grid, ensuring a stable and efficient supply.

3. O&M Enhancement: The study of the effects of wind farm controllers on different Operations and Maintenance (O&M) strategies is significant. Improved O&M practices can lead to better turbine availability and extended wind farm life, reducing downtime and maintenance costs.

Opportunities:

1. Exporting Expertise: Ireland can leverage its expertise in wind farm optimization and control to export this knowledge to other countries. This can potentially generate revenue through consulting, technology licensing, and collaboration with international wind energy projects.

2. Investment in Wind Energy: The positive outcomes of this project make a strong case for continued investment in wind energy infrastructure in Ireland. This can attract both domestic and foreign investment, creating job opportunities and boosting the renewable energy sector.

3. Research and Innovation: The project highlights the importance of ongoing research and innovation in the field of wind energy. Encouraging further research, particularly in collaboration with academic institutions and industry, can lead to more breakthroughs and advancements.

Recommendations:

1. Policy Support: Policymakers should consider implementing policies and incentives that promote the adoption of the newly developed wind farm controllers and aerodynamic models in existing and future wind farms. This can include subsidies, tax incentives, or regulatory changes that encourage wind farm operators to invest in these technologies.

2. Industry Collaboration: Encourage collaboration between the wind energy industry and research community. Joint efforts can help accelerate the deployment of innovative technologies and ensure that research findings are practically implemented.

3. Grid Modernisation: Invest in grid modernization to accommodate the increased integration of wind energy. This involves upgrading the electrical grid infrastructure to handle fluctuations in renewable energy supply more effectively.

4. Skill Development: Invest in education and training programs to build a skilled workforce capable of maintaining and operating wind farms with the new controllers and technologies.

5. Data Sharing: Encourage the sharing of data and best practices among wind farm operators in Ireland to optimize wind farm performance collectively.

In summary, the project's outcomes offer Ireland the opportunity to enhance its wind energy sector, increase energy efficiency, and contribute to its sustainability goals. Policymakers, researchers, and industry stakeholders should collaborate to ensure the effective implementation of these advancements in the wind energy sector.

2.7 Conclusions and Next Steps

The project's conclusions indicate that the development and testing of new wind farm controllers and aerodynamic models have the potential to significantly enhance wind farm efficiency, grid integration, and overall energy yield while mitigating turbulence effects and improving Operations and Maintenance (O&M) practices. The next steps should involve scaling up the implementation of these technologies in operational wind farms across Ireland, with a focus on policy support and incentives to encourage adoption, fostering collaboration between industry and research communities, and ongoing research to further refine and optimize these innovations. This will not only contribute to Ireland's renewable energy objectives but also position the country as a leader in wind energy technology and grid integration.