A NUMERICAL STUDY OF RECOVERY PROCESSES IN OFFSHORE WIND FARMS

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by

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Dedicated to my Mother and Tai Ji

Certificate

This is to certify that the thesis entitled "**A Numerical Study of Recovery Processes in Offshore Wind Farms**" being submitted by **Ms. Tanvi Gupta** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of original bona fide research carried out by her. Ms. Tanvi Gupta has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

(Prof. Somnath Baidya Roy)

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Abstract

Wind turbines in a wind farm extract energy from the atmospheric flow and convert it into electricity, resulting in a localized momentum deficit in the wake that reduces energy availability for downwind turbines. Atmospheric momentum convergence from above, below, and the sides into the wakes replenishes the lost momentum, at least partially, so that turbines deep inside a wind farm can continue to function. In this thesis, I quantitatively explore the behaviour and recovery processes in a hypothetical deep offshore wind farm and a coastal offshore wind farm under sea breeze conditions.

The particular emphasis in this study is on comparing the spatial patterns and magnitudes of horizontal- and vertical-recovery processes and understanding the role of mesoscale processes in momentum recovery in offshore wind farms. For this purpose, I use the Weather Research and Forecasting (WRF) model, a state-of-the-art mesoscale model equipped with a wind turbine parameterization, to simulate the dynamics and thermodynamic of atmospheric flow within and around hypothetical offshore wind farms with different wind turbine spacings under realistic initial and boundary conditions. The wind farms consist of wind turbines with 84 m hub heights, 112 m rotor diameter (D), and rated capacity of 3.075 MW. Different inter-turbine spacings range from a densely packed wind farm (case I: low inter-turbine distance of 0.5 km ~ 5 rotor diameter) to a sparsely packed wind farm (case III: high inter-turbine distance of 2 km ~ 20 rotor diameter).

First, I study a wind farm located deep offshore where the atmospheric flow is not directly influenced by land masses. Apart from the inter-turbine spacings, I also explore the role of different ranges of background wind speeds over which the wind turbines operate, ranging from a low wind speed range of 3–11.75 ms^{-1} (case A) to a high wind speed range of 11–18 ms^{-1} (case C). Results show that vertical turbulent transport of momentum from aloft is the main contributor to recovery in deep offshore wind farms except in cases with high-wind-speed range and sparsely packed wind farms, where horizontal advective momentum transport can also contribute equally. Vertical recovery shows a systematic dependence on wind speed and wind farm density that is quantified using low-order empirical equations. Wind farms alter the mesoscale flow patterns, especially for densely packed wind farms under high-wind-speed conditions. In these cases, the mesoscale circulations created by the wind farms can transport high-momentum air from aloft into the atmospheric boundary layer (ABL) and thus aid in recovery in wind farms.

Most of the current offshore wind installations are located in coastal regions where they are often affected by sea-breezes. Hence, I further quantitatively study the behaviour and recovery processes for coastal offshore wind farms under sea-breeze conditions. I use a modified Borne’s method to identify sea breeze days off the west coast of India in the Arabian Sea. For the identified sea breeze days, I simulate a hypothetical wind farm covering 50 x 50 km^2 area using the Weather Research and Forecasting (WRF) model, again driven by realistic initial and boundary conditions. I use three wind farm layouts with the turbines spaced 0.5 km, 1 km, and 2 km apart. The results show an interesting power generation pattern with a peak at the upwind edge and another peak at the downwind edge due to sea breeze. Wind farms affect the circulation patterns, but the effects of these modifications are very weak compared to the sea breezes. Vertical recovery is the dominant factor with more than half of the momentum extracted by wind turbines being replenished by vertical turbulent mixing. However, horizontal recovery can also play a strong role for sparsely packed wind farms. Horizontal recovery is stronger at the edges where the wind speeds are higher whereas vertical recovery is stronger in the interior of the wind farms.

To the best of my knowledge, this is one of the first studies to look at wind farm replenishment processes under realistic meteorological conditions including the role of mesoscale processes. Also, this study for the first time examines replenishment processes in offshore wind farms under sea breeze conditions. Overall, this study makes a significant contribution in advancing our understanding of recovery processes in wind farms and wind farm–ABL interactions.

सार

पवन फार्म में पवन चक्कियाँ वायुमंडलीय प्रवाह से ऊर्जा निकालती हैं और इसे बिजली में परिवर्तित करती हैं, जिसके परिणामस्वरूप स्थानीय गति में कमी होती है जो पवन फार्म में बाद की पवन चक्कियों के लिए पवन ऊर्जा की उपलब्धता को कम करती है। वेक में ऊपर, नीचे, और किनारों से वायुमंडलीय गति अभिसरित होकर गति में हुई कमी की आंशिक रूप से भरपाई कर देती है, जिससे पवन फार्म के काफी भीतर की पवन चक्कियाँ कार्य करने में सक्षम रहती हैं। इस थीसिस में, मैं एक काल्पनिक गहरे अपतटीय पवन फार्म और समुद्री हवा की स्थिति के तहत एक तटीय पवन फार्म में पुनर्प्राप्ति प्रक्रियाओं का पता लगाती हैं।

इस थीसिस में, क्षैतिज और ऊर्ध्वाधर-पुनर्प्राप्ति प्रक्रियाओं के स्थानिक प्रतिरूप और परिमाण की तुलना करने और पवन खेतों में गति पुनःपूर्ति में मेसोस्केल प्रक्रियाओं की भूमिका को समझने पर विशेष जोर दिया गया है। इस उद्देश्य के लिए मैंने पवन चक्की मानकीकरण से लैस एक अत्याधुनिक मेसोस्केल मॉडल, मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ) मॉडल का प्रयोग करके काल्पनिक अपतटीय पवन फार्मों के भीतर और आसपास वायुमंडलीय प्रवाह की गतिशीलता और थर्मोडायनामिक का अनुकरण यथार्थवादी प्रारंभिक और सीमा स्थितियों के तहत किया है। पवन फार्मों में 84 मी हब ऊंचाई, 112 मी रोटर व्यास (D), और 3.075 मेगा वाट की रेटेड क्षमता वाली पवन चक्कियाँ हैं। सघन पवन फार्म (केस I: 0.5 किमी ~ 5 रोटर व्यास की कम अंतर-पवन चक्की दूरी) से लेकर विरल पवन फार्म (केस III: 2 किमी ~ 20 रोटर की उच्च अंतर-पवन चक्की दूरी) तक अलग-अलग अंतर-पवन चक्की दूरियाँ अनुकरणित की गयी हैं।

सबसे पहले, मैंने गहरे अपतटीय स्थित पवन फार्म का अध्ययन किया है जहां वायुमंडलीय प्रवाह सीधे भूमि द्रव्यमान से प्रभावित नहीं होता है। अंतर-पवन चक्की दूरी के अलावा, मैंने पृष्ठभूमि की हवा की गति की विभिन्न श्रेणियों की भूमिका का भी पता लगाया, जिस पर पवन चक्कियाँ संचालित होती हैं।

पृष्ठभूमि हवाएँ कम गति ३–११.७५ मीटर प्रति सेकण्ड (केस ए) की श्रेणी से ज्यादा गति ११–१८ मीटर प्रति सेकण्ड (केस सी) की श्रेणी तक मानी गयी हैं। परिणाम बताते हैं कि उच्च-पवन-गति सीमा और विरल पवन फार्म के मामलों को छोड़कर, जहां क्षैतिज संवेगात्मक गति परिवहन भी समान रूप से योगदान कर सकता है, अन्य सभी परिस्थितियों में ऊपर से गति का ऊर्ध्वाधर अशांत परिवहन गहरे अपतटीय पवन खेतों में पुनर्प्राप्ति के लिए मुख्य योगदानकर्ता है। ऊर्ध्वाधर पुनर्प्राप्ति की हवा की गति और पवन फार्म घनत्व पर एक व्यवस्थित निर्भरता देखी गयी है। इस निर्भरता को निम्न-क्रम के अनुभवजन्य समीकरणों का उपयोग करके निर्धारित किया गया है। पवन फार्म मेसोस्केल प्रवाह प्रतिरूप को महत्वपूर्ण रूप से, विशेषकर उच्च-हवा-गति की स्थितियों के तहत सघन पवन फार्म्स के लिए परिवर्तित कर देते हैं। इन मामलों में, पवन फार्म्स द्वारा बनाए गए मेसोस्केल परिसंचरण उच्च गति वाली हवा को वायुमंडलीय सीमा परत (एबीएल) में ले जा सकते हैं और इस प्रकार पवन फार्म्स में पुनर्प्राप्ति में सहायता कर सकते हैं।

अधिकांश वर्तमान अपतटीय पवन प्रतिष्ठान तटीय क्षेत्रों में स्थित हैं जहां वे अक्सर समुद्री हवाओं से प्रभावित होते हैं। इसलिए, मैंने समुद्री हवा की स्थितियों से सम्बंधित तटीय पवन फार्म्स के व्यवहार एवं पुनर्प्राप्ति प्रक्रियाओं का मात्रात्मक अध्ययन किया है। मैंने अरब सागर में भारत के पश्चिमी तट से दूर समुद्री हवा के दिनों की पहचान करने के लिए एक संशोधित बोर्न विधि का उपयोग किया है। पहचाने गए समुद्री हवा के दिनों के लिए, मैंने मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ) मॉडल का उपयोग करके 50 x 50 वर्ग किमी क्षेत्र के एक काल्पनिक पवन फार्म का अनुकरण किया है, जो फिर से यथार्थवादी प्रारंभिक और सीमा स्थितियों द्वारा संचालित होता है। मैंने तीन पवन फार्म नक्शों का उपयोग करते हैं जिसमें पवन चक्कियाँ 0.5 किमी, 1 किमी और 2 किमी की दूरी पर हैं। इस अध्ययन के परिणाम एक दिलचस्प बिजली उत्पादन प्रतिरूप दिखाते हैं। पवन फार्म में आगे की ओर अधिकतम बिजली उत्पादन देखा गया है। साथ ही में समुद्र की हवा के कारण पवन फार्म में पीछे की ओर भी

अधिकतम बिजली उत्पादन देखा गया है। पवन फार्म परिसंचरण प्रतिरूप को प्रभावित करते हैं, लेकिन इन संशोधनों के प्रभाव समुद्री हवाओं की तुलना में बहुत कमजोर होते हैं। ऊर्ध्वाधर पुनर्प्राप्ति गति पुनःपूर्ति का प्रमुख कारक है जो कि पवन चक्कियों द्वारा निकाले गए गति के आधे से अधिक को ऊर्ध्वाधर अशांत मिश्रण द्वारा भर देता है। हालाँकि, क्षैतिज पुनर्प्राप्ति भी विरल पवन फार्म्स के लिए एक मजबूत भूमिका निभा सकती है। क्षैतिज पुनर्प्राप्ति पवन फार्म्स के किनारों पर अधिक मजबूत होती है जहां हवा की गति अधिक होती है जबकि पवन खेतों के अंदरूनी हिस्सों में ऊर्ध्वाधर पुनर्प्राप्ति अधिक मजबूत होती है।

मेरी जानकारी के अनुसार, मेसोस्केल प्रक्रियाओं की भूमिका सहित यथार्थवादी मौसम संबंधी स्थितियों के तहत पवन फार्म पुनर्प्राप्ति प्रक्रियाओं को देखने के लिए यह पहला अध्ययन है। इसके अलावा, यह अध्ययन पहली बार समुद्री हवा की स्थिति के तहत अपतटीय पवन खेतों में पुनर्प्राप्ति प्रक्रियाओं की जांच करता है। कुल मिलाकर, यह अध्ययन पवन फार्म्स और पवन फार्म-एबीएल परस्पर क्रिया में पुनर्प्राप्ति प्रक्रियाओं की हमारी समझ को आगे बढ़ाने में महत्वपूर्ण योगदान देता है

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABL	Atmospheric Boundary Layer
AEP	Annual Energy Production
ASCAT	Advanced Scatterometer
BEM	Blade-Element Momentum
CASES-99	Cooperative Atmosphere-Surface Exchange Study 1999
CTRL	Control
EWP	Explicit Wake Parameterization
FINO	Forschungsplattformen in Nord- und Ostsee (German) / Research platforms in the North and Baltic Seas (English)
GWEC	Global Wind Energy Council
HAWT	Horizontal Axis Wind Turbine
INCOIS	Indian National Centre for Ocean Information Services
IRENA	International Renewable Energy Agency
KE	Kinetic Energy
LES	Large Eddy Simulations
LLJ	Low-Level Jet
MATLAB	Matrix Laboratory
METAR	Meteorological Terminal Aviation Routine Weather Report
MKE	Mean Kinetic Energy
MYNN	Mellor–Yamada–Nakanishi–Niino
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
PDE	Partial Differential Equations
RAMS	Regional Atmospheric Modeling System
RANS	Reynolds Averaged Navier-Stokes’
RKE	Resolved Kinetic Energy
RRTMG	Rapid Radiative Transfer Model for General Circulations
SST	Sea Surface Temperature

TKE	Turbulent Kinetic Energy
WF	Wind Farm
WRF	Weather, Research and Forecasting
WS	Wind Speed