COVER PAGE – IOWA ENERGY CENTER OPPORTUNITY GRANT PROGRAM

☐ Pre-proposal ☒ Invited Full Proposal IEC Full Proposal Number: 14-008-OG	Project Category: Research and Development ☒ Demonstration/Deployment ☐ Education and Workforce Development ☐

ORGANIZATIONAL INFORMATION

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Organization Employer Identification Number:	42-6004224					
Organization Contracting Official:	Name:	Tamara Polaski	E-mail:	tra@mail.iastate.edu		
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Type of Organization:	☐ Community College ☐ Iowa Regents Institution ☐ Public School District	☒ Independent College/University ☐ Private Non-Profit / Foundation ☐ Private School System				
Organization Iowa Senate District: 23 Organization Iowa House District: 45	Organization Federal Congressional District: IA-4					

PROJECT INFORMATION

Project Title (100 Character Limit)	Innovative Dual-Rotor Wind Turbine Designs to Improve Wind Farm Efficiency				
IEC Funds Requested	$116	Project Start Date	02/01/2014	Project End Date	01/31/2015

INVESTIGATOR INFORMATION

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	Department/Unit:	Aerospace Engineering				
Co-PI:	Name:		E-mail:			
	Department/Unit:					
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AUTHORIZATION

[signature]	Dr. Anupam Sharma Dr. Hui Hu	Assistant Professor Professor	01/28/2014
Authorized Applicant Signature	Typed/Printed Name	Title	Date

TARGETED FUTURE FUNDING

Name of the potential external sponsor this project is targeting:
National Agencies: Department of Energy & National Science Foundation Industries: General Electric Company and Siemens.
Program announcement/solicitation number (if known):
DoE: Office of Energy Efficiency and Renewable Energy (EERE) A2E program RFP expected by 04/2014 NSF: Energy for Sustainability program under CBET (annual funding cycle; targeting 11/2014) NSF: Fuid Dynamics program under CBET (annual funding cycle; targeting 02/015)

Innovative Dual-Rotor Wind Turbine Designs to Improve Wind Farm Efficiency

Dr. Anupam Sharma and Dr. Hui Hu,
Department of Aerospace Engineering, Iowa State University, Ames, Iowa, 50011.
Email: sharma@iastate.edu and huhui@iastate.edu

Abstract

We seek opportunity grant funds from the IEC to explore a novel dual-rotor wind turbine (DRWT) concept to improve aerodynamic efficiency of isolated turbines as well as wind farms. The DRWT concept uses a secondary (likely smaller), aerodynamically optimized rotor to recover losses near the hub (root) of the main rotor, and to promote rapid mixing of turbine wake thus reducing wake losses in wind farms. Through variable operation of the secondary rotor, the velocity shear in the wake can be tailored to amplify mixing during conditions when wake/array losses are dominant. The increased power capacity can also be used to extract energy at wind speeds below the current cut-in speeds of single-rotor turbines. We are working proactively to seek external funding from federal agencies such as NSF and DoE as well as wind energy industries such as Vestas, GE, and Siemens to support our efforts to develop innovative DRWT systems. If funded, the results derived from this project will significantly strengthen our planned external proposals.

External Funding Opportunities

The total amount of the requested external funding is expected to be about \$2M~\$3M, which is more than twenty-fold return on the requested IEC seed funds (~\$116K). More specifically, we are planning to submit at least two proposals to the following programs at the DoE and the NSF in 2014.

1. We are planning to submit one proposal to the DoE's office for energy efficiency and renewable energy (EERE). DoE-EERE office is creating a new "Atmosphere to Electrons (A2E)" program to allocate about \$23M in FY2014 to fund researches to improve wind farm efficiency with the funding level of \$1M~\$2M per project.
2. We are also planning to submit at least one proposal to NSF's Energy for Sustainability program in 2014, which is sponsoring innovative researches related to wind turbine aeromechanics and wind farm aerodynamics. The funding level is about \$300K~\$400K per project.

Iowa produces roughly 5 GW of wind power (3rd in the nation). The economic impact of a 5% improvement in turbine efficiency (which is feasible with the DRWT concept) for the existing Iowa wind farms would bring benefits of ~ \$100M/year in the state of Iowa alone. Moreover, with 5% efficiency improvement, Iowa will be able to sustainably produce 30% of its power through wind.

Scope of Work

Concept: The proposed dual-rotor concept will employ an additional/secondary (possibly much smaller size) rotor in tandem with the main rotor of a HAWT with two objectives: (1) mitigate losses incurred in the root region of the main rotor through the use of aerodynamically tailored secondary rotor, and (2) mitigate array interference losses through rapid mixing of turbine wake; this will be achieved by tailoring the shear distribution in the turbine wake through variable-loading operation of the secondary rotor. Figure 1 shows a few possible configurations of the dual-rotor concept we propose to investigate. The most likely concept we will investigate in detail is framed in green.

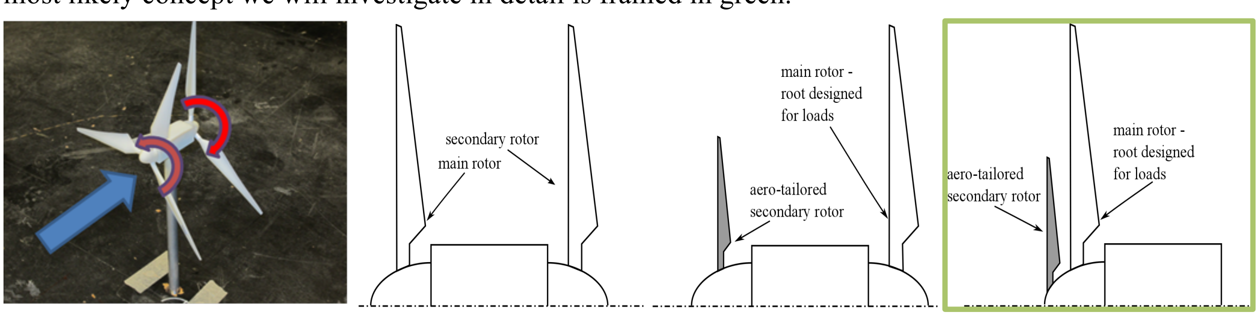

Figure 1: Dual rotor concept ideas for improved isolated turbine efficiency and rapid wake mixing.

The proposed concept is targeted at improving both isolated turbine efficiency as well as wind farm efficiency. A majority of the aerodynamic efficiency losses in isolated, utility-scale HAWTs stem from the root region, where very high thickness-to-chord ratio airfoils (aerodynamically poor) are used to provide structural integrity. In the proposed concept turbine (framed in green in Fig. 1), the secondary rotor can be made with aerodynamically optimized airfoils in the root region (since it will not have as high aerodynamic loads), which can more than recover the root losses.

The secondary rotor will also be leveraged to tailor the overall turbine wake such that it mixes out rapidly. Wake losses in wind farms have been measured to range anywhere between 8-40% (R J Barthelmie, 2007). While these losses are now reasonably well documented, there has been little work towards mitigating them. The secondary rotor can run at varying loading conditions (by varying pitch and tip speed) and thus the vertical shear in the wake can be varied. Large vertical gradient in shear itself will promote faster mixing, but we are also trying something radical. We will evaluate the possibility of using the dynamic interplay between the co- or counter-rotating tip vortices from the main rotor and the secondary rotor to promote large scale, rapid mixing of the turbine wake. If successful, this will lead to substantially increased energy flux from upper atmosphere, which will dramatically reduce turbine array (wake) losses. The ability to vary secondary rotor loading is crucial because wake losses are important at certain wind directions (aligned with turbine rows) and at certain atmospheric conditions (stable). Under such conditions, the secondary rotor can be operated with the objective of minimizing wake losses. Under conditions when wake losses are insignificant, the secondary rotor can be operated to boost isolated turbine efficiency.

Justification of Work: If the proposed dual-rotor concept is successful, it will transform the wind energy industry. Aerodynamic efficiency of current HAWTs is compromised in the root region in favor of structural strength. By using the secondary, aerodynamically tailored rotor, we can recover the root losses (estimated to be around 5%) in a typical utility-scale turbine. The secondary rotor provides control authority to change the velocity shear in the wake region. The ability to tailor the velocity shear and the possibility of exploiting the dynamic interaction between the vortices from primary and secondary rotors provide a path forward in mitigating turbine array losses.

Previous Work: Single-rotor HAWT and arguably wind farm aerodynamics (comprised of single-rotor HAWTs) have been extensively investigated using both numerical methods and experiments. Numerical methods have ranged from momentum and blade-element theories to time-steady and time-accurate CFD calculations (Vermeer, 2003) (Sanderse, 2011). Experiments have also ranged from laboratory scale to field measurements targeting both isolated and wind farm aerodynamics (Chamorro & Porte'-Agel, 2010) (Cal, *et al*., 2010). Dual-rotor turbine designs have received relatively less attention although there have been a few prototypes built and tested. A few notable dual-rotor designs and concepts are discussed below. A momentum theory based analysis for DRWT systems has also been developed (Newman, 1986).

Windpower Engineering & Development has developed a co-axial, twin-rotor turbine with the objective of harvesting more energy at lower wind speeds. The two rotors are *identical* and connected by one shaft to a variable-speed generator. Their implementation of the idea is a restricted (and potentially expensive) application of our concept. Our focus on mitigating losses rather than simply increasing energy capture differentiates our concept from the twin rotor idea. We are targeting to mitigate wake losses from a wind farm and root losses from isolated turbines. Windpower does not aim at either of these aspects. Granted that with our concept of a smaller secondary rotor the incremental power of an isolated turbine will be smaller (the incremental cost will also be much smaller), but there are potentially huge gains to be had at wind farm scale if we can successfully reduce wake losses through enhanced mixing. Airgenesis has also developed a similar twin-rotor concept, but their focus and innovation is in the area of generators. Their research and products can possibly be used in complement with our dual-rotor concept.

Enercon has a patent (US 7,074,011 B1) on a dual-rotor concept similar to the one proposed here.

Their idea is to increase turbine rotor diameter by mounting blades on long, cylindrical root sections. This however leaves a larger "hole" through which the air slips and the energy in that stream is lost. By adding the smaller rotor in front, they are able to harness this energy. The machine configuration in this patent is quite close to our proposed idea, however there are two key differences: (1) they do **not** intend to exploit the secondary rotor for purposes of wake mixing, and (2) their secondary rotor seems to be just a rescaled version of the primary rotor (as opposed to our concept to tailoring its design to be aerodynamically optimum).

Objective: With the IEC funds, we will develop our experimental and numerical models and perform conceptual experiments and simulations to strengthen our planned proposals to DoE, NSF, and wind turbine OEMs and wind farm operators. The specific objectives are:

- Accurately quantify the losses in the root region of a modern 3-bladed HAWT.
- Using RANS simulations perform a design of experiments varying secondary rotor size, position and design to optimize for isolated turbine performance and downselect 2-4 turbine ideas for detailed investigation.
- Build laboratory-scale models of the down-selected concepts & experimentally quantify isolated turbine performance improvement.
- Perform proof-of-concept calculations for the dual-rotor concept using LES. Quantify and potentially retire aeroacoustics and aeromechanics risks.
- Perform flow measurements & visualization to investigate wake flow dynamics. Use data from these experiments to validate our numerical model.
- Investigate (numerically & experimentally) the ability of the secondary rotor to enhance turbine wake mixing.

Details: The PIs have already performed some preliminary investigation (numerical and experimental) of the proposed concept. The results from these investigations show significant improvement in turbine performance. Our preliminary studies have explored the dual rotor concept with two identical rotors. The effect of co- versus counter-rotation of the secondary rotor has been investigated and counter-rotation was found to be more efficient. We have also numerically investigated the performance of a stand-alone dual-rotor turbine with varying heights of the secondary rotor.

Numerical Modeling: Our numerical methodology is based on solving the Reynolds-Averaged Navier-Stokes (RANS) equations with the turbine rotors modeled as momentum sources (actuator disk approach). It has been validated against analytical results from the 1-D momentum theory as well as against experimental measurements (see Fig. 2). Using this model we have also explained the atmospheric micro-scale phenomenon of surface flow convergence observed in wind farms (Selvaraj, 2013).

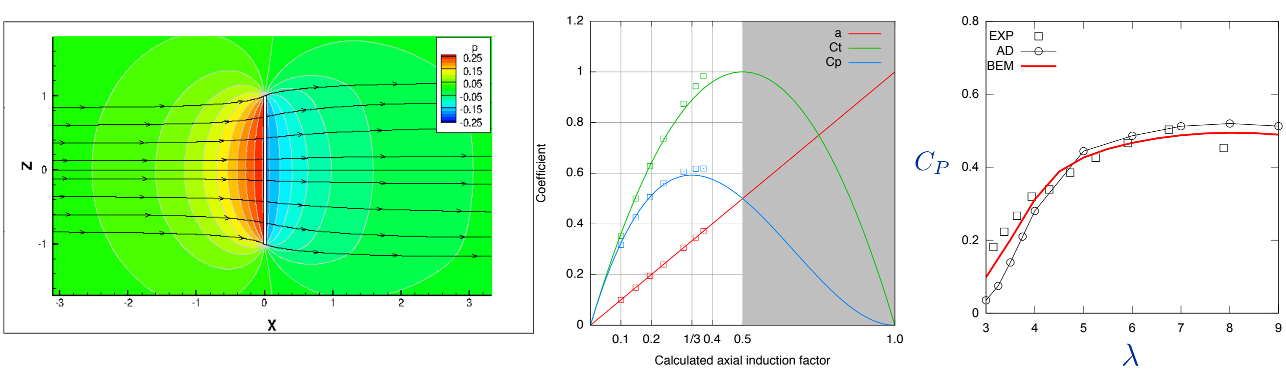

Figure 2 Validation of the RANS wind turbine model against 1-D theory (center) and against data (right).

To gain more confidence in the method's capability to handle multi-rotor configurations, we have performed comparisons against analytical results for multiple co-axial actuator disks (Newman, 1986). Comparisons of aerodynamic thrust force and power coefficients are shown in Fig. 3. Using this method, we have performed a few preliminary investigations of the dual rotor concept. The aerodynamic performance of an isolated DRWT has been assessed with varying size as well as loading of the secondary rotor (see Fig. 4). This is a small part of the thorough screening design of experiments study that we propose to complete as a part of this proposal.

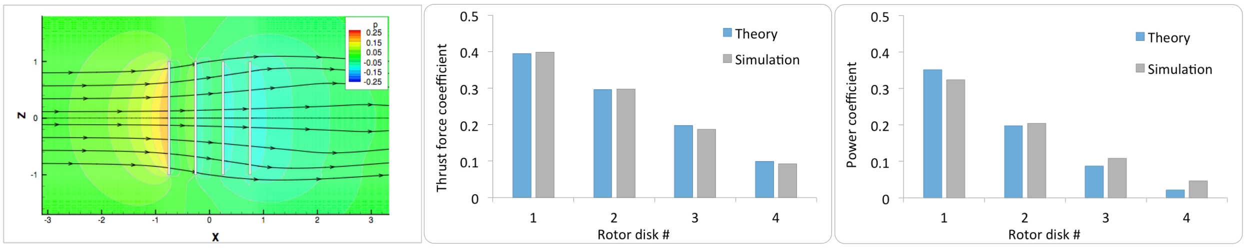

Figure 3 Validation against an analytical model **(Newman, 1986)** for multiple actuator disks.

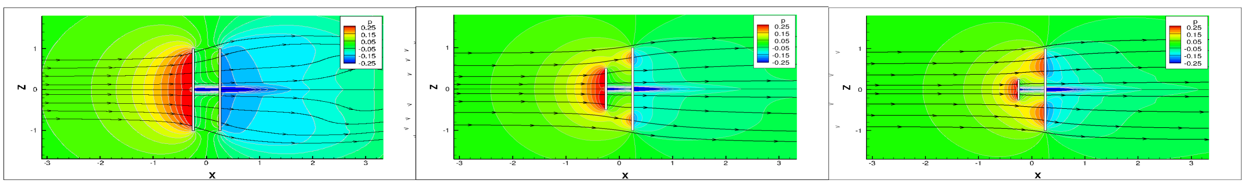

Figure 4 Preliminary simulations for the dual-rotor concept for different secondary rotor sizes.

The RANS modeling approach is useful in performing screening tests to down-select promising candidates. However, its limited fidelity (e.g., steady state assumption, turbulence models) handicaps us in evaluating: (1) accurate estimates of isolated turbine performance improvement, and (2) the interplay between the vortices from the primary and secondary rotors. The second item is crucial to enhancing our understanding of the physical mechanisms and exploiting them to achieve rapid mixing of turbine wakes. We therefore propose to use Large Eddy Simulations (LES) to numerically investigate this concept. We will be using the SOWFA (Software for Offshore Wind Farm Aerodynamics) software (Churchfield, 2012) developed at NREL. While the name says “Offshore” the model is applicable for onshore turbines as well. SOWFA solves the spatially filtered, incompressible forms of continuity and Navier-Stokes equations using spatial and temporal discretization. Spatial filtering introduces sub-filter scale (also called sub-grid scale or SGS) stresses, which are modeled in SOWFA using the Smagorinsky model (Smagorinsky, 1963). The width of the spatial filter is taken to be the grid-filter width. Direct inclusion of wind turbines (by simulating the geometric surfaces of turbine blades, tower and nacelle) is computationally expensive and arguably not required for wake dynamics calculations. The computational cost challenge as well as debatable fidelity of the numerical methods in replicating the complex, turbulent flow dynamics drives the choice of using a simpler rotor aerodynamics model. Therefore, an actuator line model (Sorensen, 2002) will be used to parameterize wind turbine rotors. While the application of LES to this concept is new, the team has extensively used LES for other applications (e.g., aerodynamic noise prediction). The incompressible forms of the governing equations solved by SOWFA are

$$\begin{aligned}
\frac{\partial \widetilde{u}_i}{\partial x_i} &= 0, \\
\frac{\partial \widetilde{u}_i}{\partial t} + \widetilde{u}_j \left(\frac{\partial \widetilde{u}_i}{\partial x_j} - \frac{\partial \widetilde{u}_j}{\partial x_i} \right) &= -\frac{\partial \widetilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_j^2} \\
&\quad - \underbrace{f_i/\rho_0}_{\text{turbine force}} + \underbrace{\delta_{i1} F_P}_{\text{driving pressure}} + \underbrace{\delta_{i3} g_0 (\widetilde{\theta} - \langle \widetilde{\theta} \rangle)/\theta_0}_{\text{buoyancy force}} + \underbrace{f_c \epsilon_{ij3} \widetilde{u}_j}_{\text{coriolis force}}, \\
\frac{\partial \widetilde{\theta}}{\partial t} + \widetilde{u}_j \frac{\partial \widetilde{\theta}}{\partial x_j} &= -\frac{\partial q_j}{\partial x_j} + \alpha \frac{\partial^2 \widetilde{\theta}}{\partial x^2},
\end{aligned}$$

In above, the expressions with overhead tilde are spatially filtered, p^* is the modified pressure, the surface heat flux, $q_j = \widetilde{u_j\theta} - \widetilde{u}_j\tilde{\theta} = -(\nu_{sgs} / Pr_{sgs})\partial\tilde{\theta} / \partial x_j$, and the deviatoric part of the stress tensor, $\tau_{ij} - \delta_{ij}\tau_k k / 3 = -2\nu_{sgs}\widetilde{S_{ij}}$. We have begun testing the SOWFA software on model problems and plan to develop it further using the IEC funds to investigate dual rotor wind turbine aerodynamic performance in isolation and in wind farm configurations. The LES solver will also allow us to investigate and quantify aeromechanics and aeroacoustics risks that we have identified (described later) with this concept. For this, we will make considerable simplifying assumptions such as assuming the rotor blades to be flat plates and apply Sears' gust response function to calculate aeromechanic response of the downstream rotor. We have used somewhat similar approach to study broadband noise from aircraft engine compressors. Since the LES simulations require long computation times, only a selected (using RANS simulations) few designs will be simulated using LES.

Experiments: In coordination with the numerical study described above, a comprehensive experimental study will also be undertaken to evaluate the aerodynamic performance and aeromechanics of the proposed dual rotor concept. Wake characteristics of dual-rotor wind turbine (DRWT) models with co-rotating and counter-rotating configurations will be investigated and compared with a conventional single-rotor wind turbine (SRWT) model in order to elucidate the underlying physics to explore and optimize the design of a DRWT system for higher power yield and better durability. The proposed experiments will be conducted in the large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) Wind and Gust tunnel available at the Iowa State University. Isolated turbine tests will be conducted first to study and compare the wake characteristics of a DRWT with that of a SRWT. Different pitch settings of the secondary rotor will be tested to investigate the variation in wake decay with rotor loading. We have the capability to measure not only the turbine power output and net (dynamic) loads (forces and moments), but also perform detailed wake flow measurements using a high-resolution Particle Image Velocimetry (PIV) system as well as Hotwires. The PIV system can be used to perform both *free-run* and *phase-locked* measurements to quantify the characteristics of the turbulent flow behind a turbine. The PIV and Hotwire measurements along with the LES simulation results will provide rich data sets to understand the interaction between trailing vorticities from the main and the secondary rotor of a DRWT system and to explore ways of using this interaction to promote rapid mixing. The isolated turbine measurements will be conducted with both uniform and spatially non-homogeneous inflow to investigate the effect of atmospheric boundary layer flow on DRWT systems.

In the recent past, we have experimentally investigated aerodynamic performance of wind farms comprised of SRWTs. We will extend this investigation to wind farms that use the proposed DRWT systems. An array of DRWT models will be placed in atmospheric boundary layer winds with different mean and turbulence characteristics to simulate different atmospheric stability conditions. The effects of the relative rotation directions of the back rotors with respect to the upstream rotor for the DRWT systems, the yaw angles of the turbines with respect to the oncoming winds, array spacing and layout, and the terrain topology of wind farms on the turbine performances and the wake interferences among multiple wind turbines will be investigated in detail. Individual turbine loads measurements as well as PIV visualizations will be performed for wind farm configurations. The detailed flow field measurements will be correlated with the dynamic wind loads and power output measurements to elucidate underlying physics in order to gain further insight into the characteristics of the dynamic wind loads and wake interferences among multiple DRWTs. A preliminary experimental study has been conducted recently to reveal the changes in the wake flow characteristics behind DRWT systems with the two rotors in either co-rotating or counter-rotating configurations in comparison with those of a conventional SRWT. Figure 5 shows some example results from that preliminary study. With the IEC funds we will be able to replicate this study for the proposed DRWT concept with smaller secondary rotor and further study the effect of variable loading of the secondary rotor. Due to large differences in Reynolds numbers of wind tunnel flow versus flow over a full-scale turbine, we recognize that the experimental results have to be interpreted and used carefully. This is important especially in the near wake region where chord-based Reynolds number is the relevant non-dimensional parameter. The results from scaled-model tests therefore have to be used to obtain insights into flow physics and perform qualitative comparisons between models. The experimental data will also be used for validating our numerical LES model. For this purpose, we will perform two numerical simulations for validation purposes (one for isolated configuration and one in wind farm configuration) at the same Reynolds number as in the experiments.

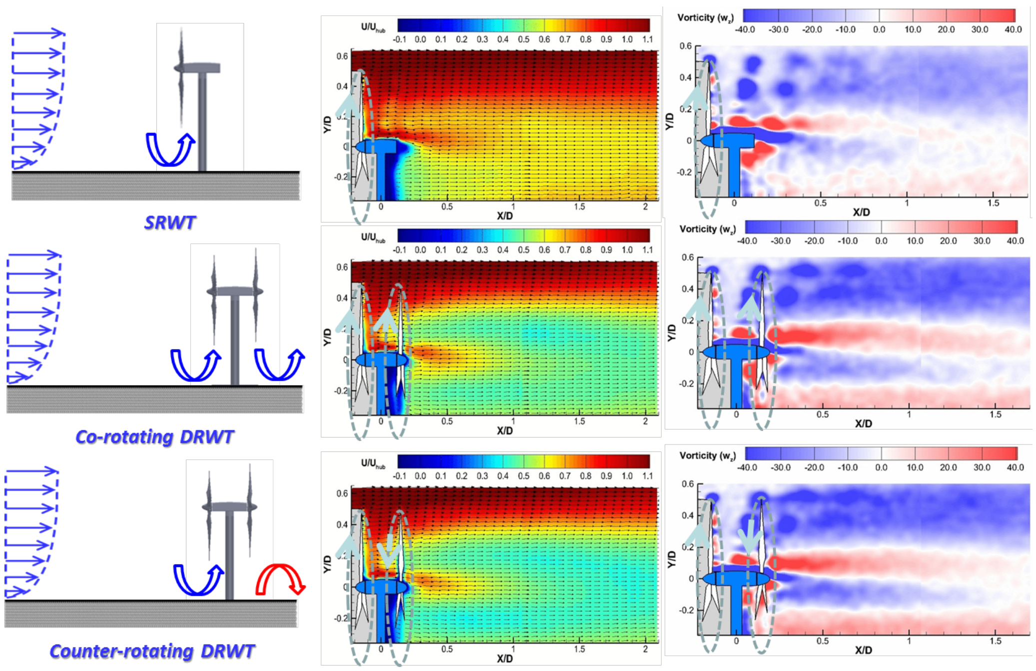

Figure 5: Experimental evaluation of single and dual co- and counter rotating HAWT designs. The axial flow velocity and vorticity distributions in the near wakes of wind turbines are shown in the figures.

Specific Tasks:

Completion of the following technical tasks will significantly improve the quality of our planned proposals to the DoE EERE and the NSF Energy for Sustainability programs.

***Task #1**:* Analytically and numerically quantify the losses in the root region of a modern HAWT.

***Task #2**:* Vary the secondary rotor size and carry out isolated turbine performance versus size tradeoff study. Downselect 2-4 DRWT designs through a numerical design of experiments study. Document performance improvements by comparing $C_P - \lambda$ curves against single-rotor HAWTs.

Task #3: Improve simulation fidelity by adopting large eddy simulation (LES) modeling approach over RANS. Adapt SOWFA software to study DRWT systems.

Task #4: Investigate the possibility of inducing large-scale dynamic interaction between the main and the secondary rotor tip vortices by varying secondary rotor loading. Using PIV and hotwire measurements, characterize the wake of an isolated dual-rotor turbine for varying loading of the secondary rotor.

Task #5: Numerically and experimentally investigate a dual-rotor wind farm configuration to estimate wind farm efficiency entitlement.

Task #6: Quantify (possibly retire) the aeroacoustics and aeromechanics risks due to the aerodynamic interaction between the two rotors of a turbine.

List of deliverables:

1. Submit two full-length proposals (one to the DoE EERE program in 2014 and one to the NSF Energy for Sustainability in 2014).
2. Present the results from this preliminary work in two technical papers at the Torque and ASME

conferences followed by submissions to the Wind Energy journal. The results and project execution summary will also be documented in a report to the IEC at the completion of the project.

3. Results from this investigation will be considered for incorporating in the graduate course on wind turbine aerodynamics (WESEP-501) offered annually (in Fall semester) at Iowa State University.

	Q1 '14		Q2 '14			Q3 '14			Q4 '14			Q1 '15		
Task#	F	M	A	M	J	J	A	S	O	N	D	J	F	M
#1														
#2														
#3														
#4						◆◆								
#5												★		
#6													◆◆	★

Table 1 Tentative timeline of the proposed tasks. Proposal submission dates shown by stars; paper submissions by diamonds.

Potential Risks and Mitigation Strategy:

The following table lists the risks we can foresee and our plan to mitigate them.

#	Risk	Risk Level	Mitigation Plan
1	Can't achieve significantly enhanced mixing	High	Thorough screening analyses with RANS simulations
2	Increased fatigue loading and or noise due to aerodynamic interaction between rotors	Medium	Early evaluation using linearized theories (e.g., Sears' response);
3	Little isolated turbine efficiency improvement with the secondary rotor	Low	Explore increased spacing; larger secondary rotor diameter.

Qualifications

Credentials: Both the PIs have significant and complimentary expertise in the area of wind energy, which span experimental, numerical, and analytical approaches to problem solving. We have the necessary infrastructure (exp. lab & equipment and computational resources & software) to successfully carry out the proposed research. Our past funding & publications on related topics are listed below.

Past Funding:

1. Hui Hu (PI), Partha Sarkar and Richard Wlezien: "A Wind Tunnel Study of the Interferences of Multiple Wind Turbines over Complex Terrains for the Optimal Turbine Site Design and Durability in Operation," IAWIND Program, $100K, 07/01/2011 - 12/31/2013.
2. Hui Hu (PI) and Partha Sarkar: "Characterization of Surface Wind Energy Resources and Wake Interferences among Wind Turbines over Complex Terrains for Optimal Site Design and Turbine Durability", National Science Foundation, $300K, 01/01/2012 ~ 12/31/2014.
3. Hui Hu (PI) and Alric Rothmayer: "Icing Physics Studies Pertinent to Wind Turbine Icing and De/Anti-icing," National Science Foundation, $360K, 04/01/2011~03/31/2014.
4. Hui Hu (PI) and Alric Rothmayer: "Advanced 3D Runback Models for Surface Water Transport related to Wind Turbine Icing and De/Anti-icing"; NASA - Atmospheric Environmental Safety Technologies (AEST) program; $663K, 01/01/12 ~ 12/30/14.
5. Mathew Frank (PI), Frank Peters, John Jackman, Partha Sarkar, Hui Hu and Vinay Dayal: "Innovative Offshore Vertical-Axis Wind Turbine Rotors"; Department of Energy; $686K, 01/01/2011 – 08/31/2016.
6. Anupam Sharma, "Numerical Modeling of Wind Turbine Loads" General Electric Co., 2013; $50K 07/01/2013 – 12/31/2013.
7. Anupam Sharma, "Towards Developing a Wind Aerodynamics and Aeroacoustics (WAAO) Framework," NSF XSEDE Computing Grant; 800K CPU hours; 2013.

Recent Relevant Publications:

1. H. Hu, W. Tian, and A. Ozbay, "Experimental Investigations on Wake Interference among Multiple Turbines in Onshore and Offshore Wind Farms", *Int. Conf. on Future Tech. for Wind Energy*,

Wyoming, USA, Oct, 2013.
2. Tian W, Ozbay A, Yuan W and Hu H, "An Experimental Investigation on the Performances of Wind Turbines Sited over a Hilly Terrain", AIAA-2013-2804, *31st AIAA Applied Aerodynamics Conference*, June 24-27, 2013, San Diego, USA.
3. Yuan W, Ozbay A, Tian W, Hu H, "An Experimental Investigation on the Effects of Turbine Rotation Directions on the Wake Interference of Wind Turbines", AIAA-2013-0607; *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 07 - 10 January 2013, Grapevine, Texas, USA.
4. Hu H, Yang Z, Sarkar PP, "Dynamic Wind Loads and Wake Characteristics of a Wind Turbine Model in an Atmospheric Boundary Layer Wind", *Experiments in Fluids,* Vol. 52, No. 5, pp. 1277-1294, 2012.
5. Yang ZF, Sarkar PP, and Hu H, "Visualization of the Tip Vortices in a Wind Turbine Wake", *Journal of Visualization,* Vol.15, No.1, pp. 39-44, 2012.
6. S. Selvaraj, A. J. Chaves, E. Takle, and A. Sharma. "Numerical Prediction of Surface Flow Convergence Phenomenon in Windfarms," in Proc. of the *Conference on Wind Energy Science and Technology*, Ankara, Turkey, Oct 3-4, 2013.
8. A. Sharma, "Numerical Modeling of Wind Turbine Aerodynamic Loads," *General Electric Global Research Center Internal Report*, 2013.
9. A. Sharma, et al., "Diagnosis of Aerodynamic Losses in the Root Region of a Horizontal Axis Wind Turbine", *General Electric Global Research Center Internal Report*, 2010.

Commitment from External Partners:

We have commitments from a wind turbine OEM (Vestas; see attached letter) and a utility company (MidAmerican Energy) to support our planned proposals to DoE & NSF. Both partners are excited about the proposed concept and are eager to learn from our research findings. We will also extend our existing collaborations with national laboratories (NREL and Argonne) and with other OEMs and seek collaboration with them on the larger-scale, DoE proposals (A2E & EERE). We expect them to contribute by performing full-scale tests. On the NSF proposal, we will evaluate the possibility of working with Vestas and/or GE to submit a GOALI (Grant Opp. for Academic Liaison with Industry) proposal.

References

1. Cal, R. B., *et al.* (2010), "Experimental Study of the Horizontally Averaged Flow Structure in a Model Wind-Turbine Array Boundary Layer," *Journal of Renewable and Sustainable Energy*, vol. 2.
2. Chamorro, L. P., & Porte'-Agel, F. (2010), "Effects of Thermal Stability and Incoming Boundary-Layer Flow Characteristics on Wind-Turbine Wakes: A Wind Tunnel Study," *Boundary Layer Meteorology*, vol. 136.
3. Churchfield, M. *et al.* (2012), "A Numerical Study of the Effects of Atmospheric and Wake Turbulence on Wind Turbine Dynamics," *Journal of Turbulence*, vol. 13, no. 14.
4. Newman, B. G. (1986), "Multiple Actuator-Disk Theory for Wind Turbines," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 24, pp. 215--225.
5. R J Barthelmie, O. R. (2007), "Modelling and measurements of wakes in large wind farms," *Journal of Physics: Conference Series*, vol. 75.
6. Sanderse, B. *et al.* (2011), "Review of Computational Fluids Dynamics for Wind Turbine Wake Aerodynamics," *Wind Energy*, vol. 14, no. 7, pp. 799–819.
7. Selvaraj, S. *et al.* (2013), "Numerical Prediction of Surface Flow Convergence Phenomenon in Windfarms," in Proc. of the *Conference on Wind Energy Science and Technology*, Ankara, Turkey.
8. Smagorinsky, J. (1963), "General Circulation Experiments with the Primitive Equations I. The Basic Experiment," *Monthly Weather Review,* vol. 91.
9. Sorensen, J. N. (2002), "Numerical Modeling of Wind Turbine Wakes," *Journal of Fluids Engineering*, vol. 124.
10. Vermeer, L. J. (2003), "Wind Turbine Wake Aerodynamics," *Progress in Aerospace Sciences*, vol. 39, pp. 467--510.

PROPOSED BUDGET

Refer to instructions tab for assistance in completing this form.

Project Start Date: 2/1/14 Project End Date: 1/31/15

		Requested from the Iowa Energy Center
Salaries & Wages		
1	PI: Dr. Hu's summer support(1.0 month)	$ 12,876
2	PI: Dr.Sharma's summer support(1.0 month)	$ 10,404
3	PhD student #1 ($1800/month for 12 month)	$ 21,600
4	PhD student #2 ($1800/month for 12 month)	$ 21,600
5		
Fringe Benefits (show rates by salary or wage class)		
a.	faculty rate @31.5% for PIs	$ 7,333.13
b.	Graduate student benefits @13.0%	$ 5,616.00
	Total Personnel Costs	$ 79,429
Equipment (Itemize and provide justification in the narrative)		
a.		
b.		
	Total Equipment Costs	$ -
Supplies & Materials (Show total and justify in the narrative)		$ 6,000
Travel (itemize and provide justification)		
a.	ASME/Torque conference registration & travel	$ 5,000
b.	Travel to meet with DoE program managers (Hu)	$ 2,000
	Total Travel Costs	$ 7,000
Consultants (itemize and provide justification of rates and travel in the narrative)		
a.		
	Total Consultant Costs	$ -
Subcontracted Partners (itemize and provide total cost per subcontract in the narrative)		
a.		
	Total Subcontract Costs	$ -

Tuition (list by category and number of students)

	No. of Students		Total Tuition
Undergraduate			
Graduate (MS)			
Graduate (PhD)	2	$11857 per	$ 23,714
		Total Tuition Costs	$ 23,714

Other Costs (show total cost and provide justification)	
TOTAL COSTS	$ 116,143

Budget Justification

Salaries and Wages:

Principal Investigators: 1.0-month salary support is sought for each of the PIs (both Dr. Hu and Dr. Sharma). Duties and responsibilities include managing and coordinating research efforts and supervising students.

Graduate Students: The support for 2 Ph.D. graduate students (one for experimental work, one for numerical work) is sought to conduct the proposed research. The salary is $1,800 per month for the Ph.D. students.

Benefits:

According to ISU policy, the fringe benefits rates are estimated as follows: 31.5% for faculty, 13.0% for Graduate Assistants, and 4.6% for UG Student employees.

Equipment (at least $5,000 per item):

Since all the major research facility and instruments needed for the proposed research have already been available in the Lab, no budget is requested for purchasing new equipment/instruments.

Travel:

A total of $7,000 is sought for travel. The requested travel fund is to cover trips of the PIs and the graduate students to attend two technical conferences to present their research findings and to meet with program managers at DoE and NSF for funding.

International Travel:

One of the most significant conferences in Wind Energy, The Science of Making Torque from Wind is being held in Denmark. One of the PIs has a paper on DRWT analyses to present at this meeting.

Materials and Supplies:

Lab materials and supplies are budgeted at $6,000 for the wind tunnel usage fee, experimental rig setup, test model fabrication, and purchasing of various particle and molecular tracers, optics and other consuming supplies for the proposed project.

Tuition:

Tuition for 2 Ph.D. graduate students is sought as the other cost. The tuition fee is based on the approved ISU rate for graduate students in engineering.

Letter of Reference from Vestas in support of the proposed effort

From: **Anurag Gupta** angpt@vestas.com
Subject: Innovative Dual-Rotor Wind Turbine Designs to Improve Wind Farm Efficiency
Date: November 22, 2013 at 12:38 PM
To: Anupam Sharma (sharma@iastate.edu) sharma@iastate.edu
Cc: Anurag Gupta angpt@vestas.com, huhui@iastate.edu

Dear Dr. Sharma

Thank you for sharing your proposal re. explorations of the dual-rotor wind turbine concept (DRWT). The combination of the traditional pursuit of efficiency energy extraction from the root region and the novel of tailoring the wake dynamics of the 2 rotors for reducing turbine-turbine interaction losses is an intriguing approach; creating a wake-effect mitigation mechanism will be instrumental in going after what is now considered one of the less touched and promising areas of CoE reduction for wind energy (viz. the US Dept. of Energy's recent A2E initiatives). The integrated experimental, analytical and computational approach sketched out also provides a balanced means of tackling the problem since now you need both depth and speed to understand, then design to mitigate.

You are already aware of Vestas's interest, work and substantial investments (both physical e.g., the Sandia/TTU SWIFT facility and numerical) in this specific area. As such we're very pleased to encourage and support this seed R&D effort; we will look forward to lesson's learned from your team's work as it evolves. I wish you both all success in this endeavor, and look forward to potential future collaborations on this topic where we could combine our strengths to take this concept to higher TRL levels and hopefully, real utility scale turbines.

With regards
Anurag

Anurag Gupta, Ph.D
Chiefs Office
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