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July 25, 2014

Ms. Kirsten Walli
Secretary, Ontario Energy Board
Box 2319, 27th Floor
2300 Yonge Street
Toronto M4P 1E4
boardsec@ontarioenergyboard.ca

RE: Cedar Point Wind Energy Project OEB File Number EB-2014-0022

Dear Ms. Walli:

Please accept this correspondence as a request to submit evidence to the Board. Two copies have been sent by regular mail.

In our earlier comment submitted on July 2, 2014, we indicated that we would be submitting documents as evidence in this proceeding. The following are all in the public domain and are freely available. I have appended copies of two of the more difficult to find documents for the convenience of the other parties to this hearing.

Ontario's Long Term Energy Plan
http://www.energy.gov.on.ca/en/ltep/detailed-ltep-information-breakdown/#.U9Jmq4BdXpi

The Ontario Auditor-General's 2011 report has been referenced at earlier board hearings, and we may wish to do the same, specifically the section dealing with renewable energy projects.
Available at: http://www.auditor.on.ca/en/reports_en/en11/2011ar_en.pdf

The Independent Electricity System Operator's data.
The attached PDF document titled: Capacity Factor of Ontario Wind Energy Generating Facilities was prepared by Dr. John Harrison, Professor of Physics at Queens University in Kingston, Ontario, and is included here with his permission. Dr. Harrison has been accepted at earlier ERT's as an expert in physics. Dr. Harrison's document does not contain opinion or speculation; it contains data that was collected from the IESO website on electricity delivered to the IESO controlled grid for the period July 2009 – June 2012.

The Ontario Society of Professional Engineers: Wind and the Electrical Grid, 2014
This a joint study prepared by two bodies representing Engineering professionals in Ontario: the Professional Engineers of Ontario and the Ontario Society of Professional Engineers.
Available at: h4p://www.ospe.on.ca/chappres

The former Minister of Energy's October 10, 2013 public comments.
http://www.thestar.com/news/queenspark/2013/10/10/ontario_liberals_scrap_plan_for_new_nuclear_reactors.html

Don Jones, P.Eng. article:
Wind and nuclear and the increasing irrelevance of capacity factor in Ontario – 2014 February The Don Jones Articles
Mr. Donald Jones is a retired nuclear industry engineer. He has written articles appearing on a number of blogs, including Rod Adams' Atomic Insights, Stephen Aplin's Canadian Energy Issues, and Scott Luft's Cold Air Currents.
A number of his articles also appear in the BULLETIN, journal of the Canadian Nuclear Society, in full or in abridged form.

This article is available at;
http://thedonjonesarticles.wordpress.com/2014/02/22/wind-and-nuclear-and-the-increasing-irrelevance-of-capacity-factor-in-ontario-2014-february/

NREL Presentation Paper:
Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control
The National Renewable Energy Laboratory, NREL, is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
This document is appended for the convenience of the other parties.

We ask the Board's indulgence in allowing us to submit this evidence at this time since the dates for the Argument-in-chief and the responses have not been determined.

Thank you for your consideration in this matter.

Yours truly,

Original signed by:

Santo Giorno

on behalf of WAIT-PW

Capacity Factor of Ontario Wind Energy Generating Facilities - Part 1: Ontario System

Table 1: Monthly Capacity Factor (Efficiency) Given as a Percentage: July 2009–June 2012

Month	Amaranth	Dillon	Gosfield	Kings-bridge	Port Alma I	Port Alma II	Port Burwell	Prince	Ripley	Talbot	Under-wood	Wolfe Island	Overall
Nameplate (MW)	**200**	**78**	**50**	**40**	**101**	**101**	**99**	**189**	**76**	**99**	**182**	**198**	
Jul-09, -10, -11	16, 16, 14	-, -, 15	-, -, 14	11, 13, 11	18, 16, 14	-, -, 16	14, 12, 12	15, 15, 13	12, 14, 12	-, -, 14	14, 16, 14	14, 17, 12	14, 16, 13
Aug-09, -10, -11	18, 18, 15	-, -, 16	-, -, 15	21, 17, 9	21, 14, 14	-, -, 17	17, 13, 13	19, 22, 14	21, 19, 15	-, -, 17	21, 19, 16	16, 20, 17	19, 18, 15
Sep-09, -10, -11	16, 29, 18	-, -, 26	, 22, 24	18, 34, 21	21, 31, 25	-, -, 28	17, 26, 19	16, 37, 26	17, 33, 22	-, -, 24	16, 35, 23	20, 32, 19	18, 32, 23
Oct-09, -10, -11	25, 29, 26	-, -, 20	-, - , 31	35, 35, 30	39, 37, 30	-, -, 33	34, 32, 28	29, 31, 32	30, 29, 30	-, -, 31	33, 33, 30	32, 32, 33	31, 32
Nov-09, -10, -11	23, 32, 41	-, -, 59	-, 39, 56	32, 42, 51	35, 40, 55	-, 37, 59	25, 33, 48	34, 44, 31	29, 40, 53	-, -, 50	28, 39, 52	22, 33, 45	27, 37
Dec-09, -10, -11	31, 26, 31	-, -, 41	-, 42, 37	43, 51, 39	41, 47, 38	-, 51, 42	36, 39, 35	29, 31, 32	37, 53, 43	-, -, 37	39, 48, 41	35, 34, 37	35, 39
Jan-10, -11, -12	27, 27, 38	-, -, 55	-,38, 51	39, 36, 48	48, 38, 52	-, 43, 56	36, 33, 46	28, 25, 41	39, 39, 46	-, 33, 53	38, 36, 45	27, 27, 38	33, 33
Feb-10, -11, -12	24, 43, 34	, 56, 55	-, 55, 51	25, 45, 48	31, 52, 52	-, 58, 56	23, 47, 46	21, 34, 41	25, 50, 46	-, 51, 53	24, 48, 45	23, 42, 38	24, 46
Mar-10, -11, -12	28, 27, 34	, 40, 48	-, 34, 46	27, 31, 41	37, 38, 47	-, 41, 50	26, 26, 33	26, 28, 41	28, 32, 42	-, 35, 44	26, 29, 40	37, 29, 33	29, 31
Apr-10, -11, 12	34,38, 32	, 40, 39	-, 49, 38	38, 38, 34	47, 49, 38	-, 52, 43	30, 35, 28	31, 31, 30	36, 38, 35	-, 47, 35	34, 38, 34	29, 38, 32	33, 40
May-10, -11, -12	24, 23, 17	, 25, 25	-, 31, 22	24, 25, 18	37, 32, 25	-, 35, 26	27, 20, 17	25, 25, 26	24, 26, 19	-, 29, 23	22, 25, 18	20, 30, 20	25, 27
June-10, -11, -12	19, 20, 25	, 25, 31	-, 23, 28,	18, 19, 21	27, 25, 30	-, 28, 34	18, 18, 21	19, 26, 21	18, 16, 23	-, 22, 28	18, 16, 22	17, 19, 24	19, 21
Annual Average	**24, 28, 27**	**-, - , 36**	**-, -, 33**	**28, 32, 30**	**34, 35, 34**	**- , -, 36**	**25, 28, 28**	**24, 29, 28**	**26, 33, 32**	**-, -, 33**	**26, 32, 31**	**24, 30, 29**	**26, 31, 31**

Note: The first, second and third set of numbers in the columns correspond to July 2009 to June 2010, July 2010 to June 2011 and July 2011 to June 2012 respectively.

Table 1 shows the monthly capacity factor for the Ontario wind farms for the period July 2009 to June 2012; only those operating for at least a year are included (http://www.ieso.ca/imoweb/marketdata/windPower.asp). The names are those used by the Independent Energy System Operator (IESO). The capacity factor is the actual power output divided by the nameplate power; it is given as a percentage. The nameplate power for each wind farm is given in the second row. As an example, consider the July-09 entry for Amaranth: The average hourly output for that month was 32 MW. Dividing by the nameplate power of 200 MW, we get 16%. The row labeled **Annual Average** shows the 12-month averages; the overall annual average is a weighted average.

Comment: It is instructive to consider the variation of the annual average capacity factor of the Ontario wind generating systems from year to year. Table 2 shows the annual capacity factors for those systems operating for three years or more. Amaranth was brought on line in 2006 and enlarged during the 2008 – 2009 year.

Table 2: Annual Average Capacity Factor

Year July to June	Amaranth 1	Amaranth 1 and 2	Kingsbridge	Port Alma	Port Burwell	Prince	Ripley	Underwood	Wolfe Island
2006 – 2007	30		33		29				
2007 – 2008	29		35		27	29			
2008 – 2009			33		28	27	33		
2009 - 2010		24	28	34	25	24	26	26	24
2010 - 2011		28	32	35	28	29	33	32	30
2011 - 2012		27	30	34	28	28	32	31	29

Declining Capacity Factor: It is clear from the capacity factors of plants operating back to 2006 that 2009 – 2010 was a poor year across Ontario. This is most likely a fluctuation involving the variation of wind speed over time. The wind speed does vary from year to year. Wind speed records (http://toronto.weatherstats.ca/charts/wind_speed-5years.html) going back 6 years were only available to me for Toronto. The annual average wind speeds (v) are given in the second row in the Table 3.

Table 3: Wind Speed Measurements for a Selection of Ontario Sites

Year	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012
v (km/h) Toronto	17.08	16.56	16.64	16.50	17.59	16.98
$(v/v_0)^3$ Toronto	1.03	0.94	0.96	0.93	1.13	1.02
v (km/h) 5 Cities			14.44	13.90	15.11	15.02
$(v/v_0)^3$ 5 Cities (± 7%)			0.96	0.86	1.10	1.08
$(v/v_0)^3$ Blended (± 7%)	1.03	0.94	0.96	0.87	1.10	1.07

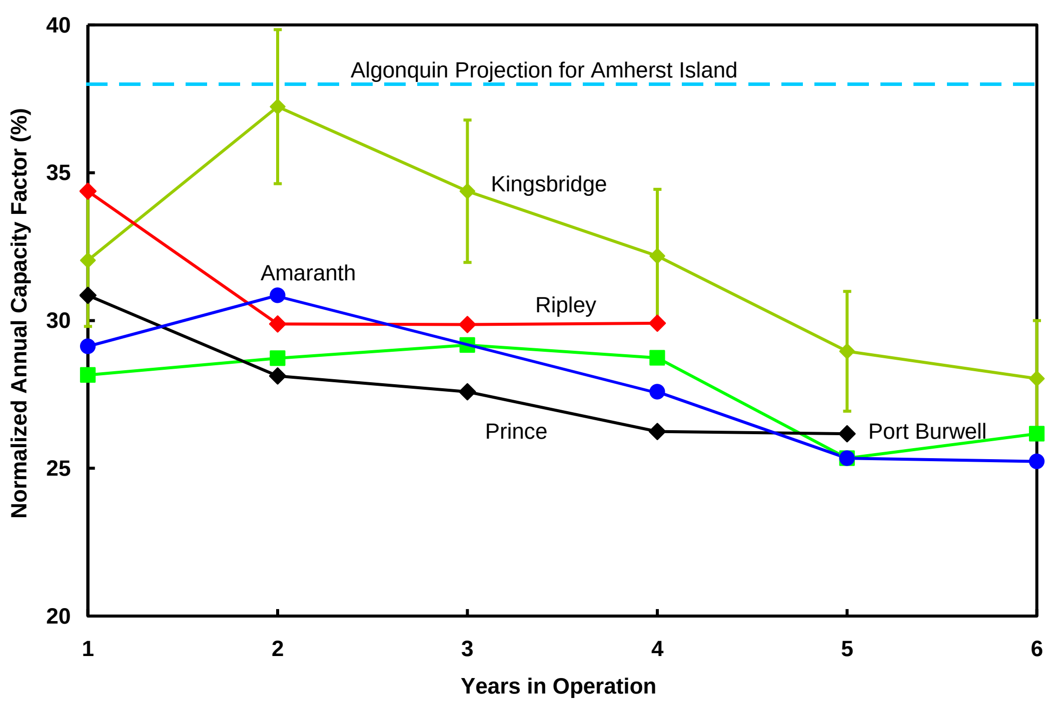
Note: The annual average wind speed measurements shown in the above table are not intended to represent the wind speeds at the wind energy generating system sites. The purpose of Table 3 is to indicate the variation of wind speed in Ontario from year to year. Although the uncertainty (± 7%) is large, the variation remains significant.

Mathematically, the output of a turbine varies as the cube of the wind speed. This is easy to understand. The kinetic energy density of the atmosphere varies as the square of the wind speed. The volume of air passing through the blade circle varies linearly with the wind speed. Multiply these two factors and the power output varies as the cube of the wind speed. That is, if the wind speed doubles the power increases eight-fold. There is a limit to the cube law at which the power output flattens off. However, for the range of wind speeds corresponding to most of the power output, the cube law is a reasonable representation.

The third row of the Table 3 shows the cube of the ratio of the annual average (v) to the 6-year average (v_0) for Toronto. The annual average capacity factor should be proportional to this ratio, $(v/v_0)^3$. Row 3 demonstrates that annual swings in the annual average capacity factor of 10% are to be expected.

In order to get a more representative picture of the wind speed variation across Ontario, the wind speed data for the past 4 years for Hamilton, Thunder Bay, Kingston, North Bay and Ottawa were blended with the data for Toronto for the past 6 years. The fourth row shows the annual average wind speeds for these 5 cities. These are converted to the average of $(v/v_0)^3$ for the 5 cities in row 5. The standard deviation is 7%. Finally, row 6 shows a blending of $(v/v_0)^3$ for Toronto and the 5 cities. Again, the standard deviation is 7%. Although the standard deviation is large, the variation from year to year can be larger and is significant.

To appreciate the variation of capacity factor with time, the measured annual average capacity factors shown in Table 2 have been corrected by dividing by the blended factor $(v/v_0)^3$ for that year. For the wind energy generating systems that have been



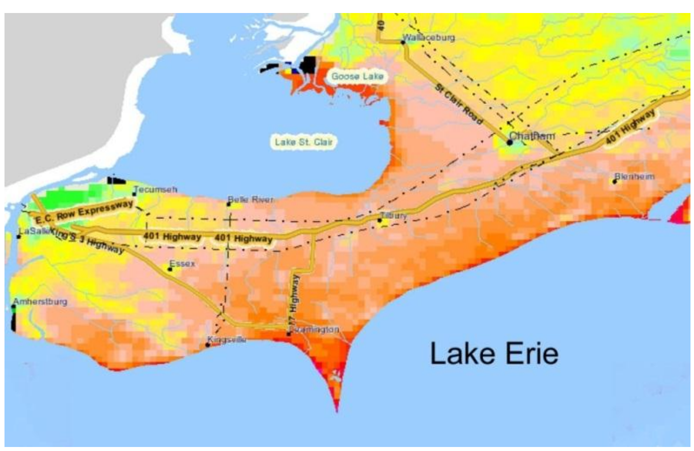
operating for 4 years or more, these normalized capacity factors are shown as a function of the number of years of operation in the figure above. The uncertainty (standard deviation) in the values of $(v/v_0)^3$ is reflected in the uncertainty in the normalized annual capacity factor. This is demonstrated in the figure only for the Kingsbridge data set.

The trend of the normalized annual capacity factors is down. A linear regression for each of the 5 wind energy generating system data sets demonstrates an average decline of (1.1 ± 0.3)% per annum.

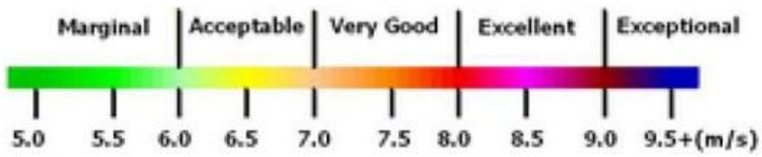
This is not the only report of capacity factor declining with time. In an extensive analysis of the Danish wind energy system Paul-Frederik Bach (2012) finds an average decline of just 0.3% per annum. Conversely, in his analysis of the Danish wind energy system over the years 2004 to 2010 Wayne Gulden (2012a) found an average decline of 1.5% per annum; Gulden normalized the capacity factors for the annual average wind speed. Gulden used the same technique to demonstrate that the Mars Hill installation in Maine, USA, is showing a declining capacity factor of a conservative 2.1% per annum (2012b).

Recent Wind Energy Generating Systems: There is some evidence that the more recent installations are generating higher capacity factors than the original ones. This can be seen for Dillon, Gosfield, Port Alma II, and Talbot. This is in part because the older installations have declined by about 4% and in part because of the use of so-called high efficiency turbines[1]. Gosfield and Talbot are using 2.3 MW turbines with101 metre blade diameters and Port Alma II is using a mix of the older Siemens 2.3 MW 93 metre blade diameter turbines and the newer Siemens 2.3 MW 101 metre blade diameter turbines (http://www.canwea.ca/farms/wind-farms_e.php).

In addition, these installations are located along the north-west shore of Lake Erie with its high wind resource (http://www.lio.ontario.ca/imf-ows/imf.jsp?site=renew_en); see over-page for the colour scale.



[1] The use of the term "high-efficiency" is a misnomer: see the Appendix.



References:
Paul-Frederik Bach (2012), Private communication

Wayne Gulden (2012a), See: http://windfarmrealities.org/?p=1284

Wayne Gulden (2012b), See: http://windfarmrealities.org/?p=1641

Appendix: High Efficiency Turbines
Wind turbine manufacturers are producing high efficiency turbines for use in regions with marginal wind resource. An example is the Siemens 2.3-113 turbine to replace the Siemens 2.3-93 turbine. The blade diameter has been increased from 93 metres to 113 metres. For power output as a function of wind speed , see: http://www.energy.siemens.com/mx/pool/hq/power-generation/wind-power/E50001-W310-A102-V6-4A00_WS_SWT-2.3-93_US.pdf and http://www.energy.siemens.com/hq/pool/hq/power-generation/renewables/wind-power/wind%20turbines/SWT-2.3-113-product-brochure.pdf

Consider as an example the power output at 7 m/s, a typical average wind speed. The wind resource is given by

$$\text{Power} = \tfrac{1}{2}\rho v^3 \pi d^2/4$$

where ρ is the density of air (1.225 kg/m^3 at 15°C and standard pressure), v is the wind speed and d is the blade diameter. The Betz limit is the maximum power that can be extracted from the wind; it is 59.3% of the wind resource. The calculated rated power at 15°C is taken from the power curves for the Siemens turbines referenced above. The efficiency of the turbines is the rated power divided by the Betz limit. These quantities are given in Table 4.

Table 4: Efficiency of Siemens Turbines with 93 and 113 Metre Blade Diameters Wind Speed = 7 m/s

Model	Wind Resource (MW)	Betz Limit (MW)	Rated Power (MW)	Efficiency (%)
Siemens 2.3-93	1.43	0.85	0.59	70%
Siemens 2.3-113	2.10	1.25	0.88	70%

The calculation shows that the two turbines have the same efficiency. The power gain is achieved through the use of longer blades.

John Harrison Sept. 2012
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Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control

Preprint

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To be presented at the 2012 American Control Conference
Montreal, Canada
June 27-29, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5000-54605
March 2012

Contract No. DE-AC36-08GO28308

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A Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control

Jacob Aho, Andrew Buckspan, Jason Laks, Paul Fleming, Yunho Jeong,
Fiona Dunne, Matthew Churchfield, Lucy Pao, Kathryn Johnson

***Abstract*—As wind energy becomes a larger portion of the world's energy portfolio and wind turbines become larger and more expensive, wind turbine control systems play an ever more prominent role in the design and deployment of wind turbines. The goals of traditional wind turbine control systems are maximizing energy production while protecting the wind turbine components. As more wind generation is installed there is an increasing interest in wind turbines actively controlling their power output in order to meet power set-points and to participate in frequency regulation for the utility grid. This capability will be beneficial for grid operators, as it seems possible that wind turbines can be more effective at providing some of these services than traditional power plants. Furthermore, establishing an ancillary market for such regulation can be beneficial for wind plant owner/operators and manufacturers that provide such services. In this tutorial paper we provide an overview of basic wind turbine control systems and highlight recent industry trends and research in wind turbine control systems for grid integration and frequency stability.**

I. Introduction

The wind industry has experienced large growth rates over the past decade and wind turbines have been installed around the world in increasing quantities [1]. As wind energy becomes more prevalent there is growing interest in controlling wind turbines or wind plants (a cluster of wind turbines as seen in Fig. 1) in an intelligent manner to minimize the cost of wind energy. This can be done by controlling the turbines to extract more energy from the wind and reduce structural loads that can cause component failure and is the focus of ongoing research. Though wind energy makes up a relatively small amount of global energy production, there are certain regions that produce a significant portion of their energy from the wind, such as Spain, Ireland, and Denmark [1]. The increasing penetrations of wind energy in these countries has raised interest in a new branch of wind turbine control research and development that focuses on wind turbine participation in frequency regulation for the utility grid.

Fig. 1. A row of turbines in a wind plant located in Alberta, CA. This wind plant contains 114 horizontal axis wind turbines (HAWTs), each rated at 660 kW with a rotor diameter of 47m and hub height approx. 50m.

Grid operators require conventional utilities to provide regulation in order to maintain the necessary balance between generation and load, which in turn regulates the grid frequency. Wind power has not historically been required to provide grid regulation services, as most modern wind turbines do not intrinsically provide any of the grid regulation services that are available with conventional generators. High wind penetration levels in the aforementioned countries have lead their transmission system operators to impose new requirements for future wind plant installations to be

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capable of providing power tracking and frequency regulation services [2] when there is ample wind resource available.

The interest in the potential for wind turbines to provide regulation services has motivated new opportunities in control system research and development. Wind turbines do not inherently provide these services, but they can be synthesized through designed control actions. Services that involve varying the active power output of the turbine will be referred to as active power control (APC). The new requirements by aforementioned European grid operators have forced turbine manufacturers to develop and implement control methodologies to provide APC capabilities. Ongoing research is focused on determining the upper bound of frequency regulation capability of wind turbines, as it seems possible that wind turbines could be more effective at providing some of these services than traditional power plants. The possible benefits of continuing the development of these methods present good opportunities for both grid operators and wind plant owner/operators. The intention of this paper is to introduce the controls engineer to standard wind turbine control systems and provide a brief overview of the methodologies used to provide APC with wind turbines.

This paper is organized as follows: Section II highlights the recent growth in the wind energy industry and provides a general overview of the wind turbine structure, standard control configurations, and an introduction to the interaction of wind turbines within a wind plant. Section III explains the basics of frequency regulation, provides the motivation for developing active power control in wind turbines, and overviews methodologies implemented by manufacturers thus far to meet these requirements. Section IV reviews the prior and ongoing research of enabling APC on wind turbines and wind plants. Finally, Section V provides concluding comments.

II. The Basics of Harnessing Wind Energy

In this section, we highlight the recent growth in the wind energy industry and provide an overview of the most common utility scale wind turbines, their operating regions, their standard control goals, and the interactions between turbines when grouped in a wind plant.

A. Growth of the Wind Energy Industry

Wind energy is a quickly growing alternative energy technology that can provide clean power. According to the World Wind Energy Association, the average growth rate of installed capacity around the world over the last decade has been 27.7% [1]. In 2010, worldwide capacity reached 196,630 MW (megawatts) out of which 37,642 MW were added during 2010, for a growth rate of 23.6% [1]. During 2010, the United States increased installed wind capacity from 35,159 MW to 40,180 MW. China almost doubled installed capacity in 2010, growing from 25,810 MW to 44,733 MW, to pass Germany and the US and become the number one country in installed capacity [1]. 2010 brought a 59% capacity increase in offshore wind, bringing the total to 3,117 MW, all of which is located in Europe, Japan, and China [1]. As wind turbine technology continues to mature, wind energy is becoming a larger portion of the global energy profile.

The 'penetration' of wind energy in the local utility grid, which refers to the percentage of electrical energy generation that comes from wind energy sources, is an important metric to measure. Though wind energy provided only 2.5% of the global electrical energy supply in 2010, several countries have a relatively high percentage of their electrical energy produced by wind power. The countries with the highest percentage of electrical energy generated from wind in 2010 were Denmark, Portugal, Spain, and Germany with 21%, 18%, 16%, and 9%, respectively [1]. It should be noted that these percentages are annual averages. At times the instantaneous percentage of total power provided by wind can be much higher. Wind energy achieved a maximum instantaneous penetration level of 59.6% in Spain in 2011 [3]. The high wind penetrations in these countries have been achieved not only from having good wind resources available, but also by aggressive national policies to produce more energy from renewable sources.

Wind turbines have increased in size to take advantage of economies of scale. The turbines installed in the U.S. during 2010 had an average rated power of 1.79 MW with average hub heights and rotor diameters of 79.8 and 84.3 meters, respectively [4]. The average rated power of turbines installed in the US has not increased significantly during the past 3 years due to the challenges associated with transporting extremely large turbines over land and the popularity of a particular 1.5 MW turbine model [4]. The installation of turbines is also subject to economies of scale, as it is more profitable to cluster wind turbines together to reduce the cost of installation, maintenance, and transmission line construction. These clusters of wind turbines are often laid out in a grid-like pattern and are commonly referred to as "wind farms" or "wind plants," the latter being the preferred term which is used in this paper. Fig. 1 shows a single row of turbines in a wind plant.

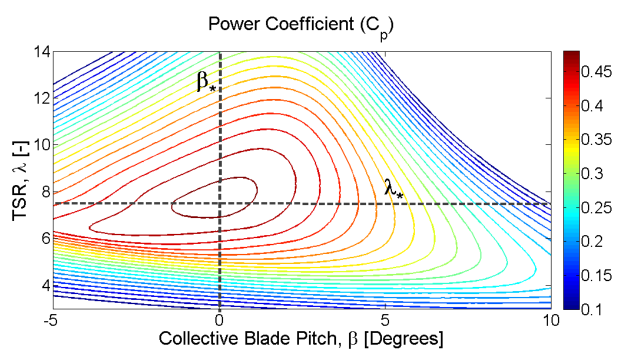

Fig. 2. C_p curves for an example 5 MW wind turbine. The dotted lines represent the collective blade pitch β_* and the tip-speed ratio λ_* at which C_p is a maximum.

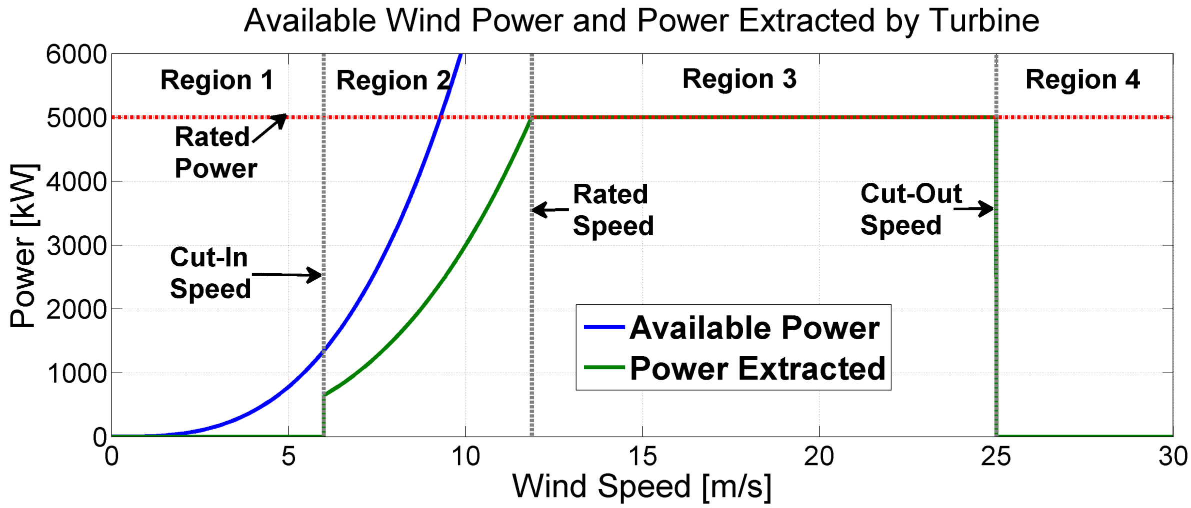

Fig. 3. Wind power, turbine power, and operating regions for an example 5 MW turbine.

B. Wind Turbine Overview

A turbine with rotor axis of rotation that is horizontal to the ground is called a HAWT (Horizontal Axis Wind Turbine). HAWTs are representative of the majority of all large scale wind turbines today. These turbines are operated in an upwind manner, where the rotor plane is actively positioned to be directly upwind of the tower through the use of a yaw motor that rotates the entire nacelle (housing for all components located at the top of the tower). Wind passing over the turbine blades produces lift and this then induces a rotational torque.

The available power in the wind is $P = \frac{1}{2}\rho A v^3$, where P is the power $[W]$ passing through the rotor disk, ρ is the air density $[kg/m^3]$, A is the swept area of the rotor disk perpendicular to the wind direction $[m^2]$, and v is the wind speed $[m/s]$. The wind turbine rotor cannot extract all of the energy from the wind stream, as this would require the wind to become stationary on the downwind side of the rotor. The fraction of available power that a turbine does harvest is its power coefficient $C_p(\beta, \lambda)$, which is a function of the collective blade pitch β and the tip-speed ratio (TSR) λ. The TSR is the tangential speed of the blade tips divided by the wind speed perpendicular to the rotor plane. A characterization of a wind turbine's C_p is shown as a contour plot in Fig. 2. The theoretical upper limit for C_p is the Betz Limit of $\frac{16}{27}$ [5].

The aerodynamic torque captured by the blades is transferred to the hub, which connects the blades to a drivetrain and then a generator. Typically, the drivetrain includes a gearbox to scale rotational speed and torque to levels that are suitable for the generator configuration. Although gearboxes are still used in the majority of turbines, direct-drive wind turbines have been developed to directly connect the hub to the generator with a single shaft to increase reliability and reduce maintenance costs that are largely associated with gearbox failures [6].

The wind turbine's generator converts the mechanical power of the drivetrain to electrical power which is either directly injected to the grid or first converted to the grid frequency via power electronics. Most large scale wind turbines installed during the 1980's and 1990's used gearboxes and fixed speed generators that produced voltage synchronous with the utility grid [6]. The wind turbine industry has since moved to using variable speed wind turbines that can maximize below-rated power production by matching blade tip-speeds against prevailing wind speeds to maximize aerodynamic efficiency, as described in Section II-C1.

Variable speed operation is typically achieved by using one of two different configurations. The first employs a synchronous generator that spins at variable speeds and uses a full power converter to ensure the produced power matches in frequency and phase to that of the utility grid and is known as a 'type 4' wind generator [7]. The second, and most common way of achieving variable speed operation is to use a doubly-fed induction generator (DFIG), known as a 'type 3' wind generator [7]. The stator of a DFIG is directly connected to the grid while the electromagnets of the rotor are excited by a time-varying waveform that is produced by power electronics that need to only convert roughly 30% of the turbine's rated power [7]. Almost all commercially available large scale wind turbines use either type 3 or 4 generators, both of which effectively decoupled from the grid via their power electronics.

C. Standard Control Configurations

The control of wind turbines is a complex problem and spans multiple fields of research, including materials, aerodynamics, and power systems. As the turbine structures become larger, their components become more expensive. Wind turbine manufacturers may attempt to counteract the increase in costs by using lighter weight components that can be more flexible. These large, expensive, and flexible components can be more susceptible to failure from fatigue and extreme loads that arise from the turbulent nature of the wind. Control system optimization to prevent extreme loads and to reduce fatigue load cycles becomes important to avoid component failure.

Wind turbine control is typically divided into four primary regions, as seen in Fig. 3. Region 1 spans operation from startup to the ‘cut-in’ wind speed where the generator is turned on and starts producing power. When wind speeds are above cut-in, but still too low to produce maximum power, the turbine is said to be in Region 2. In this below rated region the objective is to maximize aerodynamic efficiency to capture as much energy as possible from the wind stream. In Region 3, wind speeds are high enough to drive the generator at its rated power output; in this case, the goal is to regulate speed and power safely at rated levels. Region 4 occurs when the turbine shuts down due to high wind speeds to prevent damage to the turbine.

Throughout these regions, the speed and power of the turbine are controlled by varying the generator load torque and the blade pitch angles based on measurement of the generator shaft speed. The generator torque is induced by power electronics onto the load side of the drivetrain, and actuation is sufficiently fast that it is considered as occurring with negligible delay in comparison with the dynamics of the rotor and structural loads. The blades are actuated with pitch motors which are often modeled as low-pass filters with a cutoff frequency on the order of 1 Hz, saturation limits, and slew-rate limits on the order of $10°/sec$ [8]. The generator shaft speed is typically measured using an encoder, and the signal is often fed through a low-pass filter to avoid high frequency actuation. Yaw control is also employed during turbine operation to keep the rotor perpendicular to the primary wind direction, typically based on 10-second-average wind direction measurements, with a yaw rate on the order of $0.5°/sec$ [9].

1) Region 2 (Below-Rated): In Region 2, the primary goal is to capture as much power as possible. The power coefficient C_p changes with both blade pitch and TSR, as shown in Fig. 2, and is largely determined by the geometry of each specific blade design. In standard Region 2 control, blade pitch is typically held constant at the value β_* that produces the peak C_p. The goal is then to maintain the TSR at the optimal level λ_*; hence, the tip-speed, and therefore rotor speed, must vary proportionally to the wind speed. This is achieved by varying the generator torque.

The commanded generator torque τ_g is set according to

$$\begin{aligned} \tau_g &= \frac{1}{N_{gear}} k_\tau \Omega_r^2 \\ k_\tau &= \frac{1}{2}\rho A R^3 \frac{C_p(\beta_*, \lambda_*)}{{\lambda_*}^3} \end{aligned}$$

where N_{gear} is the high-speed to low-speed gearbox ratio (i.e. a constant greater than 1), Ω_r is the rotor speed (measured generator speed divided by N_{gear}), ρ is air density, A is rotor swept area, R is the rotor radius, and (β_*, λ_*) are the blade pitch and TSR, respectively where the maximum power coefficient C_p occurs. It can be shown that this generator torque control law will balance the aerodynamic and load torques to regulate the speed of the turbine to the optimal TSR in steady-state conditions [10]. Fig. 4 shows an example of generator torque command versus generator speed measurement, following this law in Region 2, and also showing transition Regions 1.5 and 2.5, as found in [8].

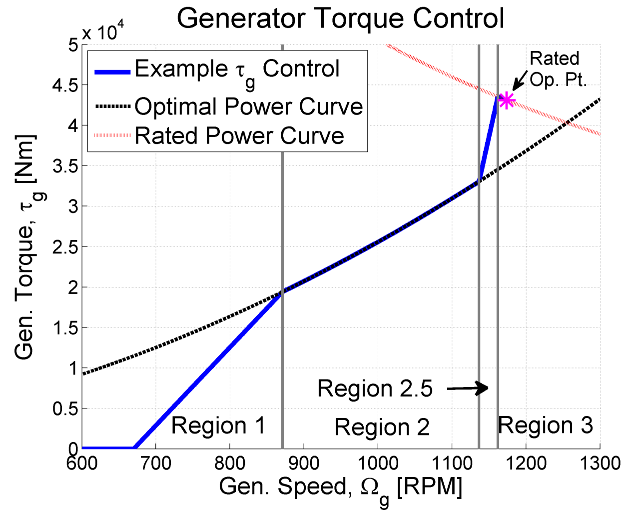

Fig. 4. An example of the generator torque control in different operating regions, as described in [8].

The torque controller may deviate from the optimal TSR at particular speeds to avoid tower resonances, and may also include drivetrain and/or tower damping by adding feedback at the appropriate resonant frequency or frequencies [11]. Though these features and the generator shaft speed measurement filter will not allow the turbine to perfectly track the optimal tip-speed ratio, the peak of the C_p curve is relatively flat and the power capture performance is acceptable.

2) Region 3 (Above-Rated): In Region 3, the primary goal is to regulate generator speed at rated by shedding extra aerodynamic power. This is done using blade pitch control, typically pitching to feather which decreases the aerodynamic angle of attack. The blade pitch angle capturing the most power is β_*, which occurs at 0° in Fig. 2. The standard convention is that pitching to feather corresponds to increasing, or positive pitch angles. Pitching to stall (increasing angle of attack) can decrease the rotor speed more rapidly, but pitching to feather decreases aerodynamic torque smoothly, is quieter, and typically induces smaller blade structural loads [5].

The blade pitch control system typically uses proportional-integral (PI) control on the generator speed error signal to regulate the generator speed at rated. The control system also includes anti-wind up or saturation limits on the integrator to account for the physical limits placed on the pitch angle of the blade (e.g., not allowing the blade pitch to go below β_*). Gain scheduling is often used to adjust the PI gains based on the current blade pitch angle. This is done to address the non-linear sensitivity of the C_p curve to blade pitch angle [8]. This PI speed controller pitches all blades to feather collectively. Individual pitch variations and higher frequency collective pitch variations may also be added to the PI pitch commands in order to reduce structural loads [11].

Because the blade pitch regulates generator speed at rated in Region 3, the generator torque can be held constant at rated torque. However, due to the stochastic turbulent nature of the wind and the slow response of the pitch actuators, at times the generator speed may vary more than 5% from the rated speed. It is common to maintain constant power output in above rated winds by commanding variations from the rated torque that are inversely proportional to fluctuations in rotor speed, as shown in Fig. 4.

D. Wind Plants and Turbine Wake Interactions

One area of research still very nascent is wind plant control to address turbine wake interactions. Wind turbines are often installed in wind plants to reduce the cost of installing transmission lines and operations and maintenance costs. As a byproduct of the extraction of energy from the wind, turbines create wakes that extend downstream [12, 13]. Wakes are characterized by lower speed and higher turbulence than that of the surrounding wind. With enough downstream distance, the wake mixes with the surrounding winds so that the wind speed and turbulence become approximately the same as that of the freestream. Turbines operating on the interior of a wind plant are often subject to wakes of upstream turbines as shown by Jensen et al. [14]. Wakes are significant because a turbine operating in the wake of an upstream turbine has less available energy to extract from the wind and is subject to increased mechanical loads-inducing turbulence. Wake effects translate to less revenue due to decreased power generation and increased maintenance costs.

Wake effects pose a significant challenge for advanced wind plant-level control systems. One method that has been studied [15, 16, 17] involves operating the upwind rows of turbines in a plant at a decreased efficiency to reduce wake effects imposed upon downstream turbines, increasing overall plant power capture and reducing loads. Such a scheme could be tuned to the current atmospheric stability conditions at a particular site, since wakes persist more strongly in a more stable (nighttime) atmosphere. Wind farm control and wake interactions are the subject of numerous papers, though not explicitly mentioned here, this research can aid in determining how wind plant level controls can further enable active power control.

III. Overview of APC

In this section, we present a brief overview of how grid frequency control is provided via conventional sources. We also explain the motivation for wind energy to provide active power control by presenting current frequency support requirements by some transmissions systems operators (TSOs). We then review industry activity to develop solutions that provide active power control capabilities that meet the new requirements.

A. Frequency Regulation Basics

In order for the grid to maintain a desired frequency, it is necessary that the total power generated be equal to power consumed by system loads and electrical losses on the grid. This balance must be preserved in the face of fluctuations in load and uncontrolled generation. If generation exceeds load, then the grid frequency will go up, whereas if total load exceeds generation, grid frequency will fall. Therefore, *regulation* provided by capable utilities is used by grid operators to compensate for these fluctuations and unplanned events such as sudden loss of generation [18]. Such capable utilities include regulation-providing generators or grid-responsive loads and storage. Fig. 5 provides an illustration of the utility grid's power generation (blue), load (green), and the regulation required (red) to match supply and demand (from Kirby [18]).

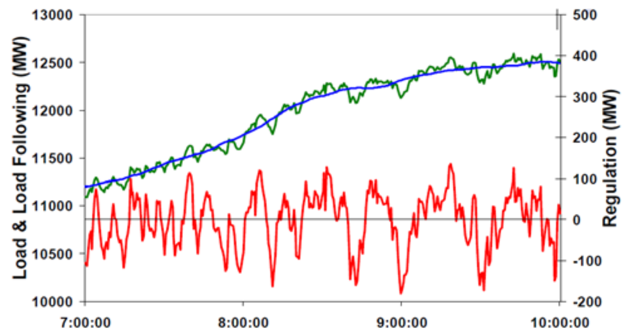

Fig. 5. Regulation: the green line depicts total system load, while the blue line represents load-following generation. The red line represents regulation required to keep generation balanced with load (reprinted with permission from [18]).

Conventionally, grid frequency response to a large disturbance is divided into separate control regimes: inertial, primary frequency response, and secondary frequency response or automatic generation control (AGC). These classifications are based on methods for providing each service with conventional generators: synchronous generator inertia for inertial response, generator governors for primary response, and finally output control responding to system operator power level demands for AGC response. For further information and exact definitions of inertial, primary, and secondary response, see [19] and [20]. It should be noted that some references refer to inertial control as a subset of primary response. Fig. 6 provides a plot of these regimes in the case where there is a sudden loss in total generation connected to the grid, and is depicted in terms of a time-domain plot of grid frequency following the loss of generation. The inertial response immediately follows the frequency event, primary control usually occurs within the timeframe of 20 - 30 seconds, and secondary control occurs within the timeframe of 5 - 10 minutes. The inertial response is conventionally determined by the physical inertia of large synchronous generators as they decelerate in response to the increased electrical load during a loss in total grid generation capacity. The frequency decline is arrested or stabilized in the second time frame, which is characterized as the primary response, or governor response, as it is normally automatically controlled by generator governors responding directly to changes in grid frequency. The final response, in which the frequency is restored to nominal, is called AGC and is performed

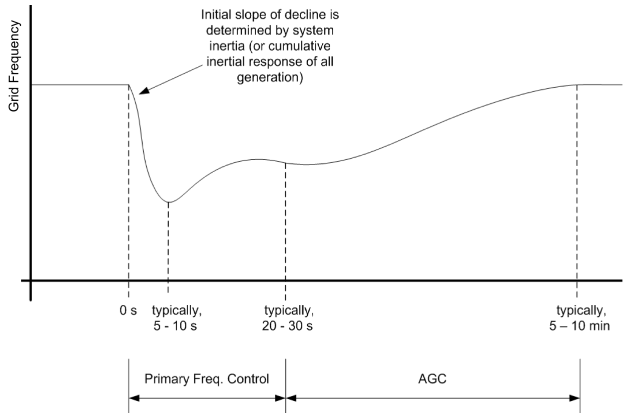

Fig. 6. Inertial, primary frequency controls, and AGC (secondary) response (figure courtesy Pouyan Pourbeik of EPRI).

by individual power plants adjusting their power levels in response to requests from the systems operator.

B. Motivation for Active Power Control in Wind Turbines

Active power control (APC) is the purposeful control of the real power output of a wind turbine or collection of wind turbines in order to assist in balancing total power generated on the grid with total power consumed. Real (also known as "active") power is the portion of energy flow which results in a net transfer of energy; this is in contrast to imaginary or reactive power flow, which reverses direction over each cycle with no net energy transfer. While reactive power may be controlled through the turbine's power electronics (even when the turbine is offline), real power is regulated by changing the actual amount of power delivered to the utility grid. In doing so, APC may allow wind power to provide important ancillary services to the electrical grid and assist in maintaining an acceptable frequency.

Intrinsically, wind turbines do not provide APC services and they have not historically been required to provide such responses [21]. Most modern turbine generators are decoupled from grid frequency through power electronics (type 3 or 4), as described in Section II-B. Therefore, the inertia of the generator and the turbine rotor do not automatically participate in the grid inertial response as would traditional synchronous generators. Further, because of this decoupling, changes in grid frequency do not elicit an automatic governor response that is common with conventional generation sources.

Increasingly, there are two main motivations for why APC should be provided by wind turbines. The first motivation is that regulation is essential for maintaining grid frequency and as wind penetration increases it can provide key support in maintaining the required balance. A FERC/LBNL (Federal Energy Regulatory Commission/Lawrence Berkeley National Laboratory) study discusses a recent decline in grid frequency response, and states that although increasing wind penetration is not the cause, frequency response could be improved through the expanded use of frequency control capabilities in wind turbines [22, 23]. Further, a recent study by the IPCC (Intergovernmental Panel on Climate Change) found that although low to medium wind penetrations (up to 20% of annual demand) poses no "insurmountable technical barriers," higher levels could require additional flexibility options such as greater use of wind power curtailment and output control [24]. As wind energy penetration increases, it is potentially displacing regulation-providing generators. At very high wind penetration levels it becomes necessary for wind turbines to also provide these services [21] as it has for several European grid operators.

In countries and regions with relatively isolated grids and relatively large levels of wind penetration, participation in grid frequency regulation by wind turbines and wind plants is crucial. A 2010 report issued by Project UpWind [2] indicates that replacing conventional generation sources with a large percentage of wind power not capable of active power control can potentially have significant impacts on stability of grid frequency. This effect is pronounced on island grids with low levels of interconnectivity to other grids, such as many of the Greek isles [25].

The necessity of participation in grid frequency regulation by wind turbines is reflected in the requirements and regulations put on wind plants by TSOs in regions with high levels of wind penetration or relatively isolated grids. For example, the Irish grid code requires that wind plants have active power curtailment capabilities, and outlines specific active power generation set-points as a function of available power in the event of a frequency deviation [26]. This code further specifies a minimum response rate for individual turbines of 1 % of rated power per second. Elsewhere, Denmark's TSOs Eltra and Elkraft require that wind plants be able to track a reserve power offset and track reference power levels generated by the system operator [27]. In Canada, Hydro-Québec requires that wind plants rated above 10 MW have the ability to modify their active power output for at least 10 seconds in response to grid frequency deviations greater than 0.5 Hz [28]. Additionally, the Spanish TSO, Red Electrica, mandates that wind plants respond to frequency deviations with proportional control of active power output within a range of percentages of rated power [29].

The second motivation for active power control by wind turbines is the potential to increase the profitability of wind plants by enabling participation in ancillary service markets. A recent study by Kirby demonstrates a potential for wind plants to "increase their own profits by providing regulation" [30].

C. Industry Activity in Support of APC

The various active power control requirements laid out by grid operators have motivated technological development by wind turbine manufacturers. These developments have been made at both individual turbine and wind plant scales. Technologies to provide response in all of the inertial, primary, and secondary time scales have been developed at the individual turbine level. For example, Siemens has patented a method for dynamically modifying an individual turbine's active power output in response to grid frequency deviations

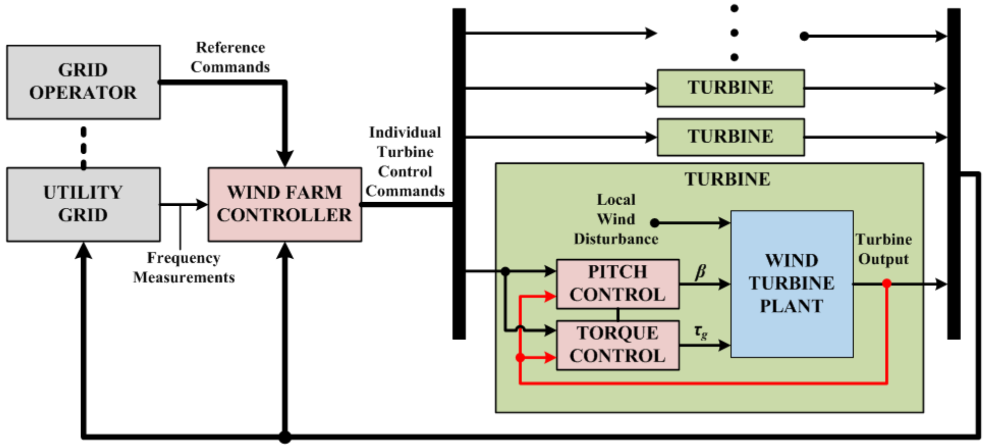

Fig. 7. A block diagram that shows the general interconnection for APC commands. The wind plant controller can measure the frequency of the utility grid and receive a power command signal from the grid operator and in turn produce a power reference for each turbine in the wind plant.

on time scales similar to inertial and fast primary responses [31]. Methodologies for monitoring power available in the wind and maintaining a specified amount of active power in reserve are patented by both Mitsubishi [32] and Vestas [33], respectively. In another patent, participation in primary and secondary regulation is achieved by using blade pitch control to specify a percentage of available power as an active power reserve, which can be changed up or down in response to grid frequency fluctuations [34].

Methods for providing active power control of entire wind plants have also been developed. Performing active power control collectively across a wind plant is intended to provide faster response and recovery to grid frequency deviations than can be achieved by performing active power control on individual turbines separately. These plant scale technologies, like those patented by Mitsubishi [35], Ingeteam [36], and General Electric [37], have focused on monitoring and forecasting available power in the wind, so that total active power generation by the wind plant can be controlled. Additionally, these patents claim to develop intelligent strategies for communicating wind, power, and frequency conditions between individual turbines. An example of such a strategy can be seen in [36], where a subset of the turbines on a wind plant are used as observers to estimate power available, and the aggregate active power output of the wind plant is set to a percentage of the estimated available power.

Two Danish offshore wind plants, Horns Rev and Nysted, serve as examples of the current state-of-the-art of the industry. Both facilities are outfitted with active power control systems capable of responding to TSO power set-point commands and automatically responding to fluctuations in grid frequency [2]. They have several available operating modes to provide APC, as described in Section IV.

Patent literature is rich with technologies that are designed to meet performance demands set forth by TSOs and allow for control of active power output. It appears that current industry standards for maintaining an active power set-point is performed using pitch control on a relatively slow time scale, leaving inertial and primary response to be handled by controlling the generator and power electronics [2]. However, it would appear that much of this development, especially specific controller topologies, is proprietary information.

IV. Implementation and Ongoing Research of APC on Wind Turbines

In this section we present an overview of the existing implementation and the ongoing research of APC on wind turbines. These two topics are combined into one section because the current methods of implementation of APC are not made explicitly clear by turbine manufacturers. Fig. 7 shows an example of a standard interconnection of a wind plant controller with the TSO or grid operator, utility grid, and the individual turbines. The individual turbine can follow the power reference from the wind plant controller by altering the standard generator torque and blade pitch feedback loops, which are described in Section II-C. Increasing the regulation performance of a wind turbine control system can be complicated due to a number of factors, including coupling with existing control loops, a desire to limit actuation usage and structural loading, and wind variability.

As described in Section III, several European TSOs now have requirements for new wind plants to provide inertial response emulation to frequency events and to track either a delta or absolute power reference signal at a required slew rate. The new requirements by the TSOs have lead to the development of APC on wind turbines to meet two different goals. The first is ‘automatic frequency control’ which is designed to emulate the inertial response of conventional generators over a limited time window immediately following a frequency event. The second goal of APC controllers is met by tracking a power reference from the TSOs over longer time scales as a secondary, or AGC response. The minimum requirements have been met by manufacturers, but ongoing research is being performed to improve the implementation of such controllers and to determine the extent of the regulation capabilities that can be provided

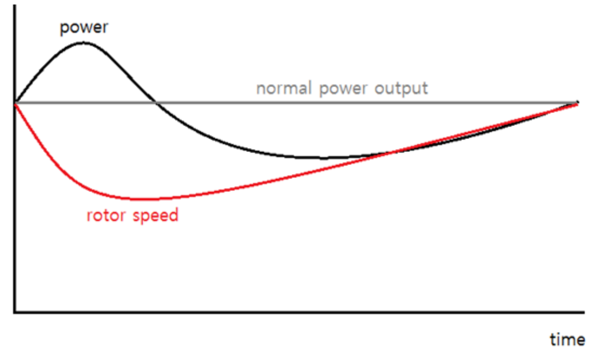

Fig. 8. Inertial response emulation showing sudden electrical power increase with a long recovery period.

by wind turbines. These areas of on-going research include variations of control methodologies to implement inertial or AGC response, advanced controllers that combine torque and pitch control to implement primary control during frequency events, and analysis of impacts on turbine lifespan induced by implementing active power control strategies.

A. Inertial and Primary Response

Inertial response emulation, which is also referred to as inertial control or kinetic energy control, is now required by several European TSOs (Section III) to help regulate the grid frequency when events occur such as that depicted in Fig. 6. This response is implemented in a wind turbine or wind plant by measuring the frequency of the utility grid and using a control algorithm to vary the output power to compensate for deviations in grid frequency. The inertial control is performed over a short time scale typically by the generator torque control to emulate the built-in response of a conventional generator [2]. Wind turbines have the capability of providing more inertial frequency regulation than conventional generators per unit of spinning inertia, due to the speed at which the power electronics can actuate the torque command signal [7].

Inertial response emulation typically provides fast increases (or decreases) in the power production through sudden increases (or decreases) in the generator torque. It is more common to have a conventional generator fail than for a large load to drop from the grid, so here we look at the case where there is a demand for a sudden increase in turbine power. A rapid increase in generator torque will cause the rotor to decelerate while power is produced above the power set-point, as shown in Fig. 8. The downside of this method is a danger of the turbine stalling and possible added loading on the mechanical parts. This response is used to increase power in the short term and often requires a period of recovery as depicted in Fig. 8. This recovery period can be problematic in that it can cause the wind turbine to produce less power after the inertial response, which could adversely affect grid frequency. However, research in [38] shows that inertial response emulation can sometimes be more effective than inertial response from conventional generators in coal power plants, covering a wider frequency range.

There are multiple approaches to extract additional power from the spinning rotor mass and still handle recovery. Both [39] and [21] use the previously mentioned method of quickly increasing torque in response to grid frequency falling, which thus causes a deceleration of the rotor speed and is called “Kinetic Energy Control I (KEC I)” and “GE WindINERTIA,” respectively. While some variation of KEC I is the most intuitive method for inertial response emulation, [39] goes on to propose another method called “Kinetic Energy Control II (KEC II),” which allows the rotor to accelerate initially before applying the higher torque. The benefit of KEC II is that the turbine power and rotor speed do not fall below normal operation speed throughout the whole course of power extraction, eliminating the recovery period and preventing turbine stall. However, a temporary over-speed can be caused when operating at rated power, and may not be a desirable solution. Another concern with KEC II is that the response speed could be delayed due to the speed-up process, and the magnitude of frequency drop can be more severe than with KEC I.

While conventional synchronous generators automatically provide inertial control and have governors for primary control, the distinction between inertial and primary responses is less clear for wind turbines without these governors. While patents for such technologies apparently exist, the methods by which primary response is achieved are generally not explicitly outlined. Consequently, primary APC of wind turbines is an ongoing area of research.

Another method of extracting additional power from the rotor inertia while enabling a primary response is covered in [40] and [41]. Both of these studies operated the turbine at higher than optimal tip-speed ratios to maintain a reserve of available wind power. With an overhead of un-utilized power, in an under frequency event, the controller can increase the generator torque to extract inertia from the turbine, causing the turbine to slow down to the optimal tip-speed ratio. These controllers therefore implement inertial response and a primary response as they produce a higher power output in response to the detection of under frequency events. This can be seen in Fig. 9, where if derated by 10% at 10 m/s wind speed and commanded to ramp up to rated power, the turbine would follow a trajectory from point A to point B. Pitch control is also used in [40] to derate the turbine and add to the primary response, but there is no consideration of stability issues arising from the interaction between the torque and pitch control loops, and simulations were only performed under constant, uniform winds. The fundamental concept in these works is worth noting, but further research in this area is required as neither [40] or [41] address the persistent over-speeding of the turbine while running in above-rated winds or the controller’s effect on the structural loads of the turbine.

Inertial and primary control can be implemented and simulated at the wind plant level. Patent literature, such as [36], suggests that intelligent, distributed response of an entire wind plant to a frequency disturbance could potentially minimize overall grid frequency deviation and improve

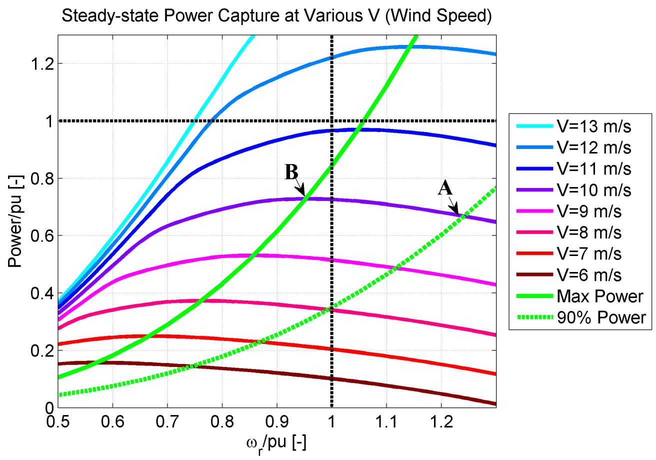

Fig. 9. Various steady-state power capture curves for given wind speeds. The 'Max Power' line is the trajectory of the turbine that achieves maximum power capture for each wind speed and the '90% Power' line is the trajectory that leaves 10% overhead power via rotor speed control. The axes are normalized to the rated values.

recovery speed. Primary grid response to frequency disturbances with varying levels of penetration by wind plants with active power controllers was simulated in [42], with results suggesting that participation in frequency response by wind plants can greatly increase grid robustness and reduce the maximum frequency deviation from nominal during a disturbance. This simulation consisted of the grid represented as an electrical bus and analyzed the effects of the wind plant APC controller when a conventional generator goes offline. While these simulation results are promising, the simulations themselves are limited by their use of a number of turbines much smaller than a typical wind plant and simplified models of turbines and turbine wake interactions.

B. Secondary (AGC) Response

A secondary (AGC) response consists of power plants raising and lowering power output in response to commands from the TSO. Conventional generators typically receive an absolute power reference from the TSO since the power plant can vary the fuel input to meet the power demand up to the plant's rated output. AGC capable wind turbines and plants also receive their power command signals from the TSO. These commands may be in terms of a 'balance control' or absolute power command signal (so long as that level of power is available from the wind) or a 'delta control' command which specifies the percentage of the available wind power to be captured. Using delta control ensures that there is a percentage of available wind power that is kept as overhead in case the TSO demands more power. There is also often a 'power gradient limiter' that is specified by the TSO which is a lower limit on the rate of change of wind plant power production to meet the TSO's setpoint [2].

1) AGC at the Turbine Level: The most popular methods for reference power tracking by wind turbines appear to be pitch angle control and rotor speed control. These methods intentionally achieve sub-optimal operation with lower C_p (Fig. 2) to track the power set-point provided by the TSO. Both [40] and [41] show that pitch angle and rotor speed controls are effective methods for primary and secondary controls of wind turbines. In addition, a similar control scheme called "GE WindCONTROL" [21] shows that the total plant level power output can be controlled to provide a desired response.

A recent study developed several novel combined torque-pitch controllers to respond as quickly as possible to a change in power reference command [43]. Though this study assumes an absolute power reference AGC signal is provided to the turbine control system, a primary response can be achieved from this controller if the power reference signal is augmented to respond to variations in grid frequency (i.e. through a droop curve). Metrics for the speed of power tracking and turbine structural loads were included in the analysis of the designed controllers found in [43]. This is an important consideration, as much of the literature on APC controllers neglects the loads induced on the turbines by the control system. In order to determine structural loads induced on the turbine, simulations must be performed with a high fidelity turbine model under various operating conditions. An example of such simulations can be found in [43] which uses the FAST turbine simulation code developed by NREL [44].

It is also useful to perform field tests to validate a designed control system. The NREL National Wind Technology Center has the ability to test developed controllers on the 3-bladed Controls Advanced Research Turbine (CART3). The testing of one of the primary/secondary APC controllers found in [43] has been conducted on the CART3. The APC controller modifies CART3's actuator commands to meet the required power reference. Data from an example field test is shown in Fig. 10. This experiment tests an initial control design that adjusts the maximum rotor speed to track a power reference. The second subplot in Fig. 10 compares the measured and demanded output power of the turbine, and it can be observed that the control successfully tracks with the desired power reference. It would appear that this initial design can be improved, since excessive tower load fluctuations can be observed near 600 and 925 seconds, where the controller may be tracking changes in the power reference too aggressively.

2) AGC at the Wind Plant Level: As was discussed in Section III, basic grid support capabilities are currently implemented on some wind plants, such as Horns Rev and Nysted. Many TSOs also require that wind plants be able to modify total active power output. Correspondingly, previous and on-going research has investigated the ability for active power control to be implemented on a plant-scale level. Simulations using simplified wind plant models have been used to verify the performance of some of these control schemes.

A significant portion of the research into implementing AGC with wind energy has been performed at the wind plant level and has focused on plant-wide tracking of a reference power signal to achieve an overall active power reserve. For

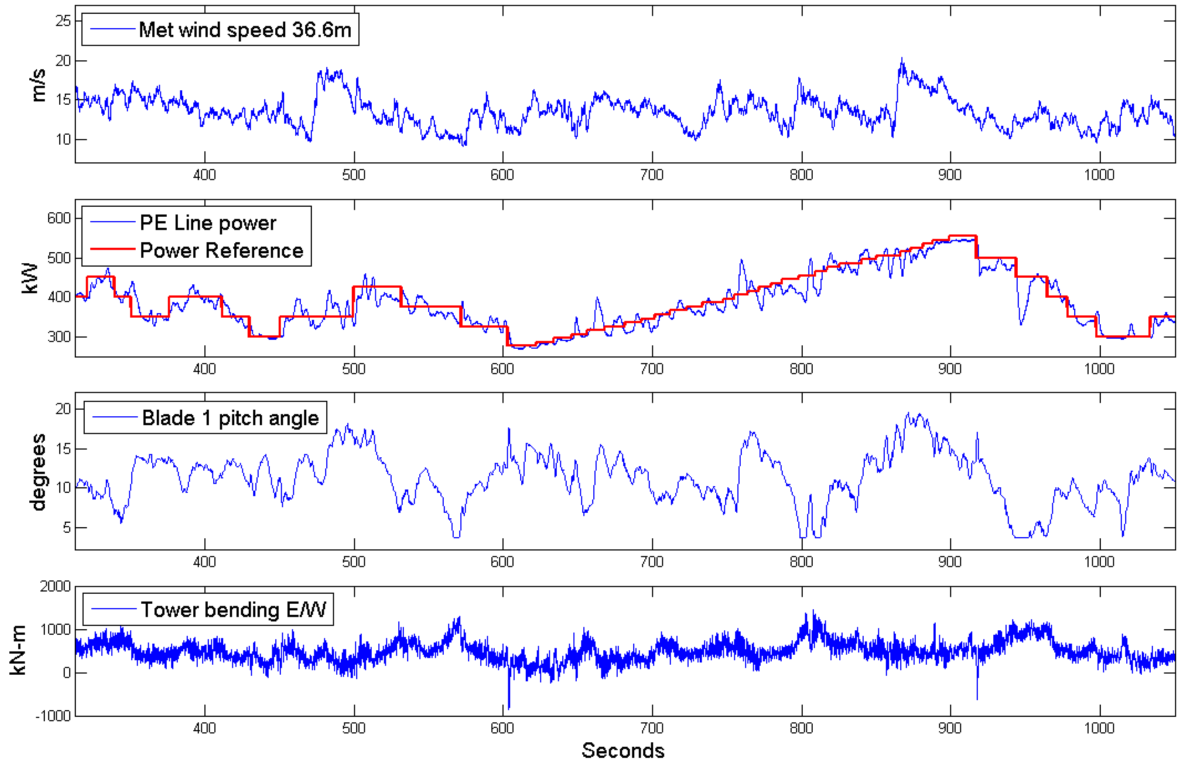

Fig. 10. Field-test data of power reference tracking on CART3 shows that sudden changes in the power reference induce increased tower bending moment. Further, note how the simultaneous change of wind speed and the power reference affect the power output. Figure from [43] (reprinted with permission)

example, Hansen et al. [45] propose using a plant-wide PI control loop to distribute power reference signals to individual turbines based on a TSO command for overall plant active power generation. Each of the turbines use a combined blade pitch/generator torque control strategy to track their individual power reference. Another method for wind plant active power tracking is proposed in [46]. Here, two plant scale controllers are used to respond to reference power commands by the TSO: a high level controller monitors mean wind speed and sets the overall plant operating point, while a lower level controller monitors local wind effects and adjusts the operating point based on power available to each turbine. Although sophisticated methods for power reference tracking and controlling active power output of wind plants have been developed, research of control methodologies specifically for concerted inertial and primary response to deviations in grid frequency appears to be sparse.

Simulations have been used to demonstrate active power controller capabilities of wind plants, or small groups of wind turbines. In [45], simulations demonstrate the robustness of a wind plant active power control strategy as the requested operation method of the wind plant is quickly switched between maximum power, balance control, and delta control modes. Long time scale simulations, on the order of multiple hours, have been performed to demonstrate active power forecasting and reserve capabilities of a wind plant [47].

The full potential and impact of APC controls at the wind plant level calls for more advanced simulation capability. Simulation tools that include high fidelity turbine models and controls capability like NREL's FAST code, usually consider a single turbine rather than a plant. FAST includes aerodynamic modeling based on blade-element momentum theory, but this does not account for far downstream wake effects that are important in wind plant simulation. In addition, it is common practice in controls simulations that the inflow turbulence is "frozen" and does not evolve as it encounters the turbine or with downstream distance. Tools relying on frozen-wake methods are likely insufficient for simulation studies of the viability of APC at the wind plant level. An advanced simulation tool called SOWFA (Simulator for Offshore Wind Applications) allows the simulation of multiple FAST actuator line models coupled with a CFD (computational fluid dynamics) solver that is capable of computing an evolving turbulent inflow and wakes that propagate downstream and interact with other turbines [48]. Variations in control inputs to individual turbines will cause variations in the wakes created and propagated by the CFD solver. Hence, this type of tool can potentially reveal sensitivities of proposed APC schemes across an entire wind plant.

V. Conclusion

In this paper we provided an overview of modern turbine control and discussed the recent development of active power control (APC) through wind turbine control systems. As wind energy continues to reach higher penetration levels, the role of wind turbines and wind plants in grid frequency regulation is becoming more important. Several European transmission system operators in countries like Spain, Denmark and Ireland now require that new wind plants have a number of APC capabilities, including emulation of inertial frequency response and power reference tracking, with the aim of using wind plants to assist in regulation of grid frequency. The decline of grid frequency stability in the United States further motivates the implementation of APC on wind turbines. This service could be beneficial even in areas without high penetration levels, as previous research suggests, grid frequency robustness can be enhanced by even a small number of wind turbines providing frequency regulation services. Ongoing research investigates the possibility of implementing an ancillary market for these regulation capabilities, as this type of market could potentially increase the economic viability of wind energy resources. If it is possible for wind plant operators to provide the services required for grid regulation without significantly increasing fatigue damage to the turbines or other turbine costs, like O&M, then wind energy might be viewed as an enabling resource for grid regulation objectives, aiding in wind energy penetrations higher than 20%.

While wind turbine manufacturers have developed the capabilities to meet the requirements set by European transmission system operators, ongoing research is being performed to determine the full capabilities of wind turbine APC. Various methodologies have been presented in literature for providing the different forms of regulation (inertial, primary, and secondary); however, further research on such methodologies is necessary. Areas of interest for future research include development of controllers that achieve faster response times to changing power demands, integration of controllers designed for inertial and secondary regulation, and optimal participation by wind plants over all regulation phases. Other areas of further research include development of strategies to balance aggressive power control against increased actuator usage and structural loads, and investigation into the potential coupling of active power control loops and conventional turbine control loops. Research into these areas can be augmented by simulations that demonstrate, for instance, the ability of a controller to provide one or all of the conventional capabilities while not preventing pre-existing turbine controllers from maintaining turbine safety and minimizing fatigue and extreme loading. Ongoing research will help determine the full benefit of widespread adoption of advanced APC services provided by wind turbines.

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