Energy storage in wind turbines: a strategic contribution to energy security

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Assessments in the following are based solely on the author’s personal opinions.

- One of the main constraints on the wide spreading of renewables is the lack of methods to store energy produced at times when there is little or no demand thereof.

- Another limitation is connected to the spreading of PV: the ever increasing lack of mechanical inertia in the electric grids.

- Wind Turbines (WT) may be able to alleviate both issues at a time:
  - *they can store a large amount of energy as kinetic rotational energy*
  - *they can provide a considerable inertia.*

- This is due:
  - *to the long blades, which have a large momentum of inertia and can therefore store much energy at times of strong wind;*
  - *to the ability to withstand large variations in rotational speed (e.g., 800-1600 rpm).*
- Thanks to these characteristics, WTs are able, if properly operated, to strategically contribute to energy security, by enabling storage of significant amounts of energy.

[3] Jacob Aho et alii, «Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control», Preprint – to be presented at the 2012 American Control Conference – Montreal, Canada, June 27-29,2012

«The wind turbine rotor cannot extract all of the energy from the wind stream , as this would require the wind to become stationary…The fraction of available power that a turbine does harvest is its power coefficient Cp(β,λ), which is a function of…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…»

«…two different configurations. The first employs a synchronous generator that…uses a full a full power converter…'type 4'…The second…use a doubly –fed induction generator (DFIG)…'Type 3'…Almost all large scale wind turbines use either type 3 or 4 generators, both…decoupled from the grid via their power electronics.»

[3] Jacob Aho et alii, «Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control», Preprint – to be presented at the 2012 American Control Conference – Montreal, Canada, June 27-29,2012

«…Turbines operating on the interior of a wind plant are often subject to wakes of upstream turbines…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-innducing turbulence….One method…involves operating the upwind rows of turbines…at a decreased efficiency to reduce wake…increasing overall plant power capture…Such a scheme could be tuned to the current atmospheric stability…since wakes persist more strongly in a more stable (nightime) atmosphere. »

[3] Jacob Aho et alii, «Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control», Preprint – to be presented at the 2012 American Control Conference – Montreal, Canada, June 27-29,2012

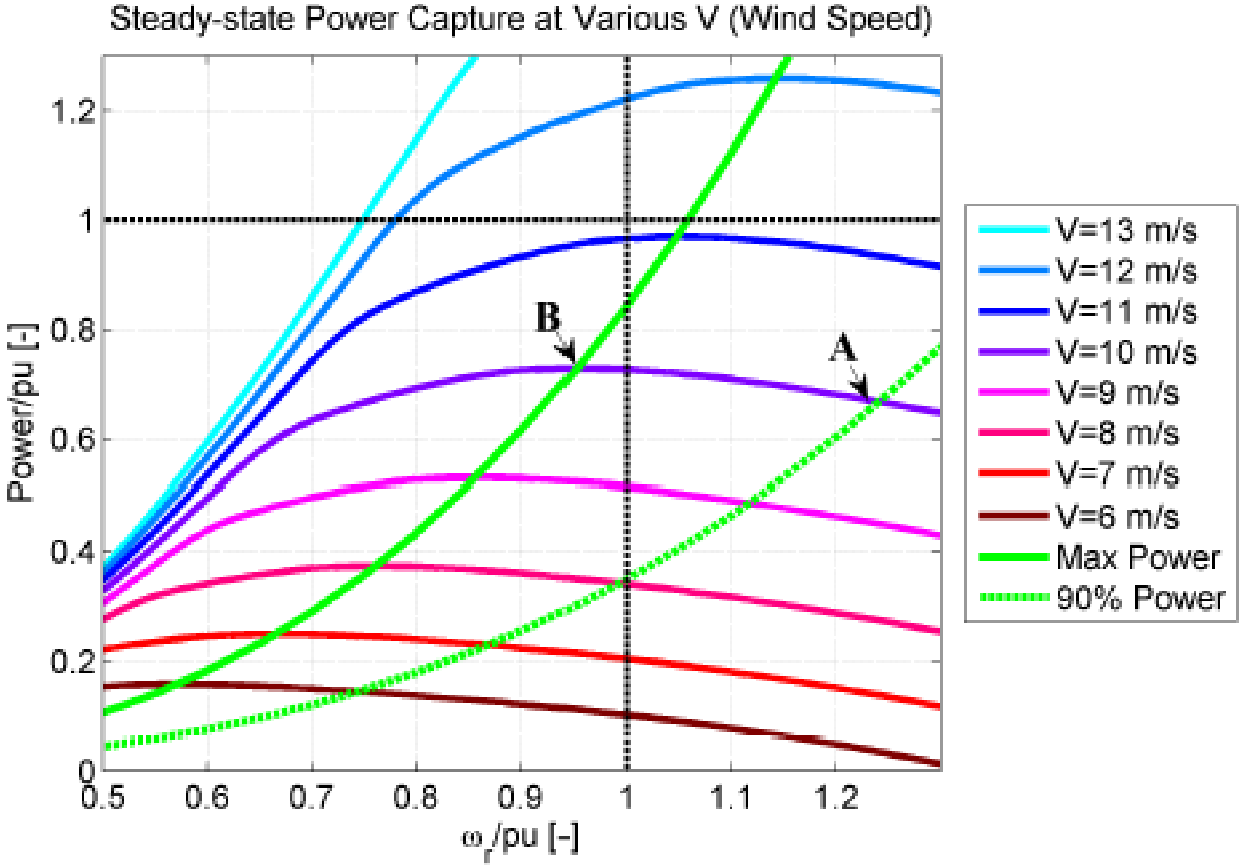

Fig. 9. Various steady-state power capture curves for given wind speeds. The 'Max Power' line is the trajectory of the turbine that achieves maximum power capture for each wind speed and the '90% Power' line is the trajectory that leaves 10% overhead power via rotor speed control. The axes are normalized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

[3] Jacob Aho et alii, «Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control», Preprint – to be presented at the 2012 American Control Conference – Montreal, Canada, June 27-29,2012

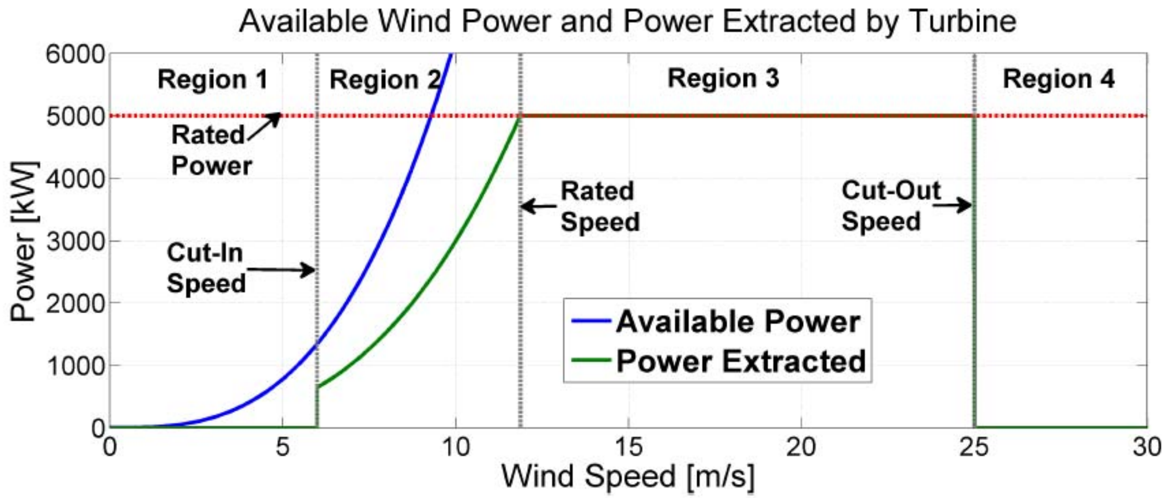

Fig. 3. Wind power, turbine power, and operating regions for an example 5 MW turbine.

<u>Region 2: below rated:</u>

- Primary goal: to capture as much power as possible. The power coefficient Cp changes with both blade pitch and TSR.
- In Region 2, blade pitch is typically held constant at the value that produces maximum Cp.
- The goal is then to maintain TSR at optimal level. Hence, tip-speed (and therefore rotor speed) must vary proportionally to wind speed.
- This is achieved by varying generator torque.

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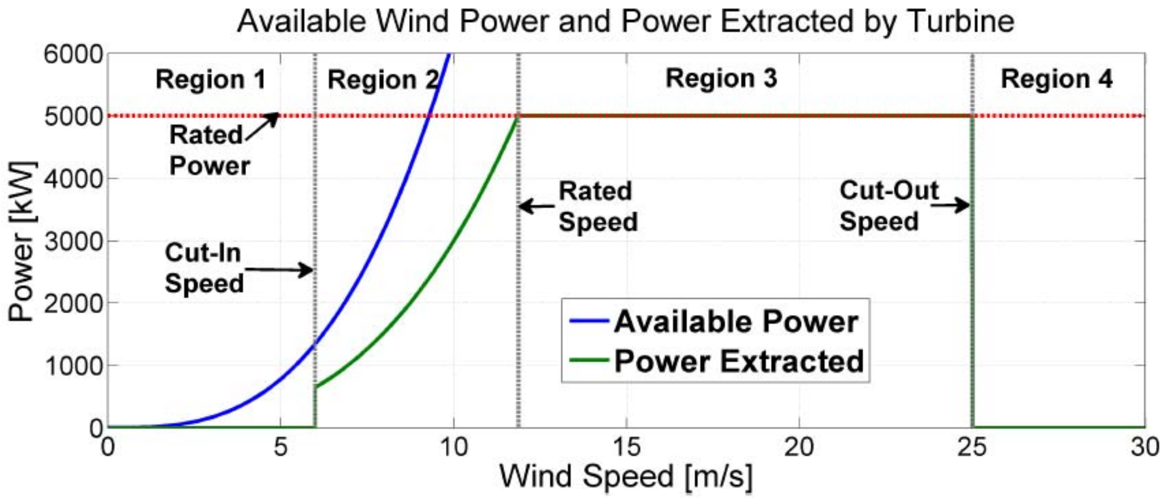

Fig. 3. Wind power, turbine power, and operating regions for an example 5 MW turbine.

<u>Region 3: above rated:</u>

- Primary goal: to **<u>regulate</u>** generator **<u>speed</u>** at **<u>rated</u>**, by **<u>shedding</u>** extra **<u>aerodynamic power</u>**.
- This is done using blade pitch control.
- The blade pitch control typically uses proportional-integral (PI) control on the generator speed error to regulate the generator speed at rated.
- Because the blade pitch regulates generator speed at rated, the generator torque can be held constant at rated torque. However, due to wind turbulence, at times the generator speed may vary more than 5% from rated speed.

- We have chosen a market WT, for which a data sheet is available.
- For this WT, we have considered the maximum and the minimum allowable rotational speed, and calculated the corresponding rotational energies.
- The difference between those energies is the energy that can be stored and, when needed, fed to the grid.

	Momentum of Inertia (high speed shaft)	Omega	Omega		Stored energy		P	P	
	Kg m2	rpm	Rad/sec		kWh		MW	kw	
Min speed	960,00	800,00	83,78	g	0,94	l		1.545,00	a
Max speed	960,00	1.600,00	167,55	h	3,74	m		1.545,00	
Rated speed	960,00	1.200,00	125,66		2,11			1.545,00	
			i=h-g		e=m-l				
		800,00	83,78		2,81			1.545,00	
					Energy available in a single WT (kWh)				
					f=e x c	c=b/a			
					17.098,30	6.091	9.409,90	9.409.900,00	b
					Energy available in ALL WTs (kWh)	N. of equivalent 1,5 MW wind turbines	Wind power (MW) in Italy, 2016 (source: TERNA)		
					n=f/4,5				
					3.800				
					N. of average (4,5 kW) households that can be supplied for 1 hour with that energy				

- Energy that can be extracted from wind farms in Italy would in theory be enough to supply 3800 average households for one our.

Why store wind energy?

- A survey on a wide sample of cogeneration (CHP) plants.
- More than four hundred CAR installations (or, more properly, “generating units”) were analysed .
- For each technology, a few efficiency indicators (weighted averages) for years 2011 and 2012 were assessed.

Why store wind energy?

- Electric efficiency: ratio of electricity produced by the CHP unit in a given year to energy (fuel) consumed to do so.
- Overall efficiency: takes into account not only electricity, but also useful heat produced. The sum of these two quantities is divided by the energy (fuel) consumed.
- “Heat Disposing Devices”, or HDDs: fans, cooling towers, exhausted gas bypasses, etc .

Why store wind energy?

	Total power (MW)		Overall efficiency		Electric efficiency		Heq (%)		PTOH		Load factor	
	HDDs		HDDs		HDDs		HDDs		HDDs		HDDs	
	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
Combined-cycle plants	727	8	0,54	0,82	0,45	0,27	71	77	5,06	0,49	n.a.	n.a.
Internal Combustion Egines (ICE)	64	16	0,68	0,83	0,39	0,42	51	28	1,39	1,03	0,86	1,03
Gas turbines	43	4	0,81	0,80	0,31	0,28	68	27	0,62	0,52	0,93	0,85

Table 1: operation data for the limited sample

- Combined cycle operation exhibits the biggest difference between plants with HDDs and without HDDs:

- HDDs are associated to **high electric efficiency**;

- HDDs are associated with **constant power output;**

- Hence, **high electric efficiency** requires **constant power output**.

Why store wind energy?

	Total power (MW)		Overall efficiency		Electric efficiency		Heq (%)		PTOH		Load factor	
	HDDs		HDDs		HDDs		HDDs		HDDs		HDDs	
	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
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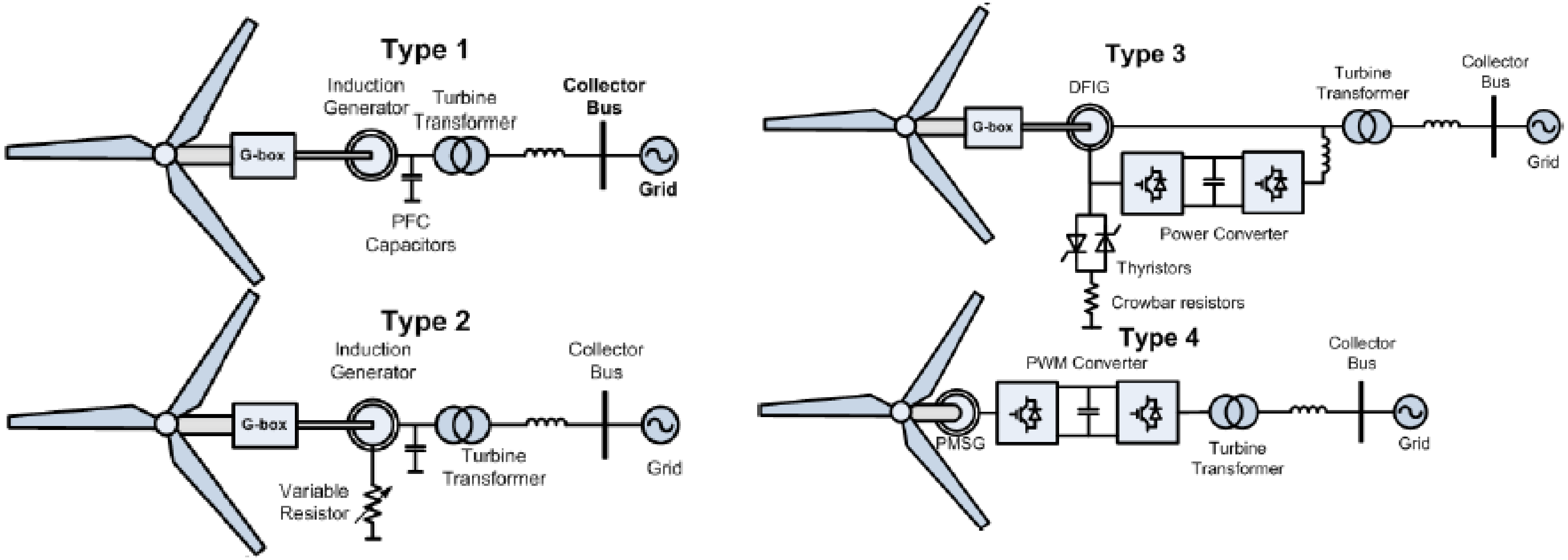
Table 1: operation data for the limited sample

- High electric efficiencies can only be achieved with a **constant** and **unperturbed** operation, which usually implies disposing of heat.
- This, in turn, lowers the overall efficiency.

- But…
- **Wind turbines can help**

[4] Muljadi, Fellow, IEEE, V. Gevorgian, Member, IEEE, M. Singh, Member, IEEE, and S. Santoso, Senior Member, IEEE,"Understanding Inertial and Frequency Response of Wind Power Plants", Preprint



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- …blade pitch control…used to avoid runaway conditions and keep the stresses on the mechanical components…within…design tolerance. The pitch angle…is usually controlled during high wind speeds to keep the aerodynamic power within limits; thus, the output power and rotor speed can be kept within boundary limits.
- ……the rotating mass of variable-speed wind turbines is decoupled from the grid frequency…

[4] Muljadi, Fellow, IEEE, V. Gevorgian, Member, IEEE, M. Singh, Member, IEEE, and S. Santoso, Senior Member, IEEE,"Understanding Inertial and Frequency Response of Wind Power Plants", Preprint

III. RESPONSES OF DIFFERENT TYPES OF WTGS TO A FREQUENCY DECLINE

The additional power… that a wind turbine can release…depends on the initial wind rotor speed. The change in rotor kinetic energy (transition from speed ω_0 to speed ω_1) can be calculated as:

$$\Delta E = \frac{1}{2} J(\omega_0^2 - \omega_1^2) = \frac{1}{2} J(2\omega_0 \Delta\omega + \Delta\omega^2) \text{ [Joule]} \quad (1)$$

Where J is wind rotor inertia [kg m2], and $\Delta\omega$ is change in rotor speed.

The power released can be estimated as:

$$\Delta P = \frac{\Delta E}{\Delta t} \quad \text{[watt]} \quad (2)$$

[4] Muljadi, Fellow, IEEE, V. Gevorgian, Member, IEEE, M. Singh, Member, IEEE, and S. Santoso, Senior Member, IEEE,"Understanding Inertial and Frequency Response of Wind Power Plants", Preprint

- As follows from…equations, the magnitude of ΔP depends on initial speed ω_0, drop in speed $\Delta\omega$, and duration of the drop Δt.
- … capability of injecting additional power into the grid makes it possible for wind power plants to participate in providing inertial response….
- the inertial response of the conventional generators…cannot be changed.
- In the case of wind turbines, the inertial response can be tuned….
- …main limiting factors…extra heat due to additional power generation and stress on mechanical components.
- The duration of inertial response is not long enough to generate thermal losses high enough to become a risk factor….
- The power electronic converters of WTGs usually have around 10% headroom because of their MVA ratings…

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…

B. Type 3 and Type 4 WTGs

The Type 3 and Type 4 WTGs are variable-speed WTGs. …power converter enables these types of WTGs to generate…power instantaneously at any commanded values. The variable-speed WTG can provide the power boost during the frequency decline **provided** that the generator, power converter, and wind turbine structure are **designed** to **withstand** the **overload** necessary. …

How to exploit wind turbines storing capacity

- First of all, a criterion is necessary to choose the time of day when energy should be stored and when is should be “de-stored”.
- Proposal: consider data about pumping.
  - High pumping can be regarded as a “symptom” of excess of energy.
  - Conversely, low pumping can be regarded as a “symptom” of lack of energy.

How to exploit wind turbines storing capacity

- Pumping storage spikes in early morning (e.g. from 206 MW to 1,106 MW between 1 a.m. and 2 a.m. on dec, 21st, 2016; source: TERNA).
- Apparently energy available exceeds demand: best time to store energy in wind turbines.
- Thermal production decreases from 23,747 MW to 22,050 MW.
- 23,747-22,050 =-1,697 MW (-7%)

How to exploit wind turbines storing capacity

- Pumping storage drops in late afternoon (e.g. from 114 MW to 2 MW between 5 p.m. and 6 p.m. on dec, 21st, 2016; source: TERNA).
- Apparently, energy available is less than demand: best time to extract energy stored in wind turbines.
- Thermal production increases from 35,041 MW to 36,508 MW.
- 36,508-35,041= 1,467 MW (+4%).

How to exploit wind turbines storing capacity

- We have seen how important it is to keep thermal production as close to constant as possible, in order to get maximum efficiency.

- One could expect that modulation of pumping plants would make it possible.

- This is not the case. Why?

How to exploit wind turbines storing capacity

- A possible explanation: lack of “flexibility” due to large power (average plant power in Northern Italy : 340 MW; calculation based on TERNA data)

- Wind turbines can provide “fine tuning”.

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establishing a network code on requirements for grid connection of generators

(5) ‘power-generating module’ means either a synchronous power-generating module or a power park module;

(6) ‘power-generating facility’ means a facility that converts primary energy into electrical energy and which consists of one or more power-generating modules connected to a network at one or more connection points;

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(17)‘power park module’ or ‘PPM’ means a unit or ensemble of units generating electricity, which is either non-synchronously connected to the network or connected through power electronics, and that also has a single connection point to a transmission system, distribution system including closed distribution system or HVDC system;

(18) ‘offshore power park module’ means a power park module located offshore with an offshore connection point;

COMMISSION REGULATION (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators

Article 14

General requirements for type B power-generating modules

…2.Type B power-generating modules shall fulfil the following requirements in relation to frequency stability:

(a) to control active power output, the power-generating module shall be equipped with an interface (input port) in order to be able to reduce active power output following an instruction at the input port; and

(b) the relevant system operator shall have the right to specify the requirements for further equipment to allow active power output to be remotely operated.

Conclusions

- WTs can be employed to meet the two most important needs of electric grids: storage capacity and rotational inertia.
- This can be achieved merely by properly operating the WT and specifically by controlling its blade angle.
- Only minor software modification (control system) are needed, but not hardware.

Conclusions

- Energy storage is a possible, strategic contribution to energy security that can be expected of WTs.
- It is recommendable that energy storage by means of WTs be considered by international organizations and be specifically addressed in future releases of European Directives, International Standards and Grid Codes.
- A few basic requirements are already in force.

Thank you for your attention

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