Game Theory Approach for Interactive Wind Farm Control

Arman Kiani and Robin Franz

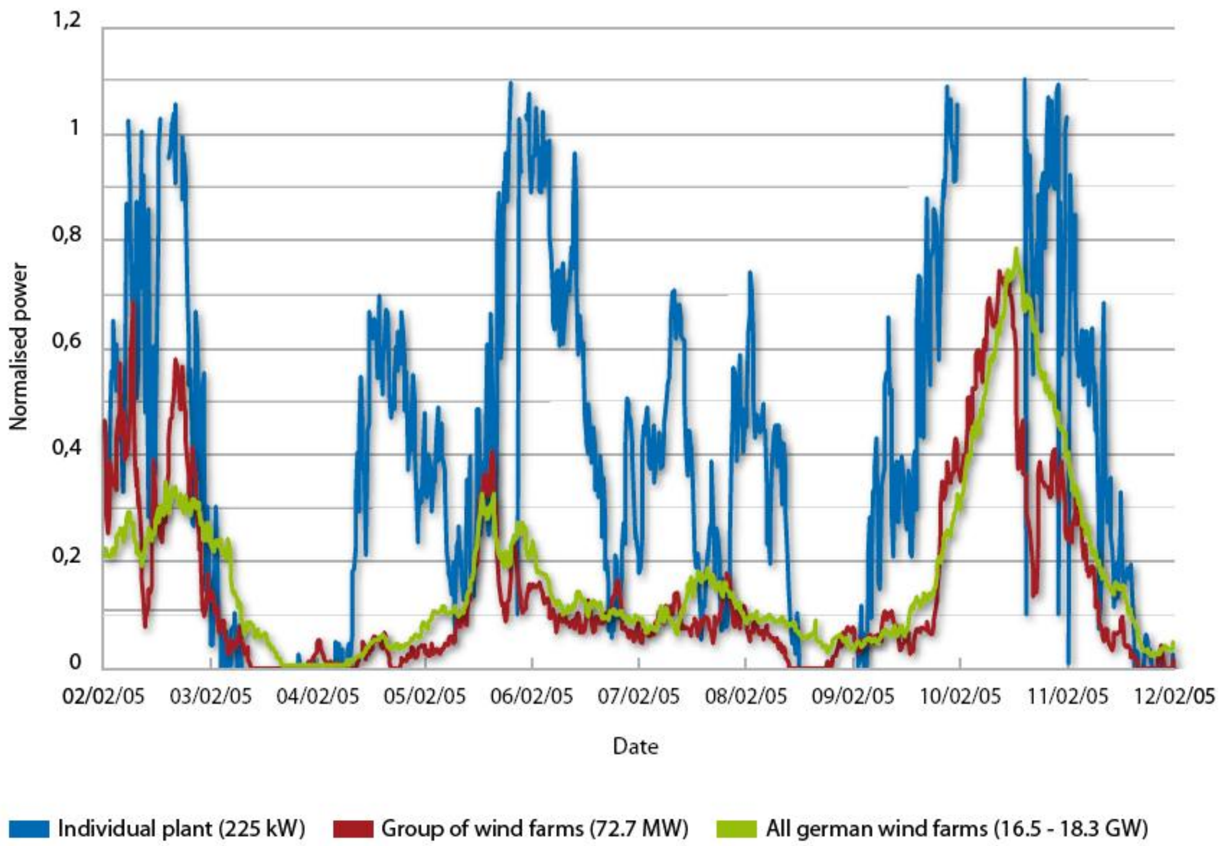
Institute of Automatic Control Engineering,
Technische Universitat Muenchen, Germany,

Active Adaptive Control Laboratory,
Massachusetts Institute of Technology (MIT), USA

Arman.kiani@tum.de

Motivation

- Why Wind Farms?
  - Renewable energy is experiencing higher priority than ever before.
  - Overall power output of a Wind Farm is less volatile than the power output of a single turbine. ⇒ Power output of Wind Farm can be fed more efficiently to power grid.



[1] ISET (2006), *Wind Energy Report,* Institut für Solare Energieversorgungstechnik, Kassel, Germany

Motivation

- Why Control of Wind Farm?
  - Wake of an upwind turbine is influencing the power output of the downwind turbines.
  - Losses up to 40% due to wake [2].
  - Smart Control needs to take into account the above mentioned interaction between turbines.

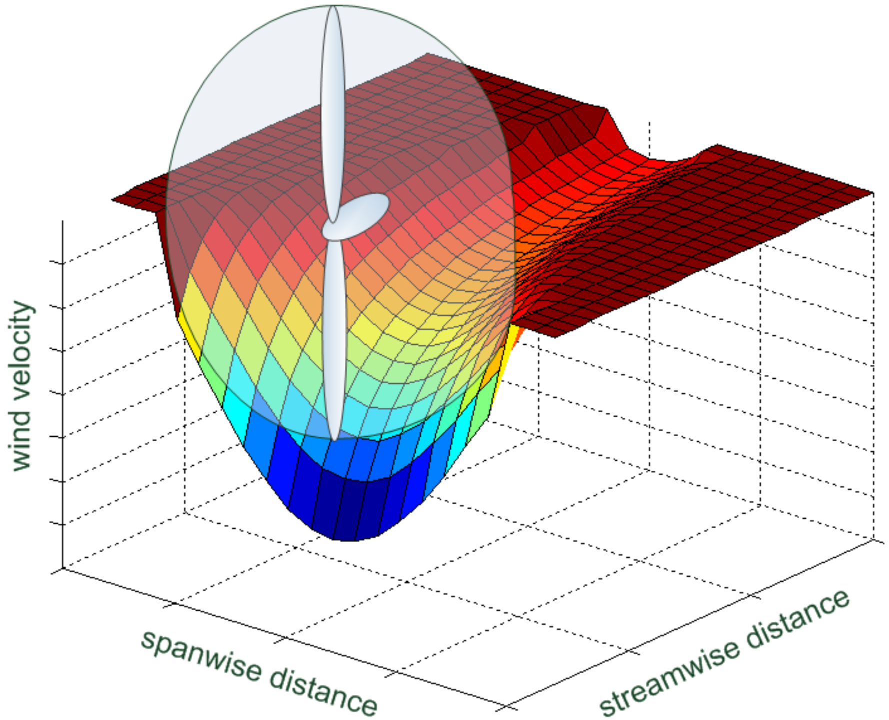
[2] A. Crespo, J. Hernandez, and S. Frandsen, *Survey of Modelling Methods for Wind Turbine Wakes and Wind Farms,* Wind Energy, 2, 1-24, 1999

[3] Horns Rev 1 owned by Vattenfall and Dong Energy. Photo by Christian Steiness, http://nanosync.wordpress.com/page/3/

Table of Contents

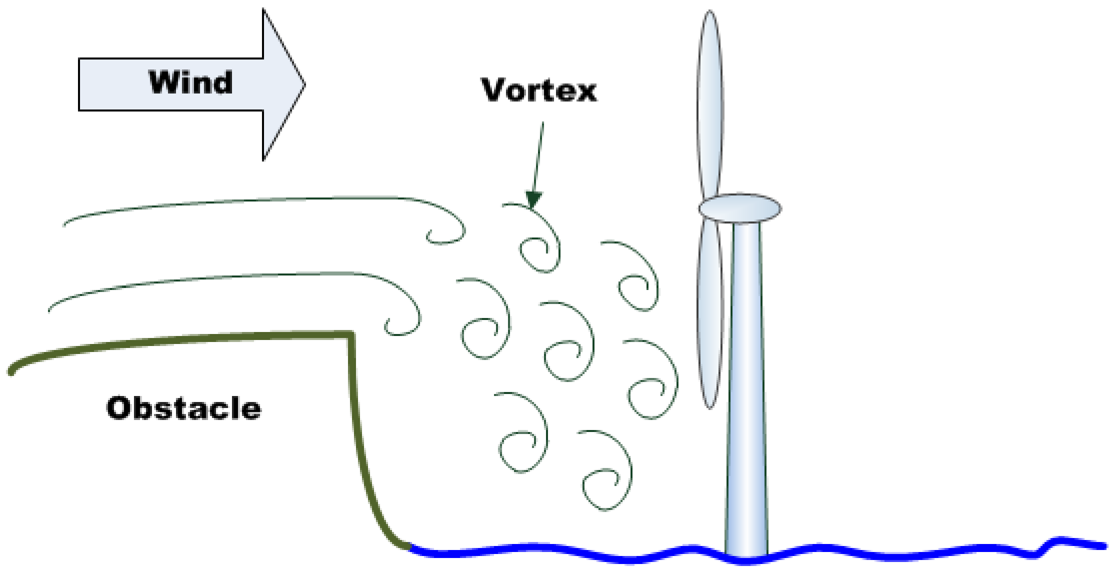
Wake of Wind Turbines

- Wake of turbine is the air flow in the downwind region of the turbine.
  - Reduced velocity due to the turbine extracting kinetic energy from ambient air flow (wind) right behind the turbine.
  - Interaction between turbines.



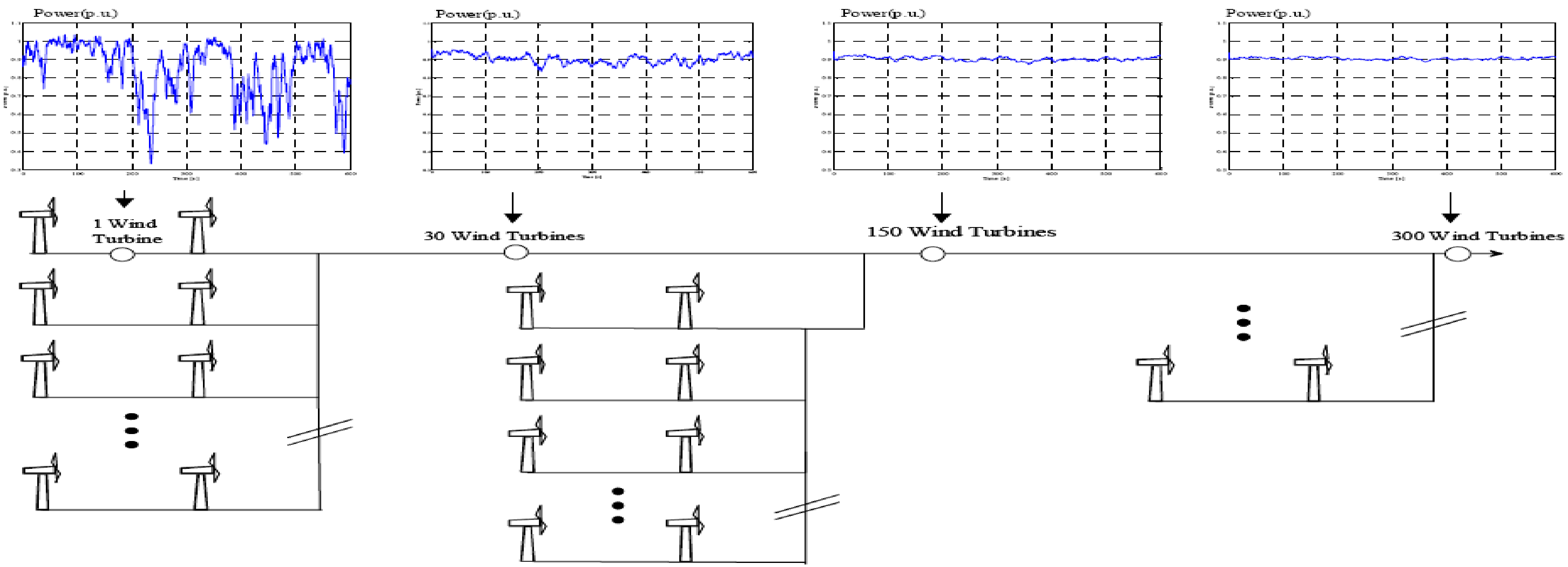
Turbulence and Wind Turbines

- Turbulence is the non-laminar part of air flow.
  - Challenge for single turbines as well as Wind Farms because turbulence increase the variability of wind velocity.
  - Characterized by vortexes.



Single Turbine vs. Wind Farm

- Volatility of output power decreases if more turbines are considered.
- Turbulence has little effect on overall power output of the Wind Farm.



Our focus: Effect of wake within Wind Farms.

Wake Modeling: Considering Interactions of Wind Turbines

$$v_i = f_i(v_{i-1}, x_i, D_i, z_i)$$

where:

i : turbine number

v_{i-1}: Input wind velocity of turbine i

v_i : wake velocity of turbine i

x_i : distance behind turbine i

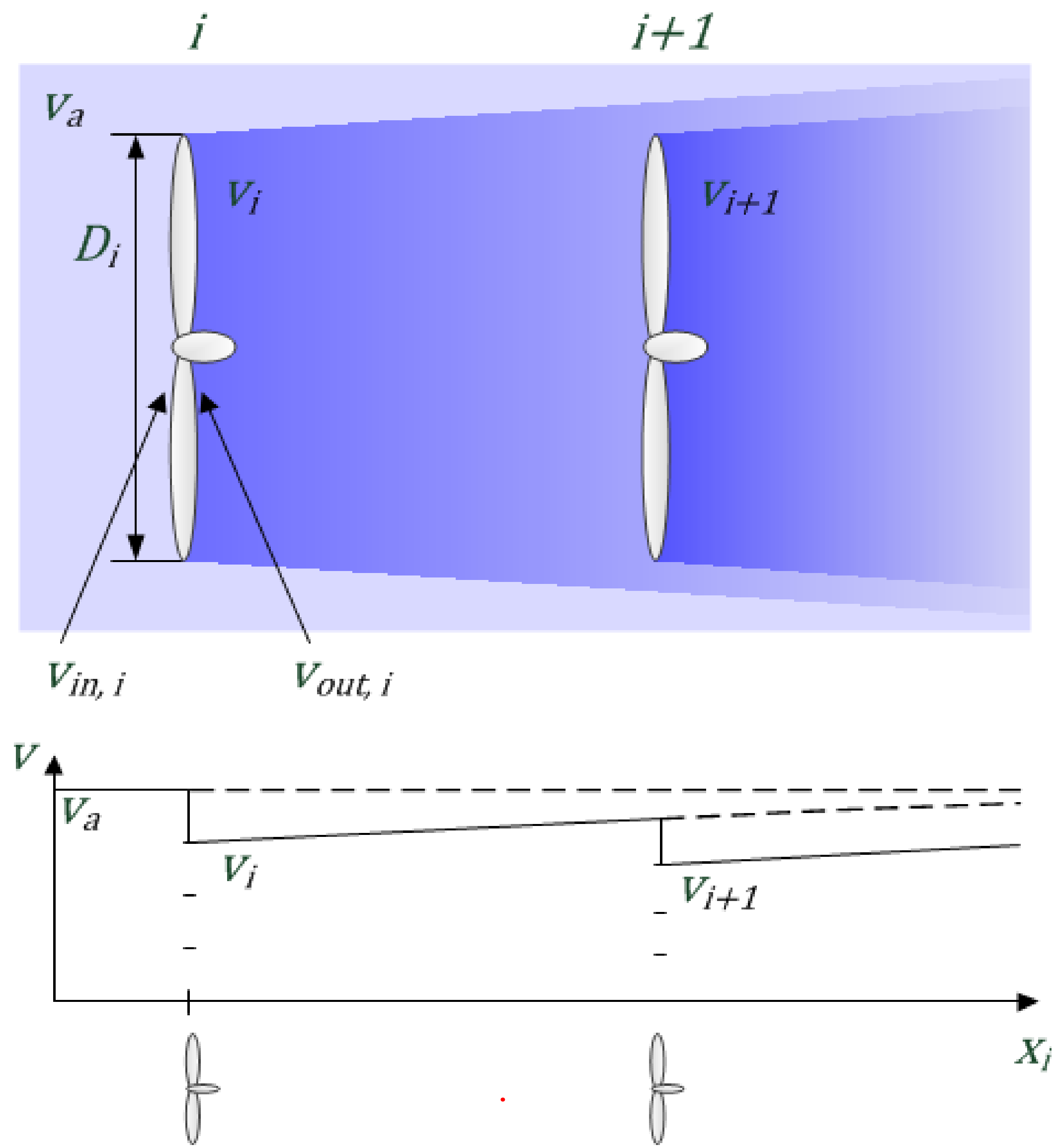
D_i : rotor-diameter of turbine i

z_i : $v_{out,i} / v_{in,i}$

$v_{out,i}$: velocity of wind right behind turbine i

$v_{in,i}$: velocity of wind entering turbine I

→ f_i highly nonlinear and complex in x



Wind Farm Challenges

- Power output of a single turbine i:

$$P_i = P_{wind}\, c_p(z_i)$$

where:

P_{wind}: *power of wind*

$c_p(z_i)$: *power efficiency coefficient as function of* z_i

For single turbine : $z_i = 1/3 \rightarrow P_i$ has its maximum. [5]

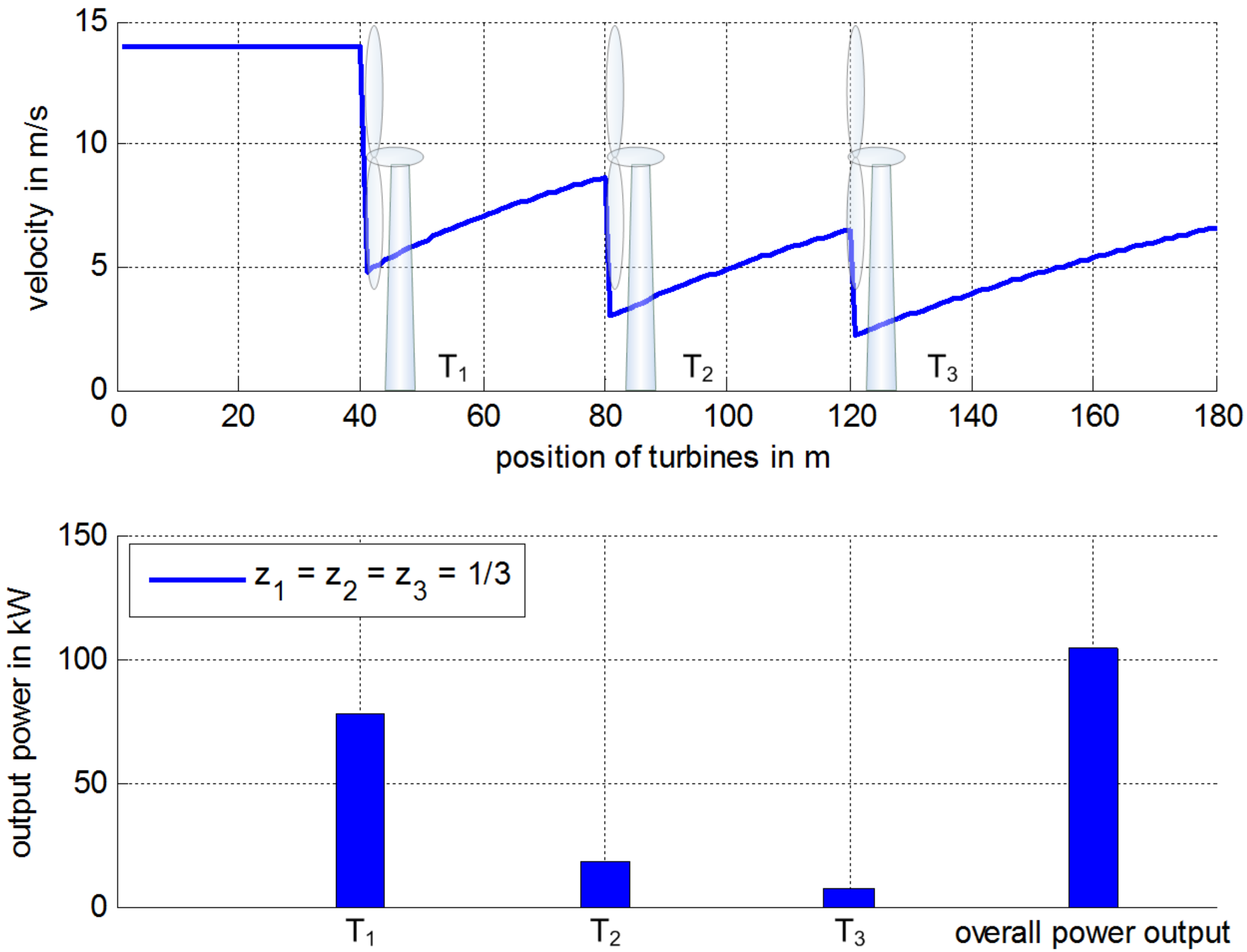
- Overall power output of Wind Farm

$\sum_{i \in N} P_i$, N: *number of turbines*

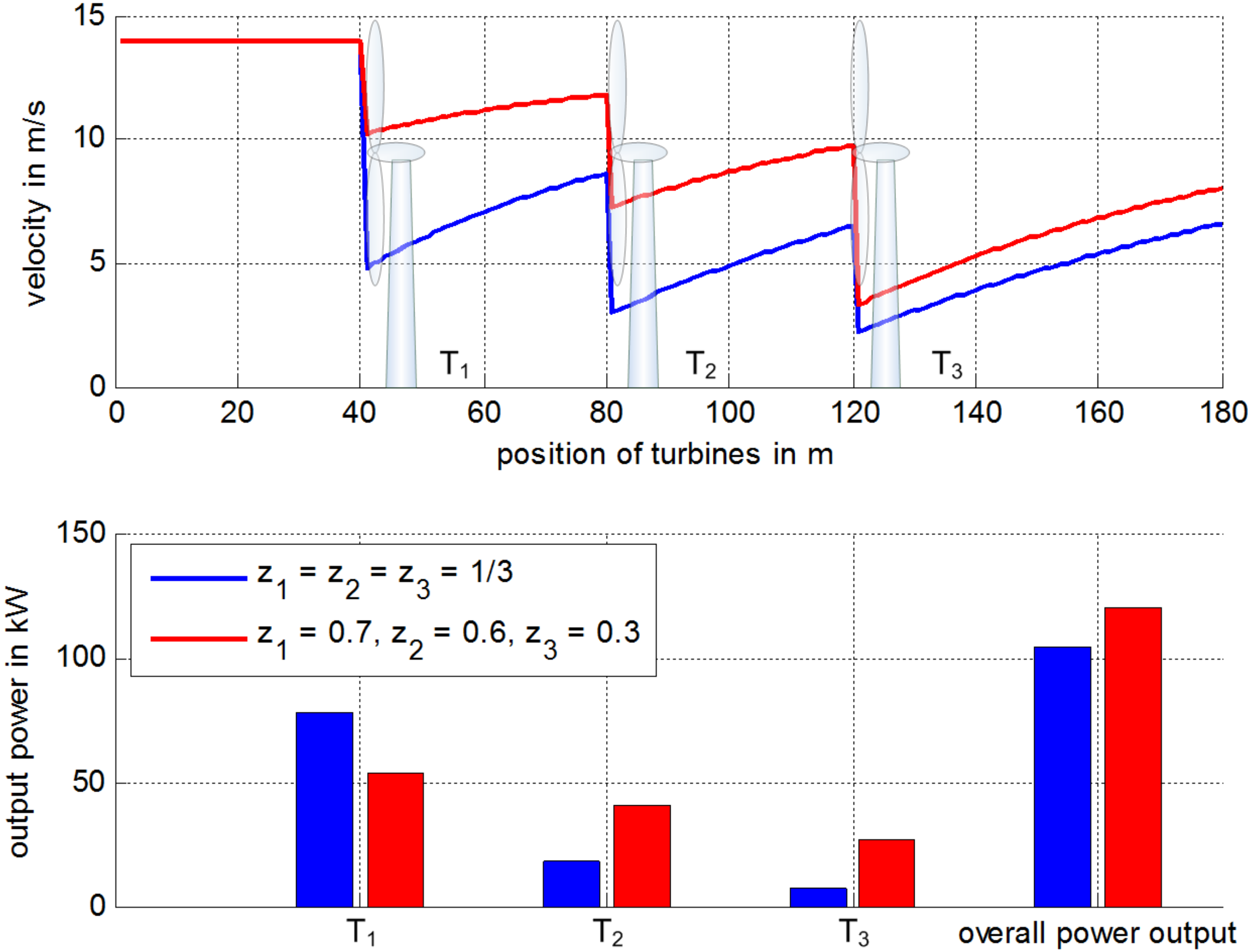
Goal: Maximize overall power output $\sum_{i \in N} P_i$.
Interaction of turbines due to wake has to be considered.

[5] Albert Betz, *Wind-Energie und ihre Ausnutzung durch Windmühlen,* Vandenhoeck & Ruprecht, Göttingen 1926; Ökobuch Verlag, Staufen 1994

No Wind Farm Control

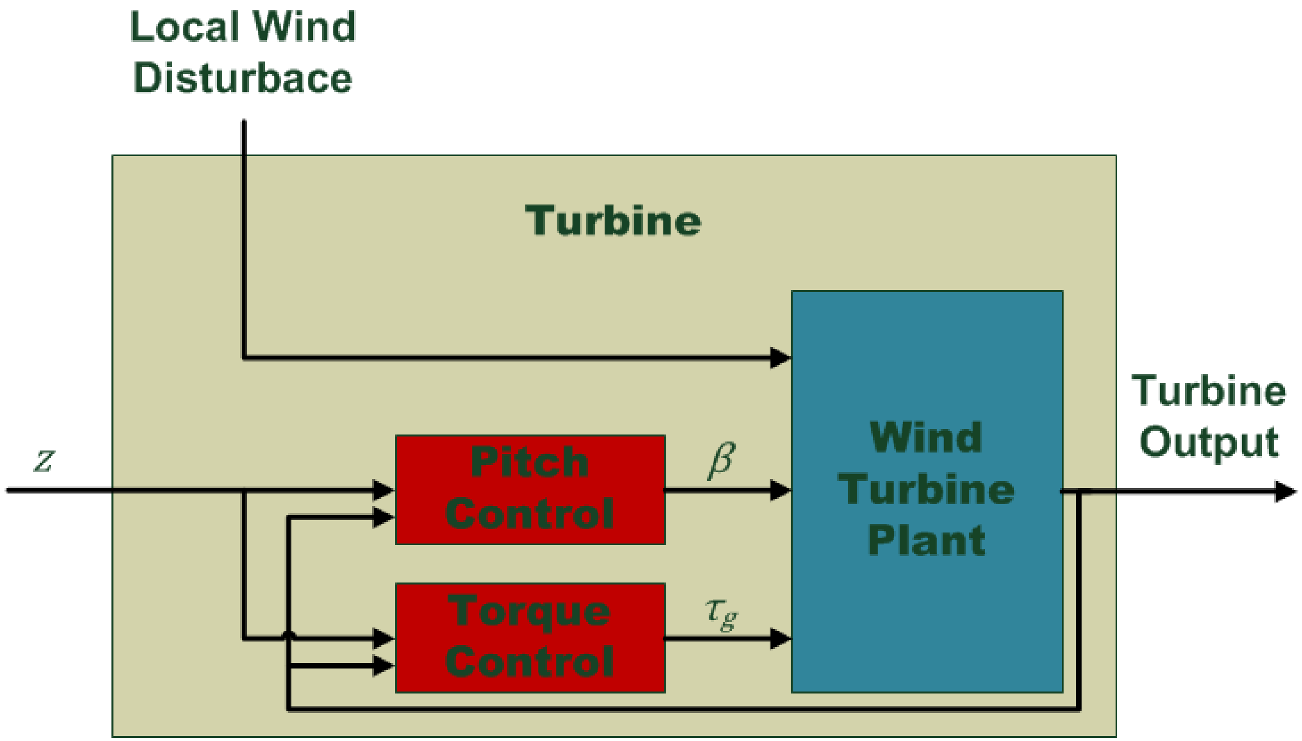


Wind Farm Control



Considering the interaction within a Wind Farm is needed for control to increase the overall power output.

Block Diagram of a Single Wind Turbine



β : pitch angle

τ_g : torque

$z : v_{out} / v_{in}$

v_{out} : velocity of wind right behind turbine

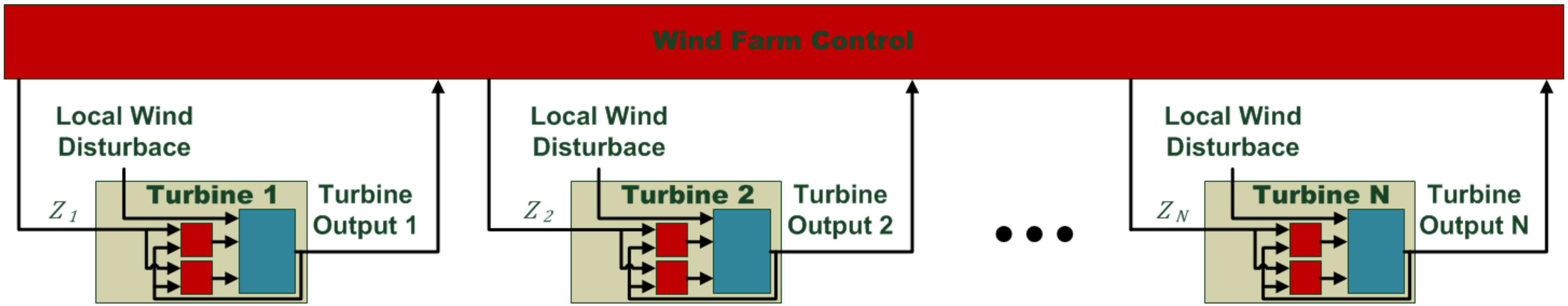
v_{in} : velocity of wind entering turbine

Central Control Structure of a Wind Farm

- Central Controller determines set-points to all turbines.

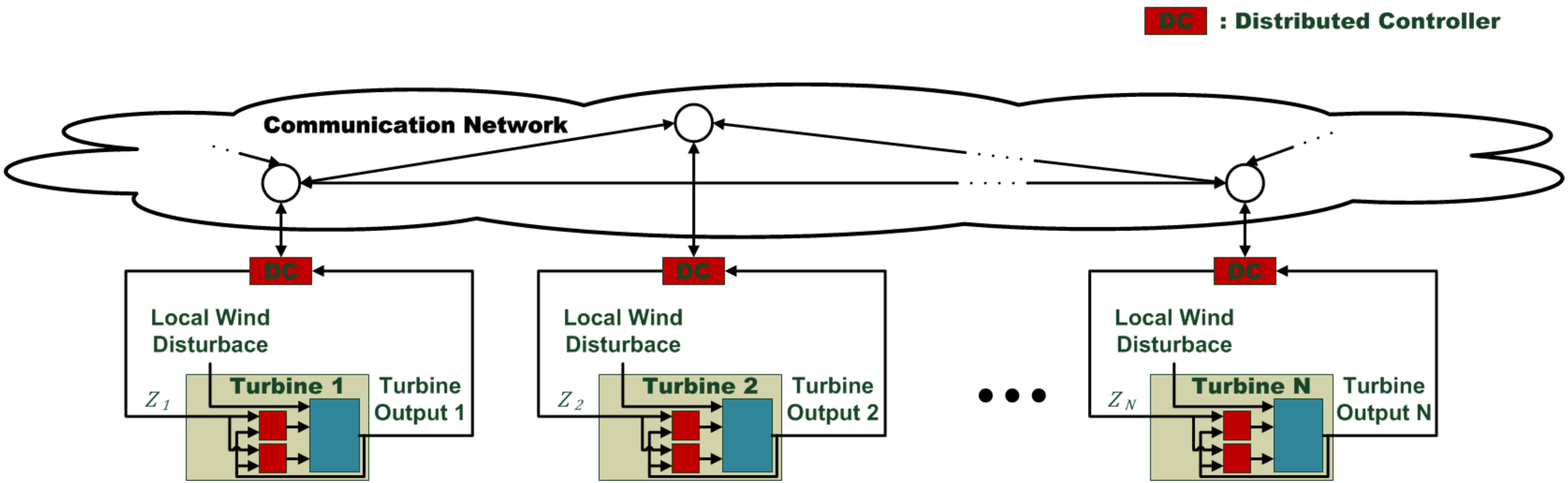
  → Due to the uncertainty and intermittency computing the real-time set-points is extremely complex.

  → No wake model is utilized for central control.



Our proposed method: Distributed control structure of a Wind Farm

- Each turbine interacts with its neighbors in order to maximize the overall power output.
- We propose coordination and collaboration of each individual wind turbine to collectively maximize the overall power output.

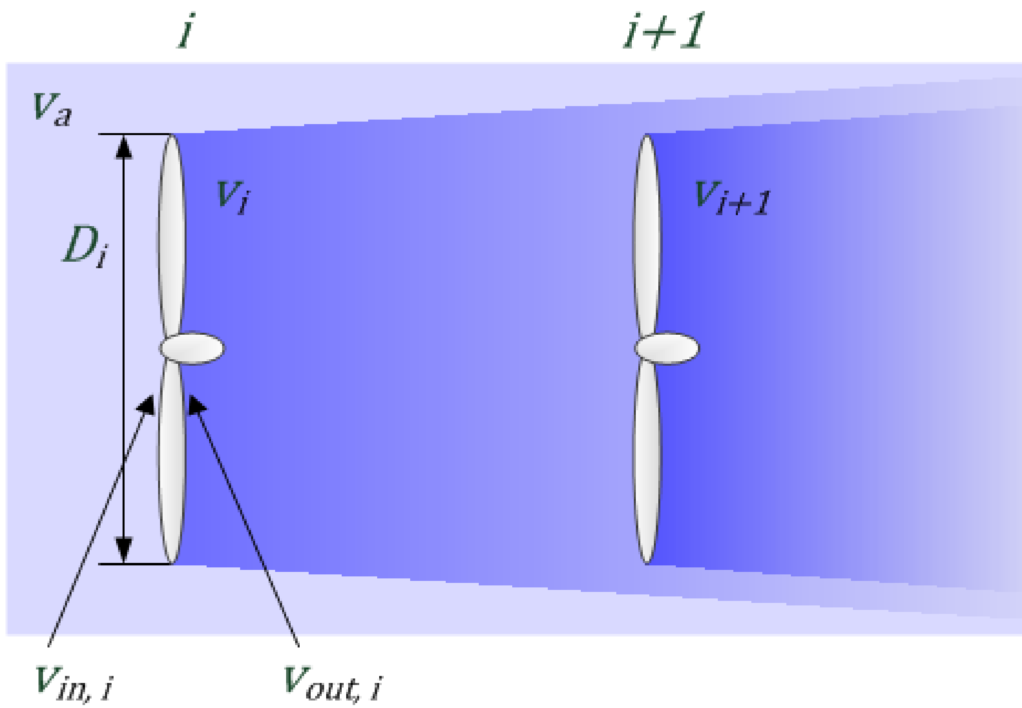


Our proposed method:
Distributed control structure of a Wind Farm

We are considering interactions between wind turbines using Game Theory
and designing the distributed control based on the notion of dynamic negotiation.

What is Game Theory Trying to Accomplish?

- **Point of Departure:** Game Theory as an interactive decision theory.
- **Assumption:** Individuals act rationally.
- **Observation:**
  - Dependence of the outcome on all the players actions.
  - The optimality of an action depends on the optimality of the other players actions.



Pitch Point: New mathematical framework required to take over the role of the optimum solution concepts in an **interactive environment.**

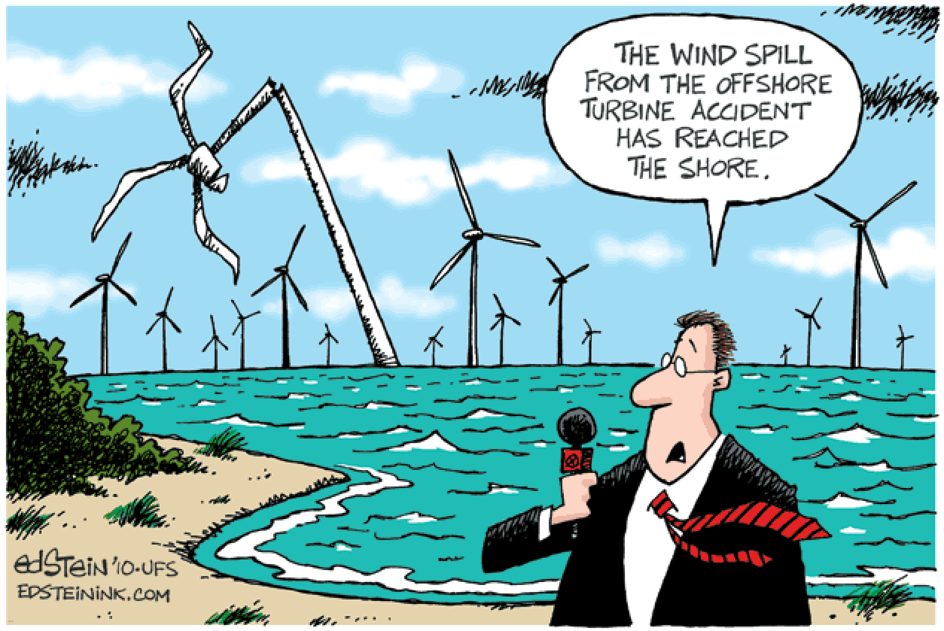
Nobel Prizes for Game Theory

1972	Arrow	Welfare theory
1978	Simon	Decision making
1994	Nash, Harsanyi, Selten	Equilibria
1996	Vickrey	Incentives
1998	Sen	Welfare economics
2005	Aumann and Schelling	Conflict and cooperation
2007	Hurwicz, Maskin and Myerson	Mechanism design

Strategic Form Games

- We consider games in which all of the participants act simultaneously and without knowledge of other players actions.

- For each game, we have to define
  - The set of players → Number of Turbines
  - The strategies → We need to design?
  - The payoffs → Output power



- More generally, the order of play (e.g., in chess) and information sets (e.g., in asymmetric information or incomplete information situations) are also needed.

Strategic Form Games for Interactive Wind Farm Control

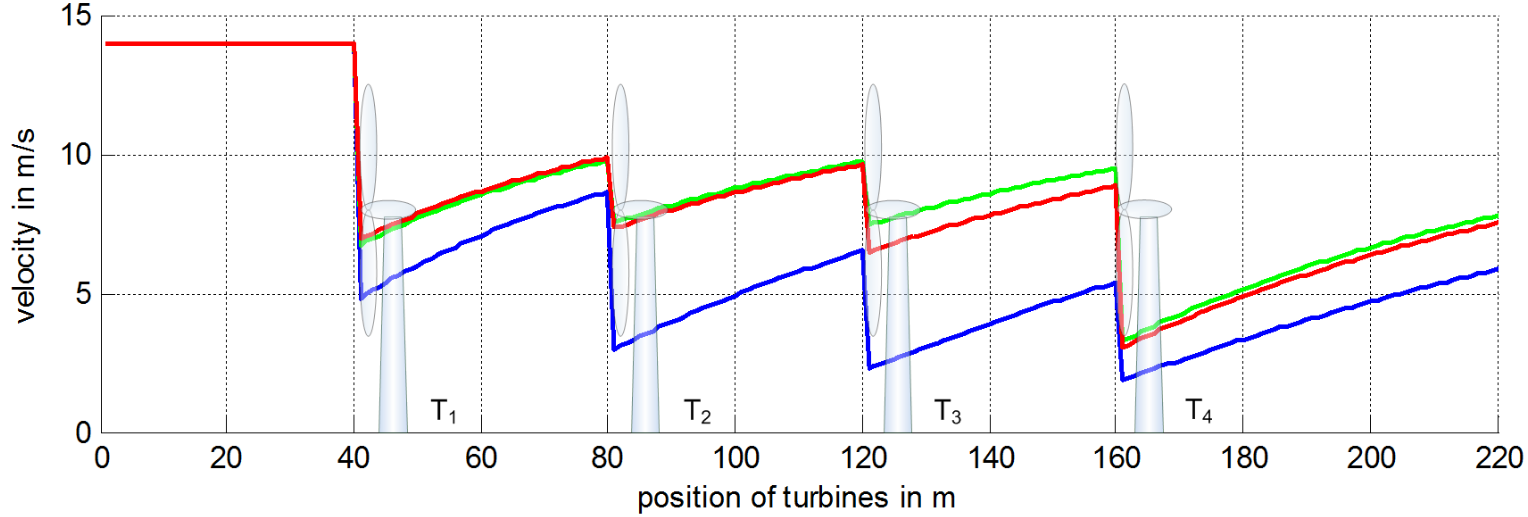
- Wind Turbines are modeled as players.
- Players interact and cooperate with each other to increase the overall output..
- Players are associated with cost functions, which they maximize by choosing a strategy from a well defined strategy space.

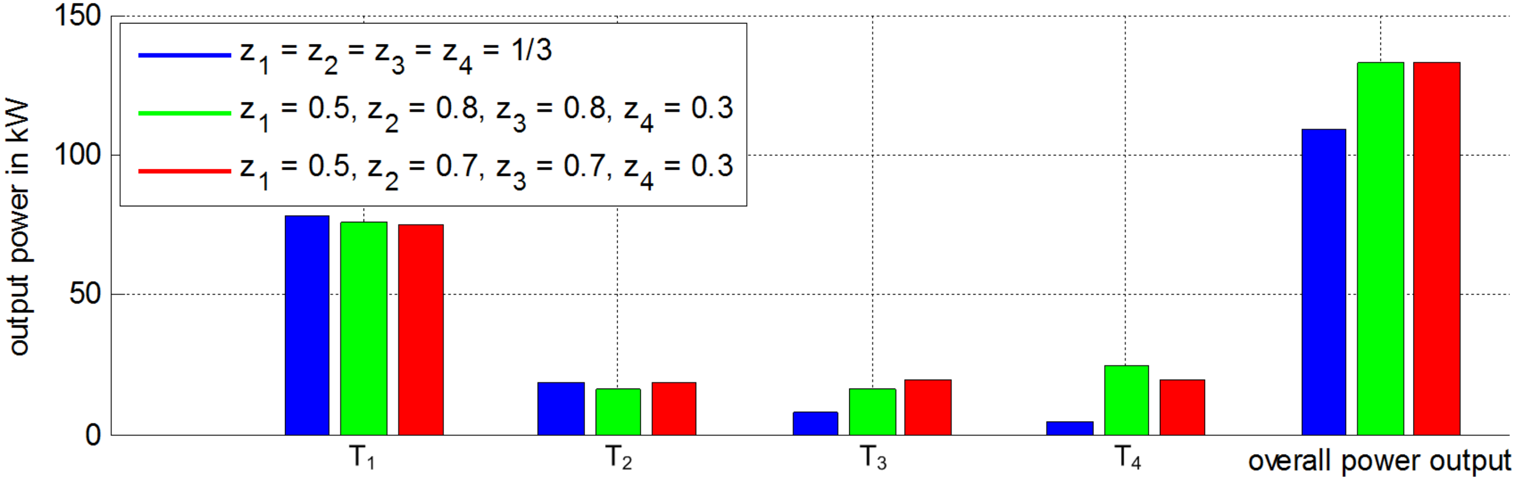
$$\max \; P_{i-1}(z_{i-1}, v_{in,i-1}) + P_i(z_i, v_{in,i}) + P_{i+1}(z_{i+1}, z_i, v_{in,i})$$
$$s.t. \quad z_i \in Z_i$$

$$z_i \in \max \begin{cases} P_{i-1}(z_{i-1}, v_{in,i-1}) + P_i(z_i, z_{i-1}, v_{in,i-1}) \\ z_{i-1} \in Z_{i-1} \end{cases}$$

- Decision variable of turbine i: z_i
- Nash equilibrium (NE) provides an appropriate solution concept, which is (approximately) optimal w.r.t. a global objective function.

Simulation Results





default values in blue, first optimization step in green, third optimization step in red.

Concluding Remarks

- Game theory provides a rich analytical framework for interactive decision making.
- We model Wind Farm problem by a collection of interacting between turbines each making local decisions in response to local wind conditions.
- The primary goal in Wind Farm control is to design local control policies for the individual Wind Turbines to ensure that the emergent collective behavior is desirable with respect to the system level objective.
- Defining the interaction framework of the agents within a game theoretic environment (game design) and then define local decision making rules that specify how each turbine processes available information to formulate a decision (learning design), we could increase the overall power extracted from Wind Farm.