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Presentation of the paper: **“The Influence of Control Strategies on the Energy Capture of Wind Turbines”**

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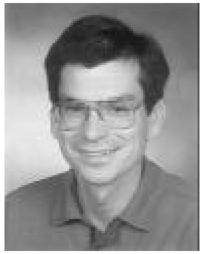
The Influence of Control Strategies on the Energy Capture of Wind Turbines



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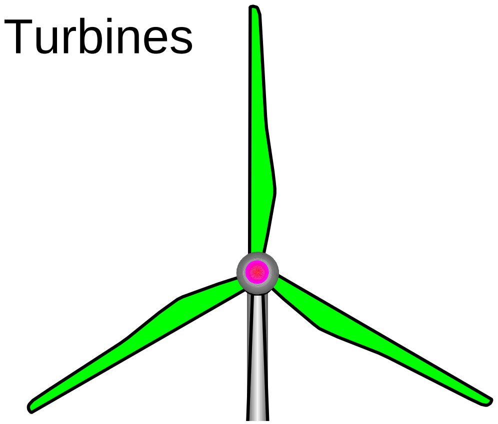
- Introduction
- Different concepts of Wind Turbines
- Simulation Model
- Results



First, I’d like to introduce Mr. Hoffmann, who is doing research work in this area during his Ph.D. studies at Darmstadt University of Technology, Department of Power Electronics & Control of Drives.

After a short introduction we will consider the ***basic characteristics of 8 diffe-rent concepts*** *of horizontal axes wind turbines. The* ***analysed concepts cover practically all types of wind turbines*** *which are on the market today. All the* ***different concepts*** *are* ***compared regarding*** *their* ***energy production*** *using* ***simulation*** *models. Finally, we will discuss the simulation* ***results****.*

Introduction

- **Many different Wind Turbines compete at the market**

- **Energy production is one of the most important features**

  - **Literature:**

"*variable speed*

Wind Turbines produce

more energy than

constant speed turbines"

2 - 7%

20%

38%

As we will see, many different concepts of wind turbines compete at the market.

*One of the **most interesting features** of a wind turbine is its **energy production**.*

***Other** features like **Power Quality** may also be of great concern, but in this work we concentrate on energy production.*

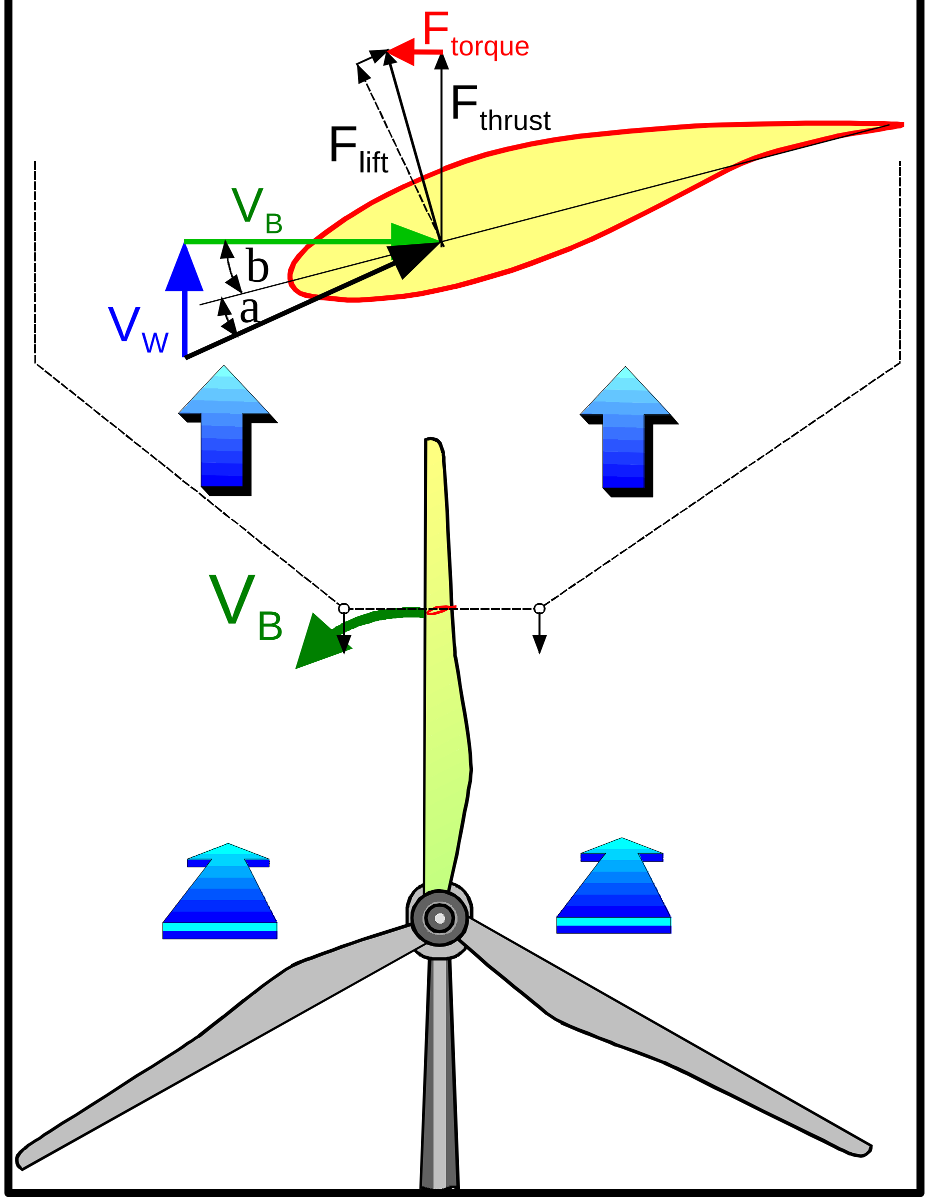
*In the **literature**, there **exist** some **comparisons** between **variable** and **constant** speed wind turbines.*

*But the **authors disagree widely in the figures of merit**. The range is from 2% to 38%..*

*From **our paper**, we will see, **how energy** production **depends on various parameters***

*To **analyse** the **system**, first let's have a **look to the way**, **how the torque** of a wind turbine is **produced**.*

Torque of a wind turbine



*In the lower part, we see the **rotor** of a wind turbine, the **wind** is coming from the **front**.*

*If we take a **look from the top to a cross section** of the vertical blade, we **see** the **profile**.*

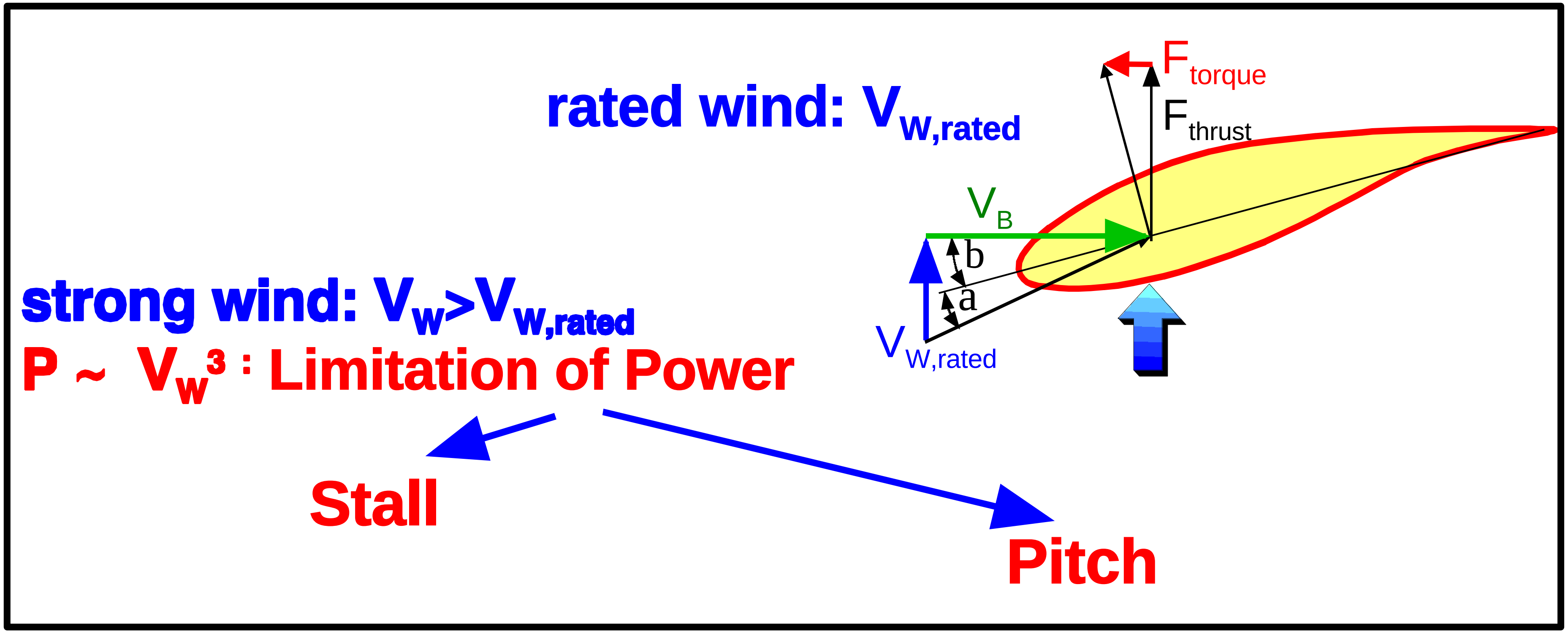
*The **wind** is coming from the front and is **represented** by this blue **vector***

*As the **blade** is **rotating**, the blade sees the **additional wind** speed **component** V_B.(green vector)*

*These two vectors give the **resulting wind** from the blade's point of view.*

***Perpendicular** to the resulting wind, the profile produces a **lifting force** and **aligned** to the wind a **small dragging** force*

***This two form the resulting aerodynamic force**, **which is decomposed into a thrust** force, which the **tower** has to **withstand**, and the **torque producing** force, that is the **only one** we are **interested** in*



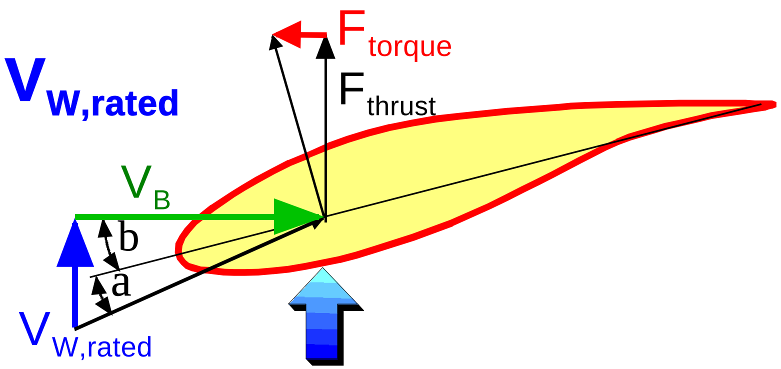
*Each turbine is **designed** to produce its **rated power** at a certain wind peed, which we call **rated wind speed**.*

*The **power inherent** in the **wind** shows a **cubic increase** with wind speed.*

*For **wind speeds above** the **rated** one, it is necessary to **limit** the **mechanical power** generated by the rotor **to the rated value** of the plant.*

*The **mechanical power** can be limited either by **stall** or by **pitch** methods.*

rated wind: $V_{W,rated}$



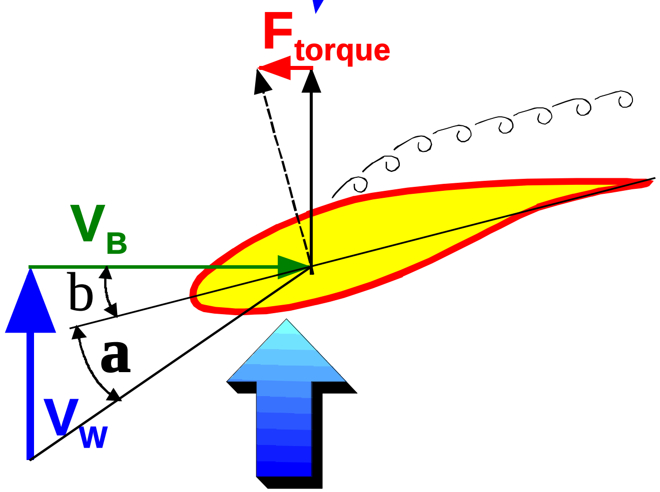
strong wind: $V_W > V_{W,rated}$

$P \sim V_W^3$: Limitation of Power

Stall

Pitch

passive

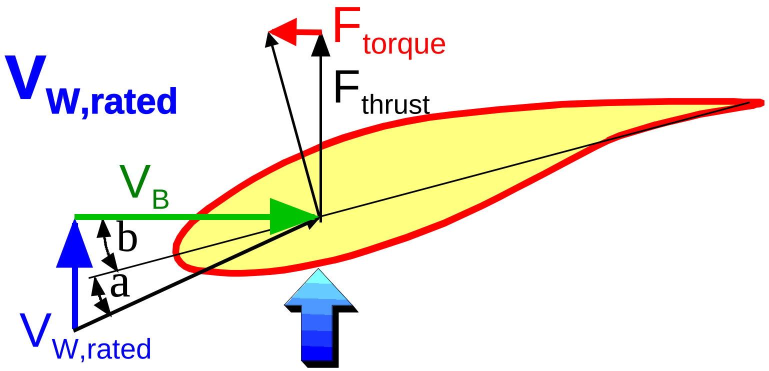


*The **simplest** design uses the **passive stall** method.*
*In this design,the **angle** b is always **constant**,**no mechanism to turn the blades around their axes** is necessary.*

*When the **wind speed increases**, the **angle** a, which is the angle of attack, **increases**.*

***Above a certain angle** a the **stall** effect occursand the **torque producing force** can be **limited approximately to its rated value**.*

rated wind: $V_{W,rated}$

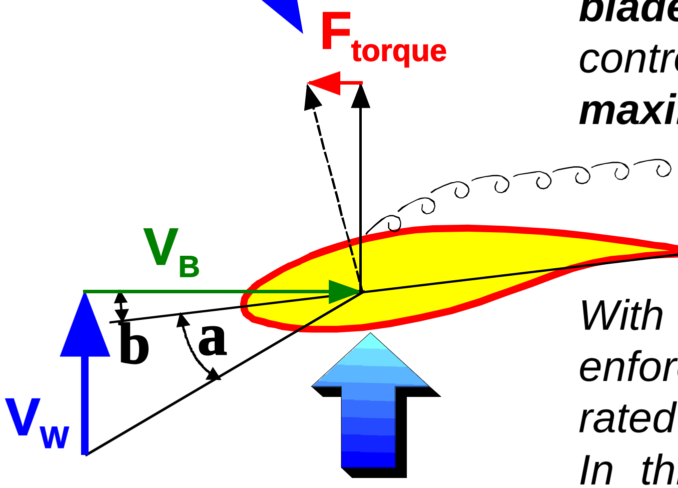


strong wind: $V_W > V_{W,rated}$

$P \sim V_W^3$: Limitation of Power

Stall

active



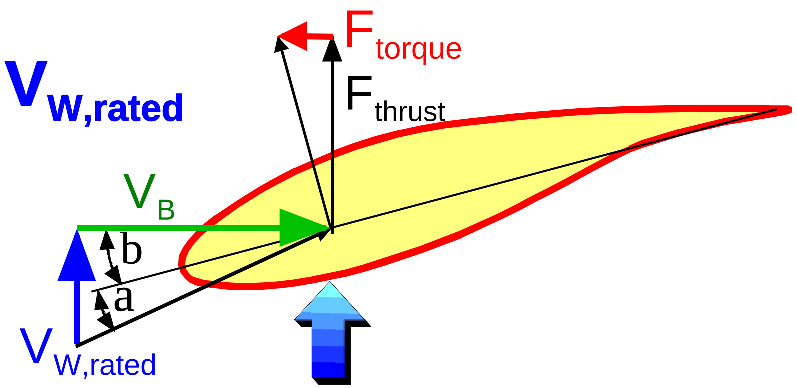
Pitch

If there is a mechanism to turn the blades around their axes, at low winds *a control loop will use this feature to* ***maximise*** *the* ***energy*** *capture.*

With ***higher wind speeds, stall*** *can be enforced in order to limit the torque to its rated value.*

In this case, ***angle*** *b* ***is decreased, the blade acts like a wall in the wind***

rated wind: $V_{W,rated}$

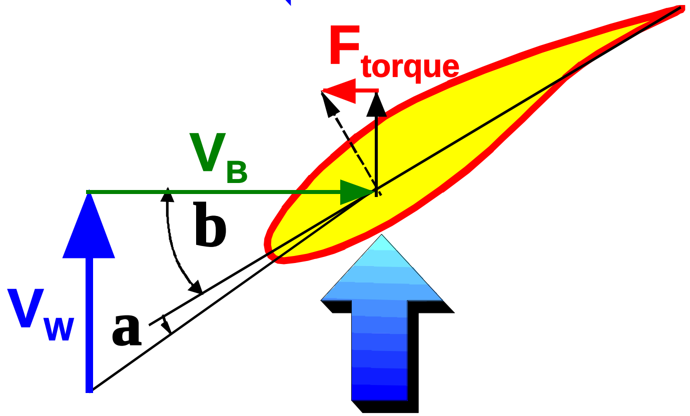


strong wind: $V_W > V_{W,rated}$

$P \sim V_W^3$: Limitation of Power

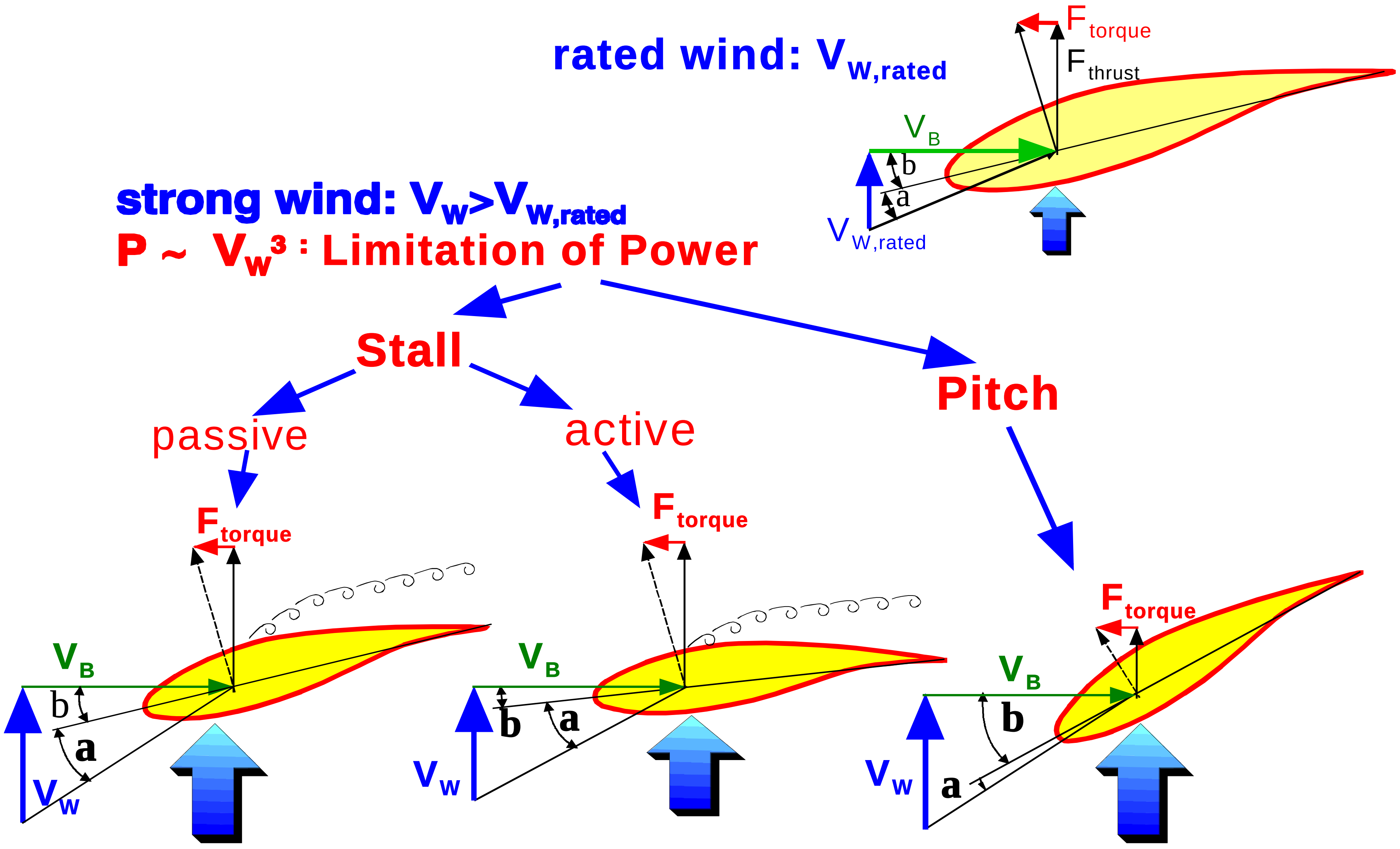
Stall

Pitch



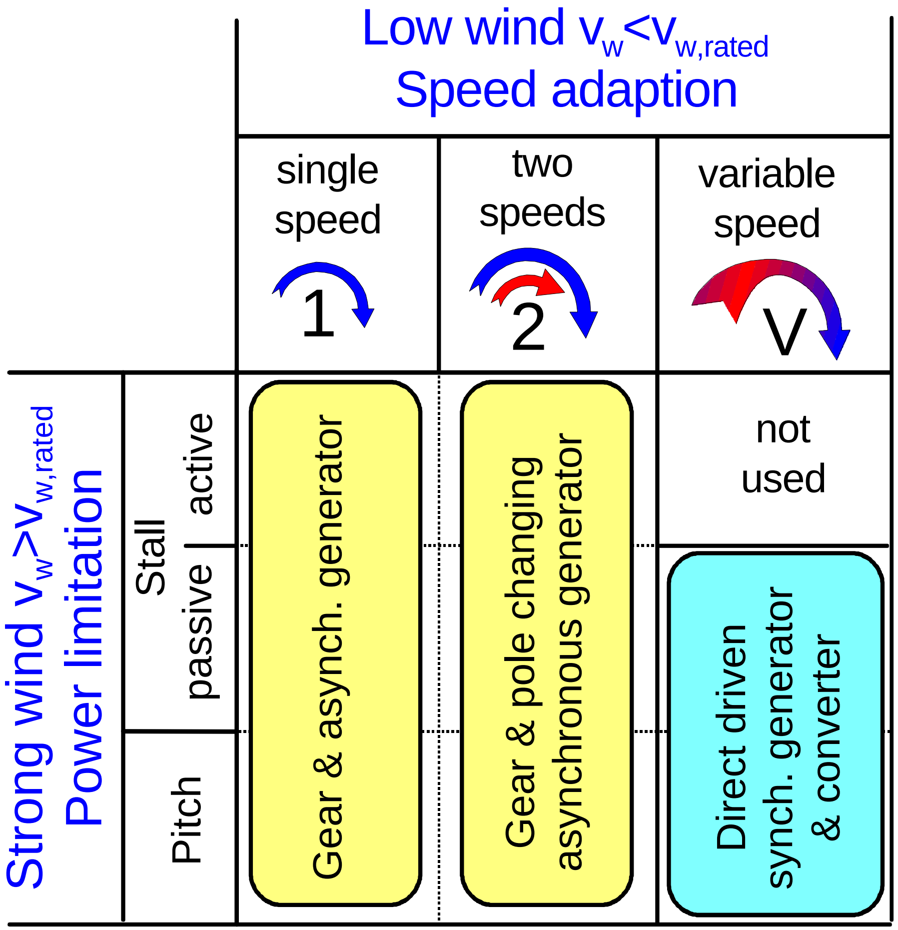
When ***limiting*** *the power by the* ***pitch method****, the* ***blades*** *are turned towards the* ***direction of a flag in the wind*** *by* ***increasing*** *the angle b.*

In this case ***all aerodynamic forces are reduced****.*



rated wind: $V_{W,rated}$
F_{torque}
F_{thrust}
V_B
b
a
$V_{W,rated}$
strong wind: $V_W > V_{W,rated}$
$P \sim V_W^3$: Limitation of Power
Stall
Pitch
passive
active
F_{torque}
F_{torque}
F_{torque}
V_B
V_B
V_B
b
a
b
a
b
a
V_W
V_W
V_W

Concepts for Wind Turbines



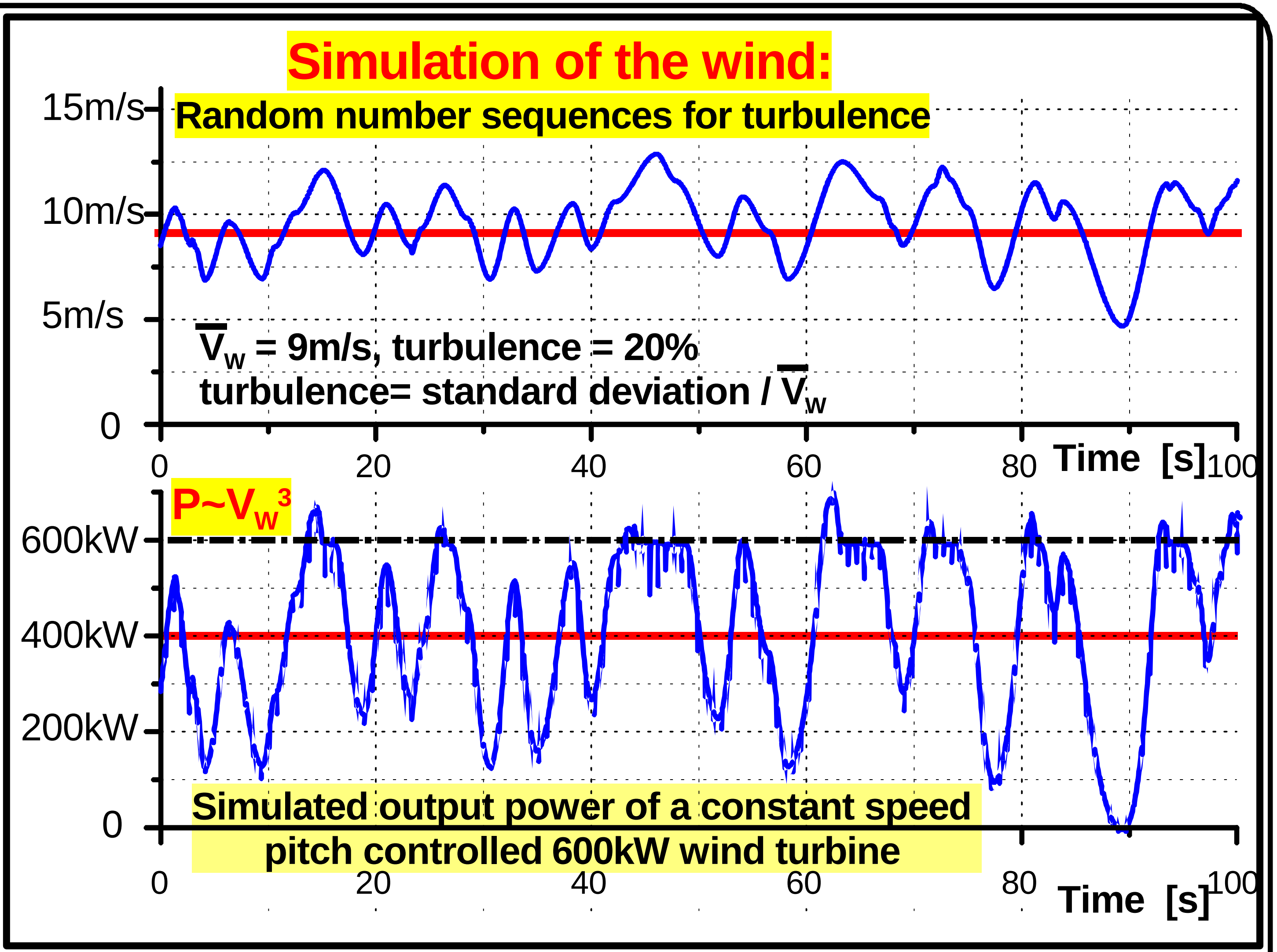
Comparison of 8 different concepts under identical conditions: → Simulation

*As we have just seen, there are **three methods** to **limit** the **power** during **strong winds**.*
*When the **wind** is **low**, an **adaptation** of the **turbine's speed** to the **wind- speed** has to be considered.*
*In the **simplest** case, **no speed adaptation** is implemented. In this **classical single speed** concept a **gear** and an **asynchronous** generator is used.*
*When a **pole changing asynchronous** generator is used, a **limited speed adaptation** is realized. **Typically, two speeds** are used in this case*

***Full speed adaptation** calls for a **variable speed concept**. Here a **power electronic converter** is always necessary. In our paper, we only took the **gearless, direct driven synchronous generator** into consideration for a variable speed wind turbine*

*To our knowledge, there is **no active stall, variable speed turbine** on the market.*
*This **matrix containing 8 different concepts** covers the **vast majority** of wind turbines on the market.*
*To **compare 8 different wind turbines**, **all must be exposed to identical conditions**.*
With real wind turbines, this would be an extremely expensive approach.
*Therefore, we use a **simulation** of the different wind turbines in this paper.*

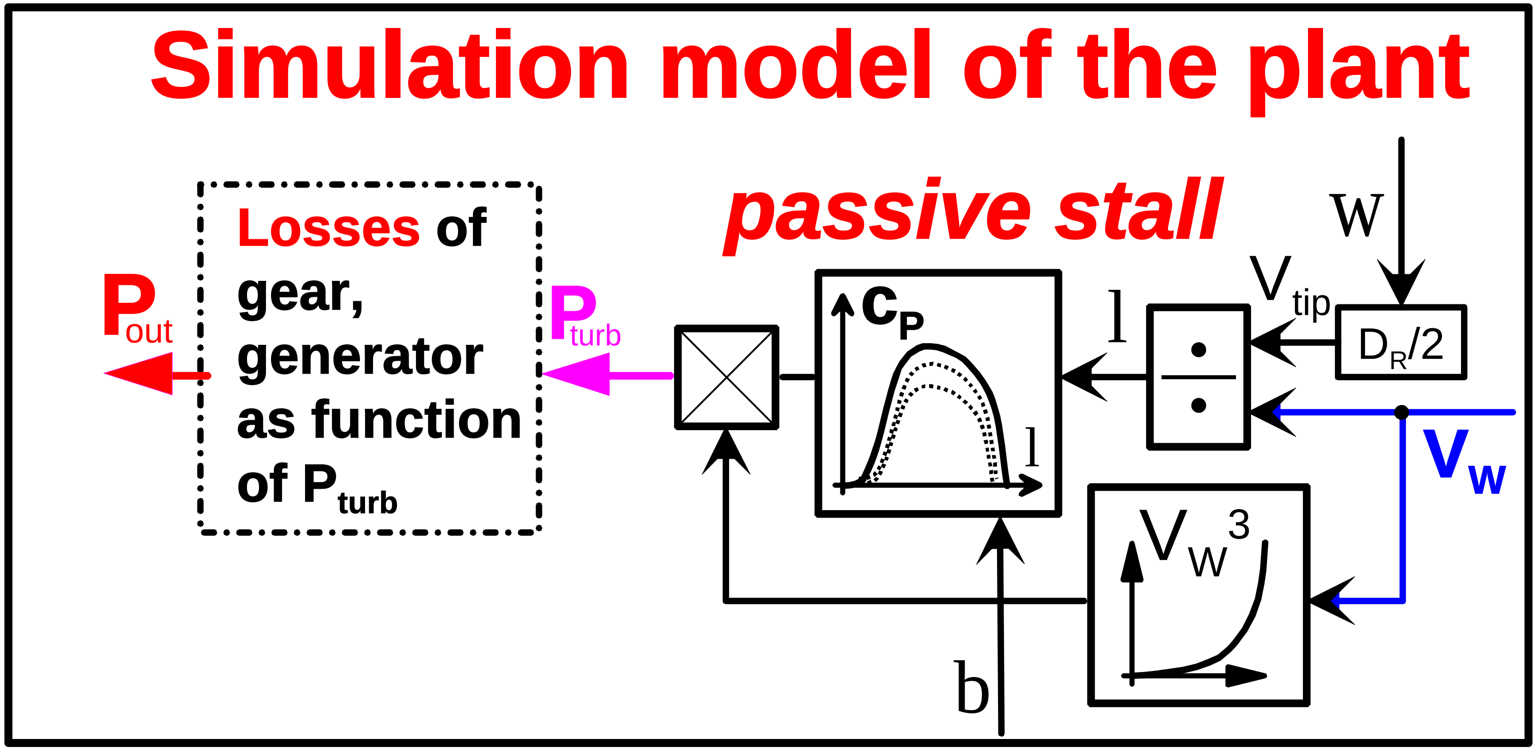
*The **simulation of the wind** must contain **all average wind speeds** and all **levels of turbulence** which may appear in reality.*
Here is an example of a wind simulation with an average speed of 9m/s and a turbulence level of 20%.
*The **turbulence** is generated by **random numbers** and is **fitted** by practical values of the **acceleration** of the air.*
*Here, the output **power** of a **constant speed,pitch controlled** 600kW turbine is shown .*



*For the **above depicted wind**, the average power is **400kW**, but the actual power fluctuates between **700kW** and **Zero.** Instead of feeding a nearly constant power to the grid, the constant speed turbine creates a rather poor power quality.*
The overshoot in power during a wind gust is due to the limited velocity of the pitch drives. It takes some time, till the angle b is increased to the power limiting value

*Next, we discuss some **simulation models** for the plant.*

*The most **simple** concept is the **constant speed, passive stall** concept. Here, the speed w and the angle b are constant. The wind speed from the previous figure enters at the right side*



The turbine's power is proportional to the 3. power of the wind speed and the turbine's characteristic, which is a function of the tip speed ratio l
*The **losses** of the gear and the generator are subtracted to give the output power.*
*The losses are a **function of** the turbine's **power**.*

When we consider a **constant speed, pitch controlled** concept, we have to **add the pitch control part**.

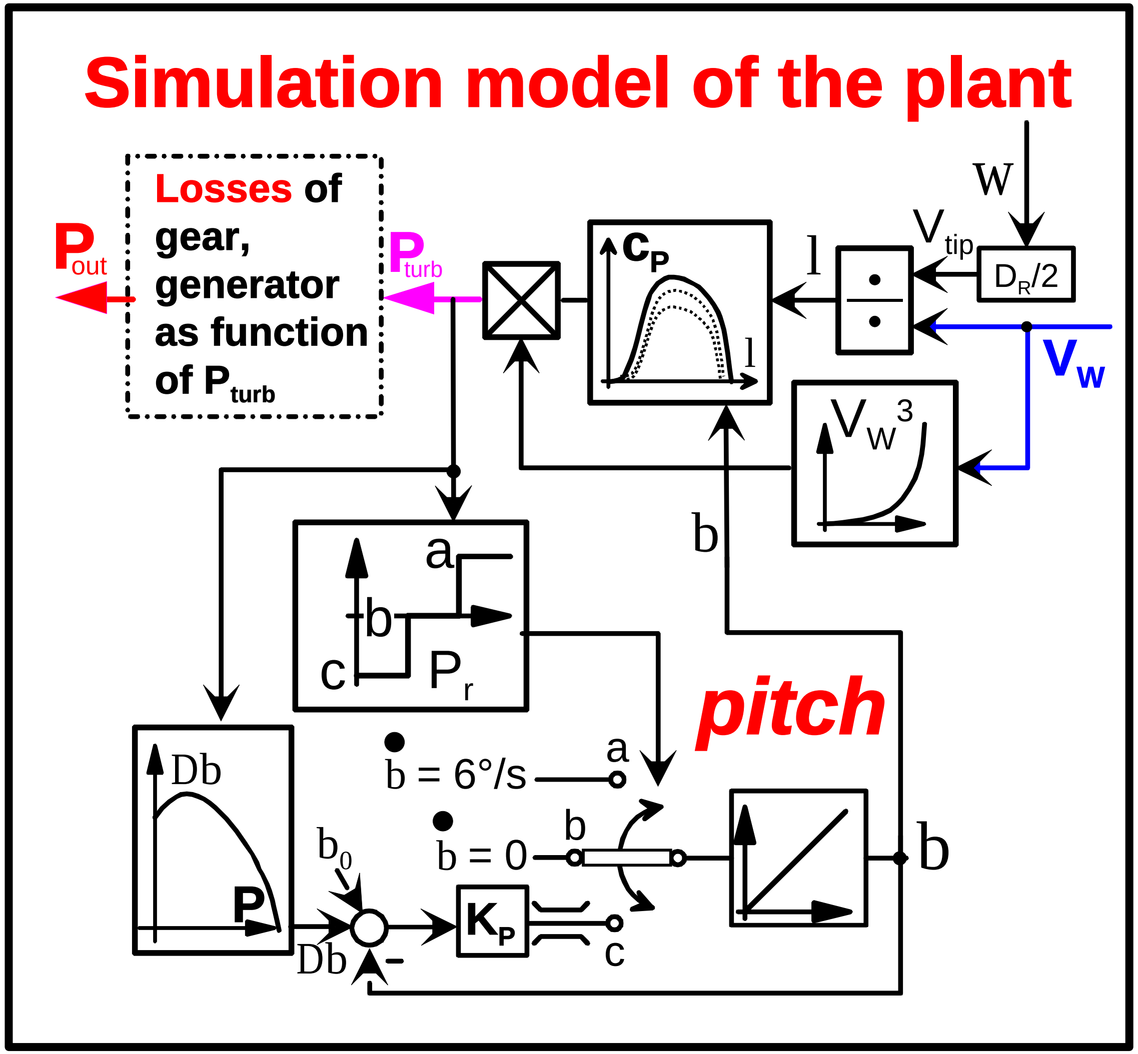
There **are three operating areas**.

If the turbine produces ***more than rated power****, the switch is in the upper position and the* ***angle*** *b* ***is constantly increased*** *with its maximum* ***speed of 6°/s****.*

If the power is ***near the rated power****, the* ***pitch drive is stopped*** *and b remains constant.*

If the power ***is below rated power****,* ***the switch is at the bottom position*** *and a* ***closed control loop*** *with a proportional controller (*K_p*) is formed. This controller gets its* ***reference from a characteristic****, which gives the* ***optimum angle*** *b as a function of the power.*

With this ***optimum angle*** *b the* ***maximum power is produced****, when the wind is below its rated value*

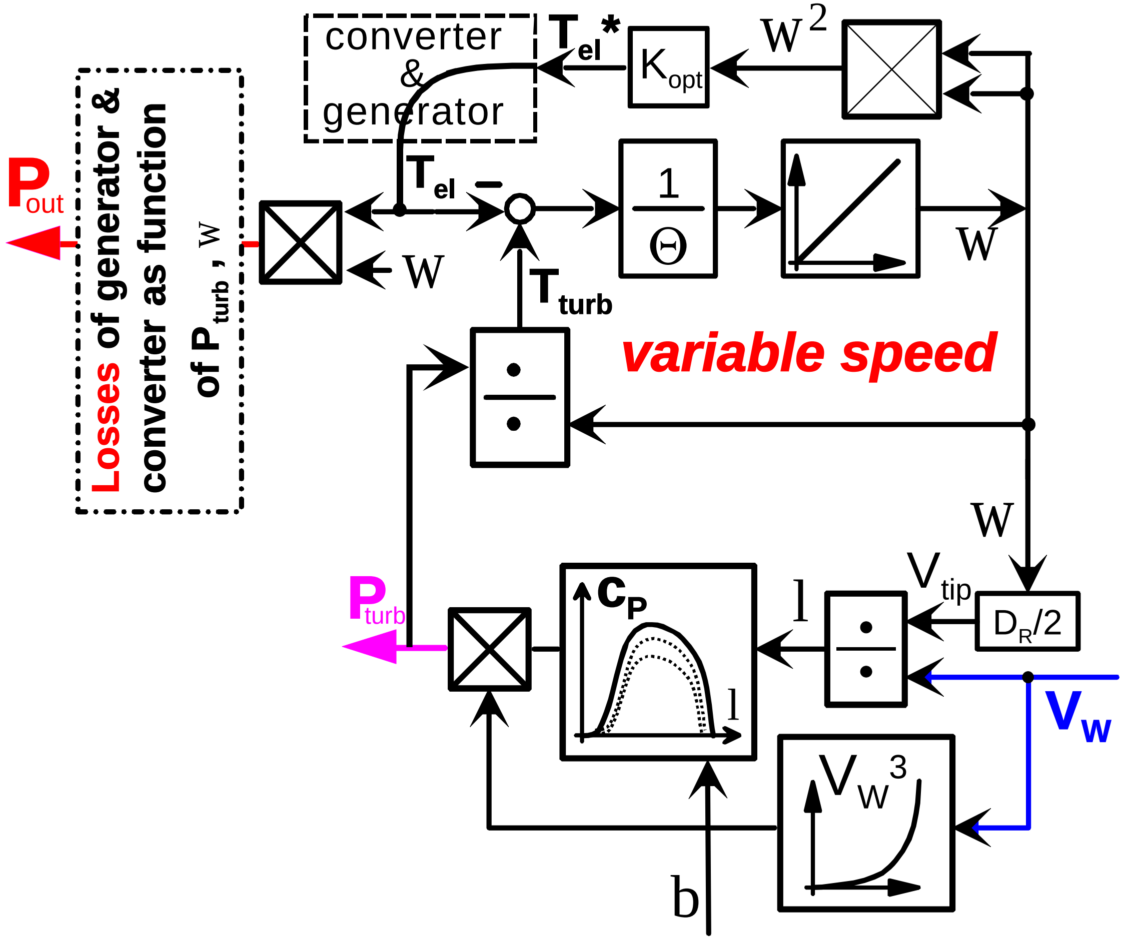


*Next we consider a **variable speed** concept where **power is limited by stall**.*

*In the upper part, the **rotating masses** are represented which are accelerated by the difference of the generator's and the turbine's torque.*

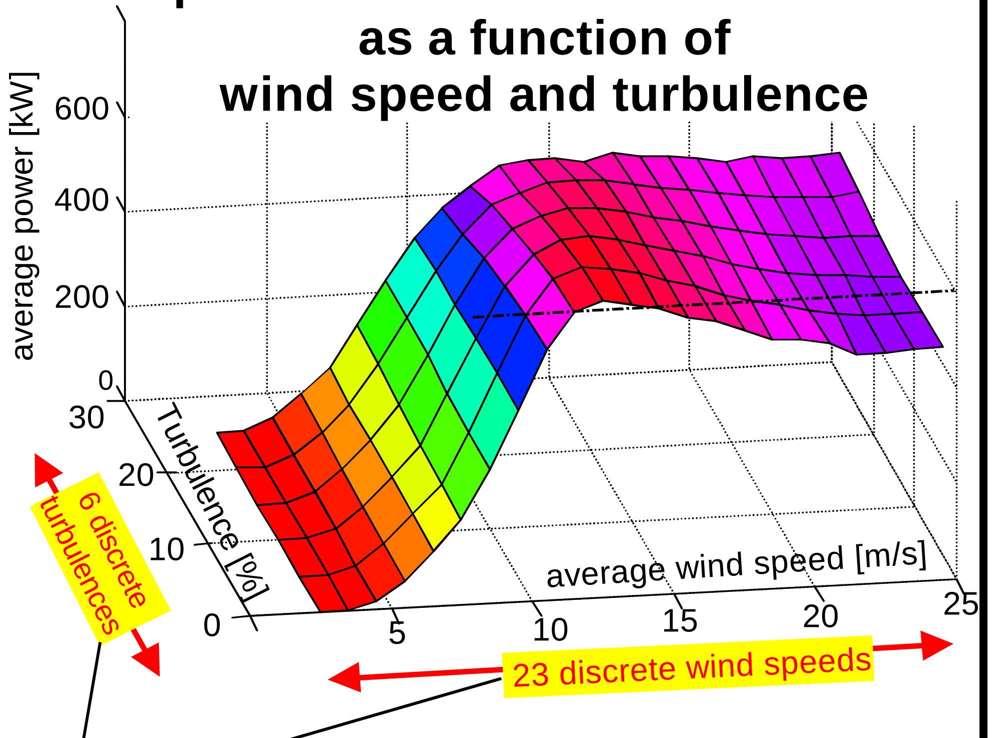
*When the **wind is below its rated value**, the **maximum power** is produced **if** the **torque** of the generator is proportional to the **square of the speed.** The **converter** and the **generator** are very **fast acting devices**. So their **time delay** in the upper loop can be **neglected.***

Simulation model of the plant



*But of course the **losses** of the converter and the generator **have to be considered** to find the **power** which is **fed into the grid.***

Output power (5 min. average) of a passive stall controlled turbine as a function of wind speed and turbulence



6 * 23 = 138 simulations (5 min. real-time each)

*** 8 different control concepts**

1104 simulations

*** 3 design tip speed ratios l_r**

*** 2 profiles**

> 6000 simulations

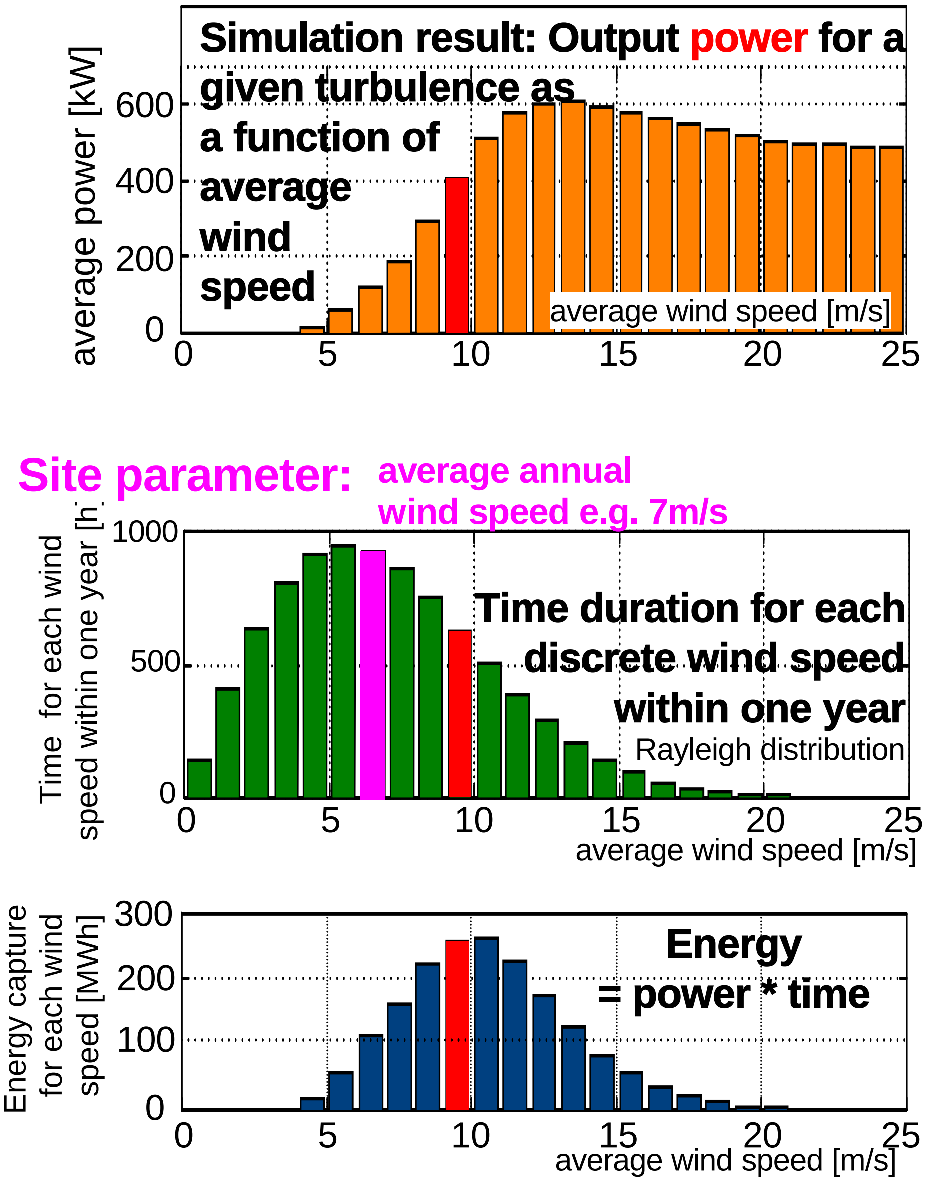
*A **combination** of average **wind speed** and **turbulence** is **applied for 5 min**. of real time to the simulation model.*

*The **result** is the **average power** which is fed into the grid **within these 5** minutes. This power is represented by one of these squares of this surface.*

*We have to **repeat** this simulation for each **combination** from **23 discrete** average **wind speeds** and **6 turbulences** which gives 138 simulations.*
*As we **compare 8 different concepts**, we have to **repeat this procedure** for each concept. (-> 1000 simulations)*
*Additionally we want to **investigate the influence of some design parameters**.*
We compare 3 different design tip speed ratios and 2 different profiles which gives a total of 6000 simulations.

*For a **given turbulence**, we can **cut one slice out of this figure.***

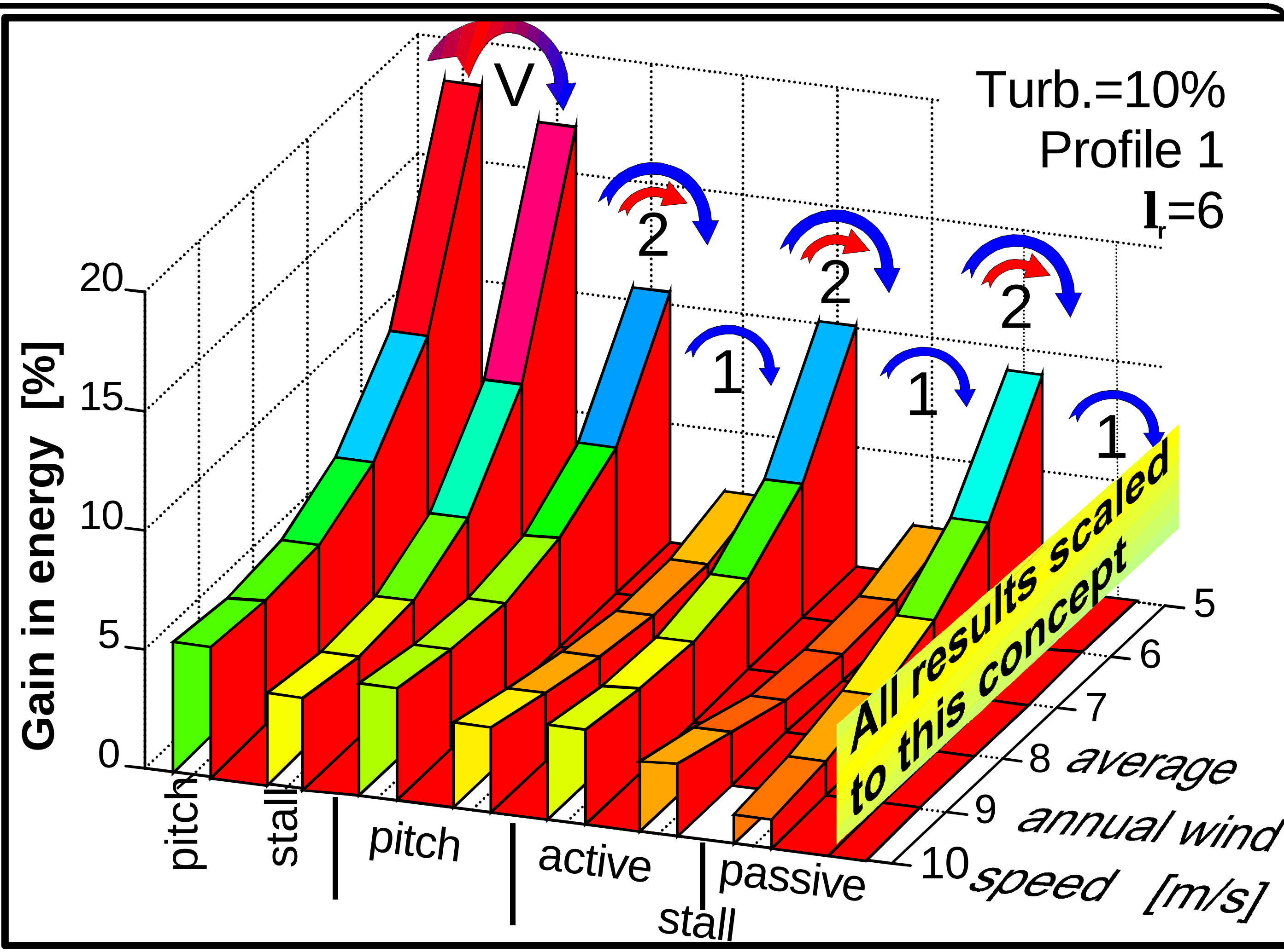
From power to energy



Then we see the output power as a function of the wind speed for a specific turbulence.

*For the **energy production** at a **given site**, the **wind speed** is decisive . A **wind map** gives the **average annual wind speed** for each location.*
*In this **example**, we have an **average annual** wind speed of **7m/s**. The **actual wind** of course may be **quite different**.*
*In this paper we use a **Rayleigh** distribution, which gives **the time duration for each discrete wind speed** within one year. The sum of all these time-bars is 8700h.*
*The **energy** produced under these conditions is found by **multiplying power** and **time**. The **sum** of all these **energy-bars** gives the total **energy produced** within **one year**.*
This is the only number we are interested in.

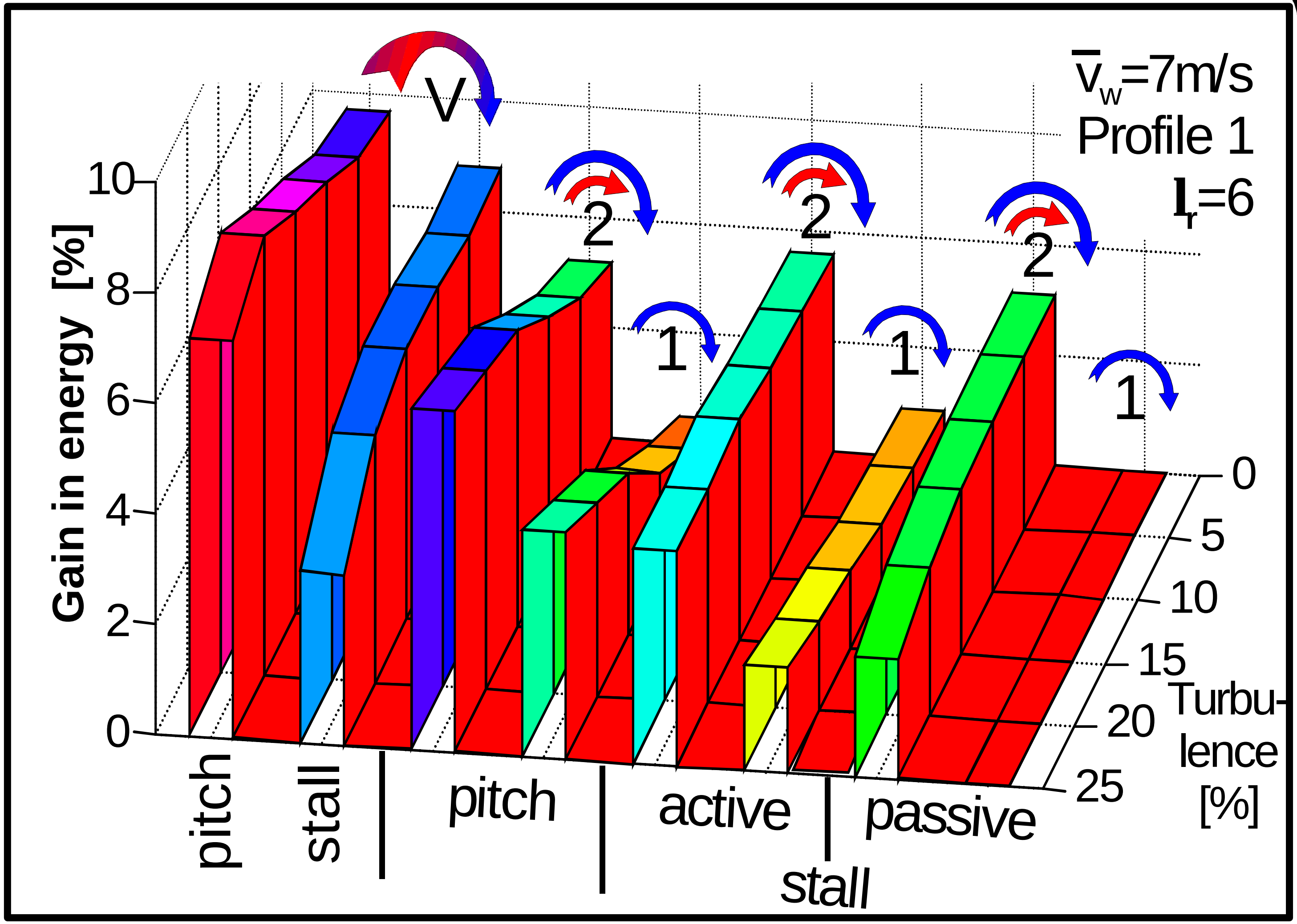
*Now we come to discuss the **results**. Here, we see the performance of the 8 different concepts when different average annual wind speeds are applied. The turbulence level is 10%. First of all we have to note, that the most simple concept, which is the single speed, passive stall concept, is used as baseline. We see the gain in energy production of the more sophisticated concepts over the most simple one. The different concepts are identified by their speed (single, two or variable speed) and the method power is limited (stall or pitch).*



*The **message** is, that for a **low average annual wind speed**, **speed adaption** of the rotor **is interesting**.*

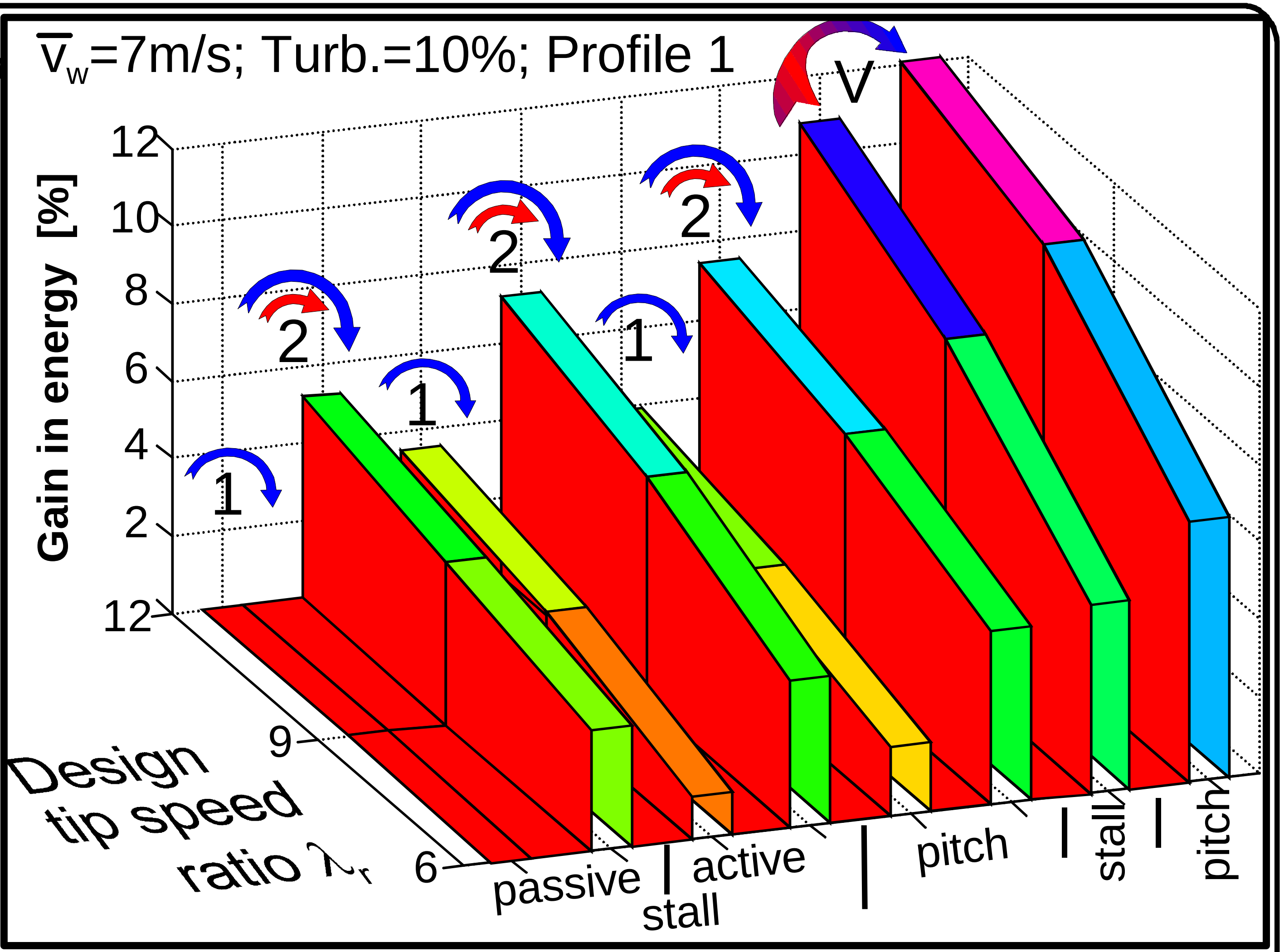
For the two-speed machines, the gain in energy production is 9-11%. The gain of the variable speed machines is 17-18%. For sites with a high average wind, all turbines are operated at their power limit for a considerably long time in the year. At the limit of power, all produce a rather similar energy.
Therefore, the differences are smaller for high average annual wind speeds.

Next result: Here the average wind speed is constant 7m/s, but ***different levels of turbulence*** *are applied. The gain of the* ***speed adapting, stall controlled*** *machines* ***decreases*** *for high turbulence levels. The reason is, that* ***speed adaptation cannot be carried out*** *in the short time of a wind gust. Instead, the wind gust stalls the rotor and energy is lost.*



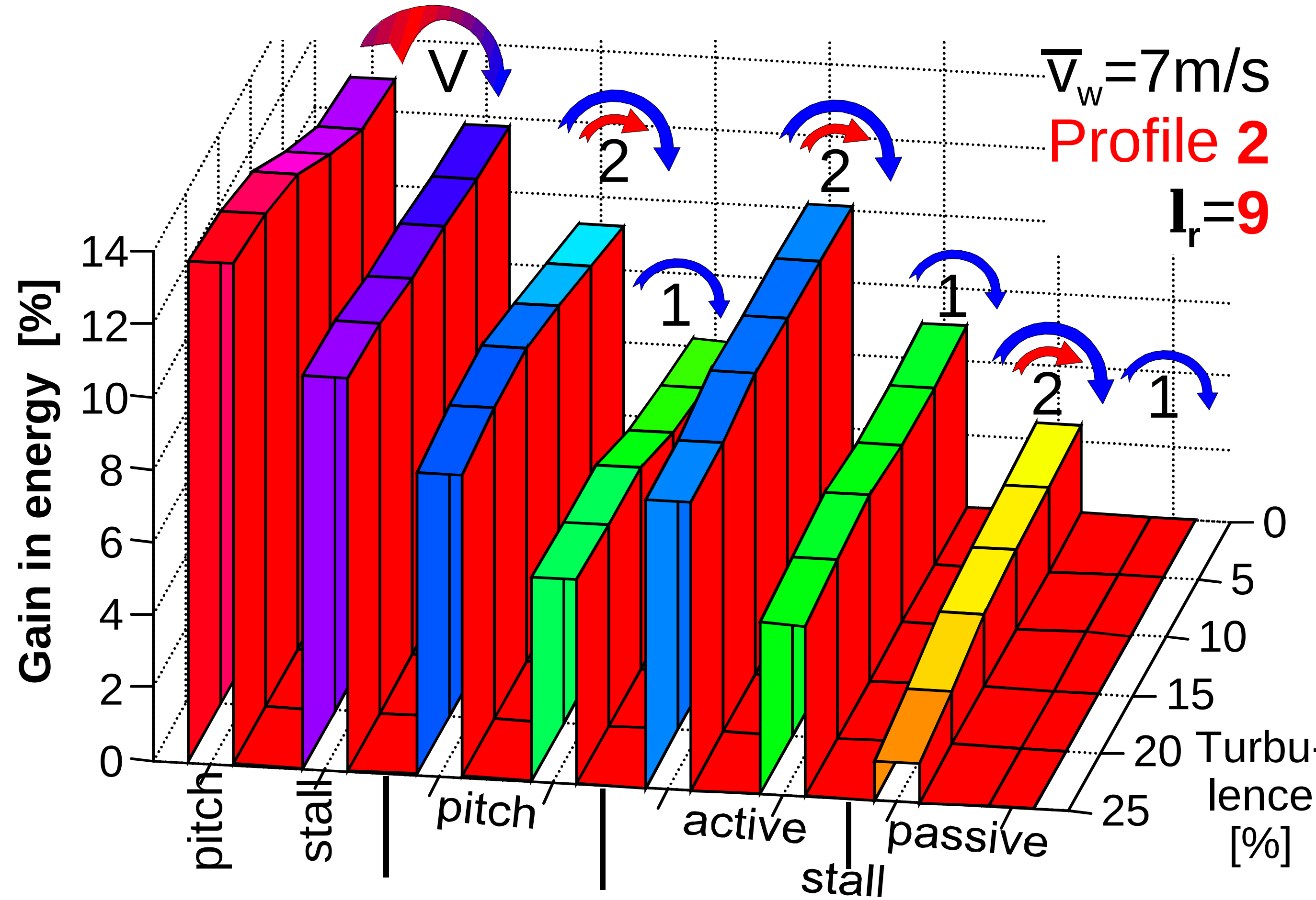
In ***contrast*** *to this, the* ***gain*** *of the constant speed,* ***pitch controlled*** *machines* ***increases*** *for* ***high levels of turbulence****. The reason is, that the pitch angle to limit the power during a wind gust is rather large and the pitch drives are not fast enough to limit the power. Therefore, in this two cases, an overshoot in power above the rated value occurs, which increases the energy.*

Next we ***change design parameters****. Here, the* ***design tip speed ratio is varied****. First, it is important to* ***note****, that the* ***absolute energy*** *capture of the* ***reference concept decreases*** *with increasing tip speed ratio. But the benefit of a higher tip speed ratio is a reduced mechanical stress on all components, as with a higher speed the same power is produced with a lower torque. With a lower torque, all aerodynamic forces will be lower.*



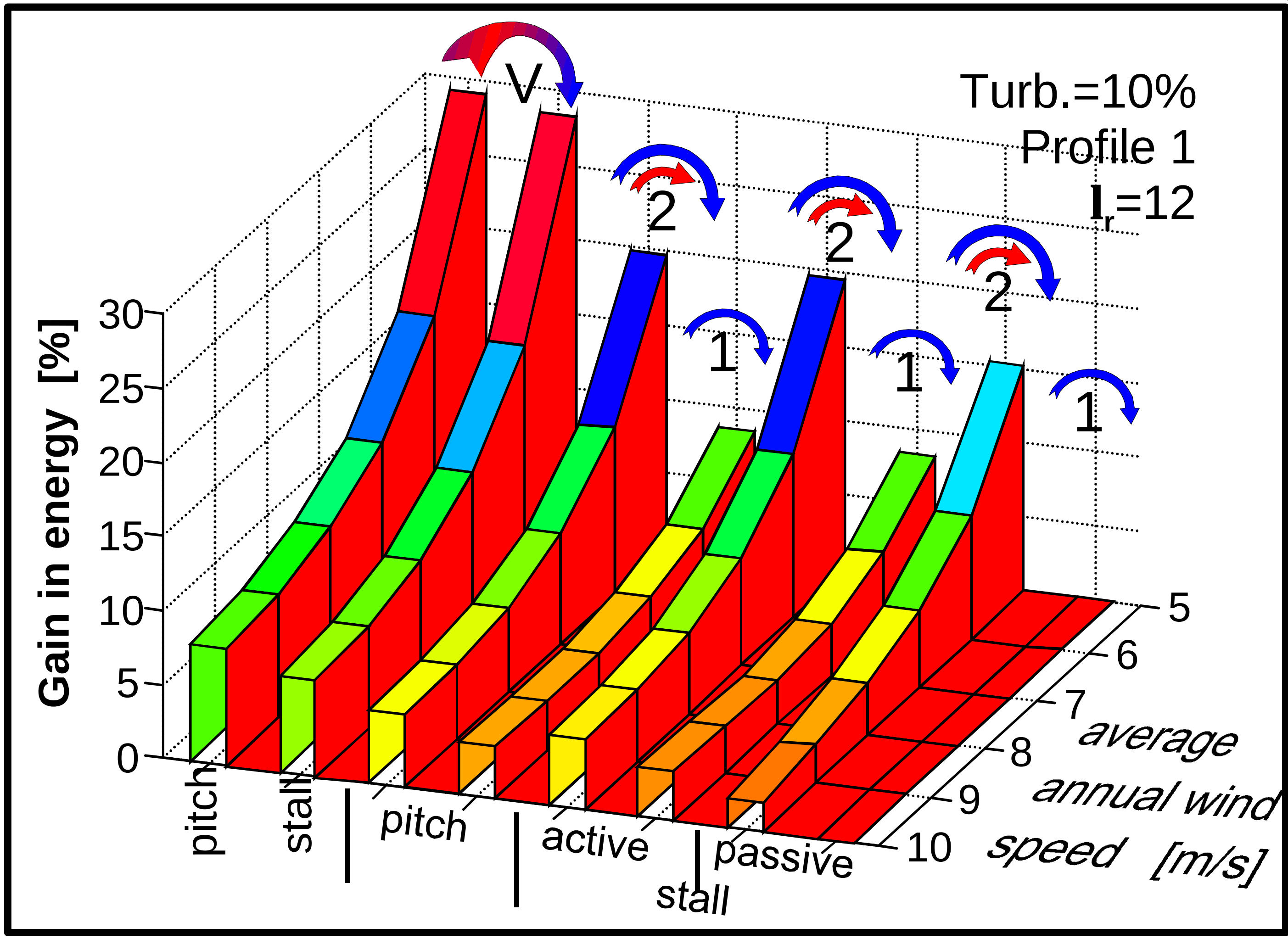
We can easily see, that for all concepts, a higher tip speed ratio increases the gain in energy. The variable speed concepts take the greatest benefit from a high tip speed ratio. This means, that a ***variable speed machine*** *will* ***pay off better****, if a* ***high tip speed ratio*** *is selected. But the drawback of a high tip speed ratio is the high acoustic noise.*

*In this figure, the annual average wind speed is constantly 7m/s and **different levels of turbulence** are applied.*
*In contrast to the last but one figure, here we use a **different profile**, which also calls for **a different design tip speed ratio**, as the power characteristic of profile 2 (Goe 535) is flat compared to the first one (Goe 785).*



***With profile 2**, the gain in energy is higher for all concepts except for the passive stall controlled concept. Additionally, here the gain is rather constant for all levels of turbulence. Especially, there is a **benefit** for the **pitch controlled, variable speed** concept at **high levels of turbulence** with this profile.*

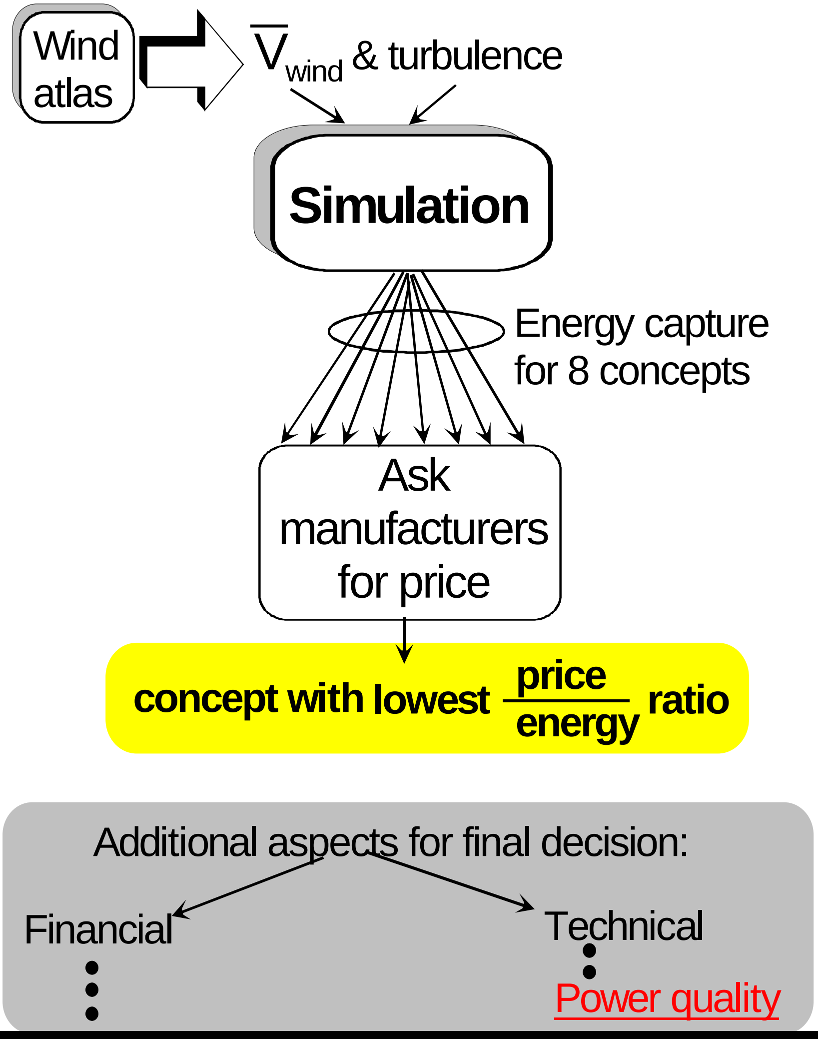
Finally, for a high design tip speed ratio different average annual wind speeds are applied . As can be seen easily, in ***all*** *cases the* ***gain*** *in energy* ***increases*** *with a high design tip speed ratio, especially at low winds. The gain of the variable speed concepts nearly reaches* ***30%.*** *But unfortunately, the combination of low average annual wind speed and high design tip speed ratio is probably unrealistic. The low wind speed is characteristic for an interior site. But there, the higher acoustic noise due to the high design tip speed ratio may not be tolerated. For an offshore site, where the acoustic noise would be no severe problem, typically the wind is strong. But for strong winds, the gain in energy for all the sophisticated concepts is not so impressive.*



Conclusion

1.) Most differences in literature are explainable by different conditions.

2.)



Conclusion:
First result:
Most differences in literature can be explained by different conditions.

But much more important is the second result:
For a given site, a wind atlas shows the average annual wind speed and the turbulence.
These data are inputs to the simulation. From the simulation, we get the energy capture of 8 different concepts.
The price for the real wind turbines has to be asked from the manufacturers.
Then the price to energy ratio is known, which is a rather important criterion for a final decision.

An additional aspect for a final decision is "Power Quality". Variable speed turbines typically provide better power quality, as energy from wind gusts can partially be stored in the rotating mass.