

New Active Speed Stall Control compared to Pitch Control for a Direct-Drive Wind Turbine

D. Bang, H. Polinder, J.A. Ferreira
Electrical Power Processing / DUWIND

Delft University of Technology
Mekelweg 4, 2628 CD Delft
The Netherlands

D.Bang@ewi.tudelft.nl, H.Polinder@ewi.tudelft.nl

R.P.J.O.M. van Rooij
Wind Energy Research / DUWIND

Delft University of Technology
Kluyverweg 1, 2629 HS Delft
The Netherlands

R.P.J.O.M.vanRooij@lr.tudelft.nl

Abstract—The objective of this paper is to assess 10 MW direct-drive permanent-magnet (DDPM) generator systems with different control strategies namely pitch control and active speed stall control. In the active speed stall control concept, there is no pitch mechanism, and the rotor speed is actively controlled by the generator to control the output power. The active speed stall control wind turbine with the DDPM generator system may be an attractive concept especially for offshore. This turbine has high potential because the wear, the maintenance and the failures of the pitch mechanism and the gearbox are omitted. The different DDPM generator systems are designed roughly, and the dimensions, weights, cost and performance of the systems are compared. To enable the active speed stall control concept, it is necessary to increase the weight and cost of generator system compared to the pitch control concept.

Index Terms—wind turbine, permanent-magnet, generator, direct-drive, stall control, pitch control

I. INTRODUCTION

The objective of this paper is to assess 10 MW direct-drive permanent-magnet (DDPM) wind generator systems with two different control strategies namely pitch control and active speed stall control.

Various wind turbine concepts have been developed and built during the last two decades. Development objectives have been to maximize energy capture, to minimize cost, and to improve power quality of wind turbines.

Among various wind turbine concepts, the passive stall control concept was mostly used for constant speed wind turbines with a geared drive squirrel cage induction generator (SCIG) system during the 1980's and 1990's. However, this concept has some disadvantages, such as a poor power quality, high thrust loads in the rotor blades above the rated wind speed and reduced energy yield because the aerodynamic efficiency is maximum at only one or two wind speeds.

Since the late 1990's, most wind turbines with power levels above 1.5 MW have been changed to the variable speed

concept mainly because of the grid requirement for good power quality.

Since 1991, direct-drive wind turbines have been built to increase the energy yield, to reduce failures in the gearbox, and to lower maintenance problems [1][2].

The scale of wind turbines installed in the world is increasing in recent years. The space to install the turbines onshore is limited in some regions of Europe, and there are higher wind speeds with less turbulence offshore than onshore. Therefore the location to install the turbines is moving to offshore. However, the maintenance of offshore wind turbines is more difficult and expensive than the maintenance of onshore wind turbines. Therefore more simple, robust and reliable wind turbines with high performance are required.

Wind turbines can be classified as illustrated in Fig. 1 considering the rotational speed, the power regulation, and the drive train. When considering the rotational speed, the turbines can be classified into the constant speed and the variable speed concept. When considering the power regulation, the turbines can be classified into the stall control and the pitch control concept. When considering the drive train, the turbines can be classified into the geared drive and the direct-drive concept. The stall control wind turbine with the direct-drive concept seems more simple, robust and reliable, because the pitch mechanism, the gearbox, and the slip rings with brushes are omitted [3]. The variable speed wind turbine has a better performance than the constant speed turbine. Therefore, in this paper two different variable speed wind turbines are considered namely with pitch control and with active speed stall control. These two concepts are depicted with bold lines and characters in Fig. 1.

The wind turbine with variable speed, stall control and direct-drive concept may be an attractive concept especially for offshore. The aerodynamic performance of this turbine is limited by controlling the rotor speed. The rotor speed can be actively controlled by changing the generator speed, which is regulated by the generator torque. Therefore, the regulated generator torque results in the control of aerodynamic power of the turbine.

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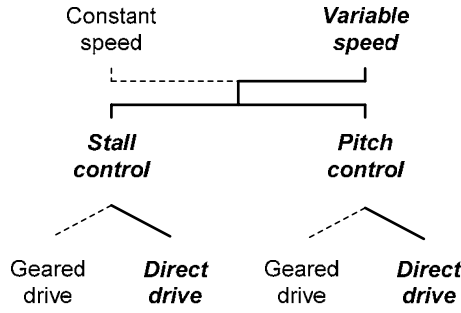


Fig. 1 Different wind turbine concepts

There are a number of possible ways to control this active speed stall control wind turbine. In this paper, three different control strategies are considered namely the speed limited, the power limited, and the torque limited.

This paper discusses rough designs of different 10 MW DDPM generator systems for pitch control and for the three different active speed stall control wind turbines. The dimensions, weights, cost and performance are compared.

The paper is organized as follows. First, it describes the wind turbine, the DDPM generator system and the pitch and the active speed stall control concepts. Secondly, the wind turbine model and the generator model are described. Next, the design and comparison of different wind turbine concepts are discussed. Finally conclusions are drawn.

II. WIND TURBINE DESCRIPTIONS

A. Wind turbine characteristics

The parameters of 10 MW wind turbine of this paper are described in Table 1. Using them, the aerodynamic power can be calculated and the turbine is modeled with the generator system. In onshore wind turbines, the blade tip speed is limited to roughly 75 m/s because of noise. However, for offshore turbines, the noise is not important, so that the tip speed can be higher than for onshore turbines [4].

B. Direct-drive PM generator

The direct-drive generator system, especially the permanent magnet (PM) excited type, has high potential for wind turbines because of the following advantages [1][6-9]:

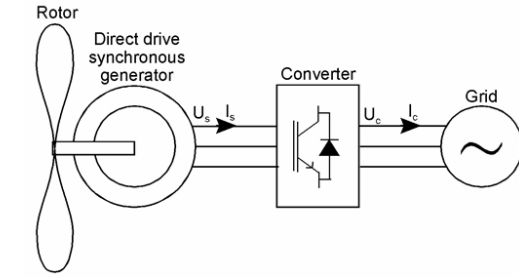


Fig. 2 Scheme of a direct-drive synchronous generator system [4]

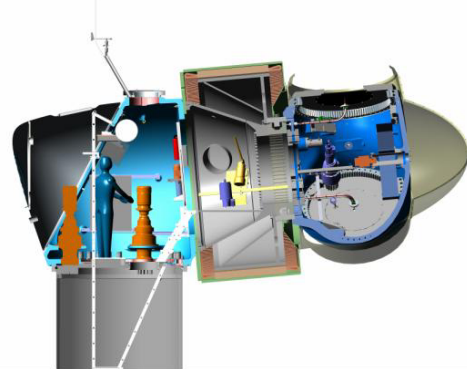


Fig. 3 Sketch of a direct-drive PM generator of the Z72 model of Harakosan Europe [5][11]

- simplified drive train by omitting the gearbox
- no additional mechanism for power supply and magnetic field excitation
- high efficiency and energy yield
- lighter and therefore higher power to weight ratio than electrically excited generator system
- low noise of the drive train

Therefore the direct-drive permanent-magnet (DDPM) generator is discussed with different control concepts, although DD generators have disadvantages such as large weight, large diameter and high cost [10].

The direct-drive generator rotates at low speed, because the rotor of generator is directly connected on the hub of rotor blades. This low speed makes it necessary to produce a very high rated torque in the direct-drive generator.

The scheme of a direct-drive generator system for the wind turbine is shown in Fig. 2 [4]. Fig. 3 depicts a sketch of DDPM generator, which is the Z72 model of Harakosan Europe [5][11].

C. Wind turbine control

1) Pitch control

The generator torque of the wind turbine with pitch control is controlled to obtain constant electrical output power above the rated wind speed. The blade pitch is controlled to keep the rotor speed close to the rated rotor speed.

As an example, Fig. 4 depicts the dependency of the aerodynamic efficiency C_p on the tip speed ratio λ and the

Table 1 Wind turbine characteristics

Rated grid power (MW)	10
Rotor diameter (m)	170
Rated wind speed (m/s)	12
Rated rotor speed (rpm)	10
Optimum tip speed ratio (blade tip speed divided by wind speed)	9.5
Maximum aerodynamic efficiency	0.515
Air density (kg/m ³)	1.225

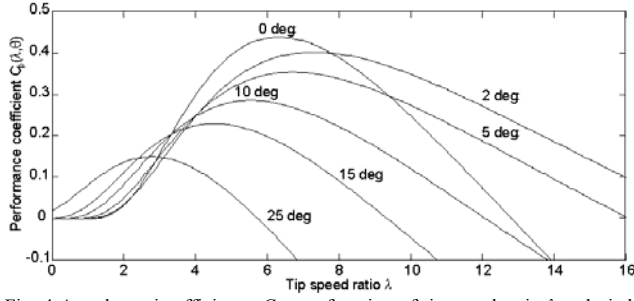


Fig. 4 Aerodynamic efficiency C_p as a function of tip speed ratio λ and pitch angle θ for a specific blade [3]

blade pitch angle θ . For this blade, maximum energy capture from the wind is obtained for $\theta=0$ and λ just above 6. To keep C_p at its optimum value over the wide range of wind speeds, the rotor speed should be proportional to the wind speed.

Between the cut-in wind speed and rated wind speed, the wind turbine of this concept is operated at fixed pitch with a variable rotor speed to maintain an optimum tip speed ratio. When the rated power is reached, the generator torque controls the electrical power output, while the pitch control is used to maintain the rotor speed within acceptable limits. During gusts the generator power can be maintained at a constant level, while the rotor speed increases. The increased energy in the wind is stored in the kinetic energy of the rotor. If the wind speed decreases, the aerodynamic torque decreases, which results in a deceleration of the rotor blade while the generator power is kept constant. If the wind speed remains high, the rotor blade pitch can be changed to reduce the aerodynamic efficiency and torque, once again reducing the rotor speed [12].

Therefore when the pitch control concept is used in the wind turbine, the power can be limited to the designed power by pitching the blades, so that the power ratings of generator, converter and cables are all same with the designed power.

2) Active speed stall control

The active speed stall control concept is a kind of passive stall control, in which rotor blades are directly fixed on the hub without a pitch mechanism. Therefore the pitch angle of the rotor blades of this concept is zero.

Aerodynamic power and torque of the wind turbine with this concept are limited by reducing the rotor speed at wind speeds above rated. The rotor speed is controlled by regulating the generator torque. Therefore the turbine with this concept can be operated at any desired tip speed ratio within the design limits of the generator and rotor blades. The rotor speed is accelerated by decreasing the generator torque below the aerodynamic torque. The rotor speed is decelerated by increasing the generator torque over the aerodynamic torque. However, it is a disadvantage of this concept that the generator must reduce the rotor speed even if the wind speed increases in order to force the rotor blades into stall. This means that the maximum torque of generator must be larger than the torque produced at rated power. To produce large

torque, over dimensioning of the generator system is required.

The wind turbine with the active speed stall control concept can be operated with various control methods to reduce the rotor speed. Therefore, there are a number of possible ways to control the wind turbine. In this paper, to design roughly and assess the DDPM generator systems of this concept, three different control methods are discussed as follows:

- Control with the speed limited
- Control with the power limited
- Control with the torque limited

III. MODELING

A. Wind turbine modeling

The aerodynamic power P_{Aero} can be calculated as a function of the wind speed as [13][14]

$$P_{Aero} = \frac{1}{2} \rho_{air} C_p(\lambda, \theta) \pi r^2 v_w^3 \quad (1)$$

where

ρ_{air} is the air density,

$C_p(\lambda, \theta)$ is the aerodynamic efficiency, which is a function of the tip speed ratio λ and the pitch angle θ ,

r is the wind turbine rotor radius, and

v_w is the wind speed.

Fig. 5 shows the calculated aerodynamic power and torque of the rotor blades as a function of wind speed at various rotor speeds.

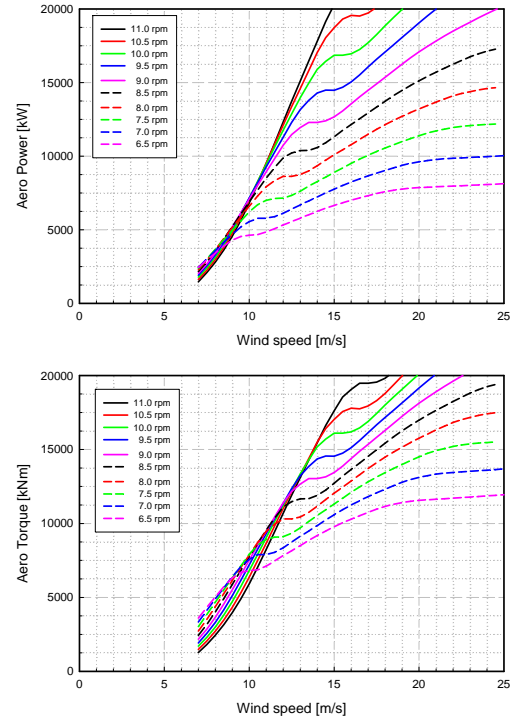


Fig. 5 Power and torque curves of the wind turbine as the function of wind speeds with various rotor speeds

The aerodynamic performance calculations for the wind

turbine are based on a blade-element-momentum (BEM) theory code [15]. The power and torque curves are used for further analyses of the active speed stall control concepts.

B. Generator modeling

The generator characteristics and cost model are described in Table 2. Fig. 6 gives a cross section of four pole pitches of the DDPM generator.

The size of generator is related to the torque, which is a function of the force density of generator. The power and torque produced by the generator can be written as

$$P_{Gen} = \omega_m \cdot T_{Gen} \quad (2)$$

$$T_{Gen} = 2\pi r_g^2 l_s F_d \quad (3)$$

where

P_{Gen} is the generator power,

ω_m is the mechanical angular speed of the generator,

T_{Gen} is the generator torque,

r_g is the air-gap radius of the generator,

l_s is the axial stack length of the generator, and

F_d is the air gap force density (the force per square metre of active air gap surface area).

The force density does not vary a lot with the size of the machine. Therefore, these equations can be used to obtain a fast estimate of the machine dimensions.

The generator power P_{Gen} and efficiency η_{Gen} are described electrically as follows;

$$P_{Gen} = 3 \cdot U_s \cdot I_s \cdot \cos \phi \quad (4)$$

$$\eta_{Gen} = \frac{P_{Gen}}{P_{Aero}} \quad (5)$$

where

U_s is the line voltage, and

I_s is the line current of the generator.

Table 2 Generator characteristics and cost modeling

Generator characteristics	
Slot filling factor k_{sfil}	0.65
Remanent flux density of the magnets B_{rm} at operating temperature (T)	1.2
Recoil permeability of the magnets μ_{rm}	1.06
Resistivity of copper at operating temperature ρ_{Cu} ($\mu\Omega m$)	0.025
Eddy-current losses in laminations at 1.5 T and 50 Hz (W/kg)	0.5
Hysteresis losses in laminations at 1.5 T and 50 Hz (W/kg)	2
Cost modeling	
Power electronics cost (€/kW)	40
Laminations cost (€/kg)	3
copper cost (€/kg)	15
magnet cost (€/kg)	25

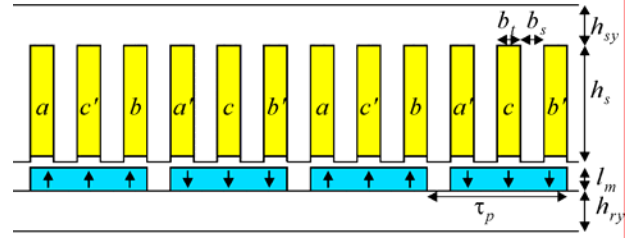


Fig. 6 A linear cross-section of a PM synchronous generator [1]

IV. GENERATOR DESIGN AND COMPARISON

The rough design results of DDPM generators with pitch control and active speed stall control concepts are summarized in Table 3, which gives some dimensions and weight of active materials of the generators. The dimensions and the weight of the three different active speed stall control concepts of the power limited, the torque limited and the speed limited are the same.

A. Pitch control

When the pitch control concept is used in the wind turbine, the power is limited to 10 MW by pitching the rotor blades. Therefore, the power ratings of generator, converter and cables are all 10 MW. Fig. 7 depicts the steady-state operation characteristics of the turbine with this control concept. At low wind speeds, the turbine is operated at maximum aerodynamic efficiency up to the rated rotor speed of 10 rpm. At high wind speeds, this control concept keeps the speed at 10 rpm. By integrating the area below the graph of energy as a function of wind speed, the annual energy yield can be obtained. For energy yield calculations, an average wind speed of 10 m/s with a Weibull distribution [1] is used in this paper. From these results, it can be concluded that the energy yield could be increased considerably by increasing the generator system power. The annual energy yield of this control concept is 48.4 GWh as described in Table 4.

Table 3 Generator dimension and weight

Items	Pitch control	Active speed stall control with Speed, Power and Torque limited
Dimensions		
Stator radius r_s (m)	5	5
Stack length l_s (m)	1.6	2.24
Air gap g (mm)	10	10
Active material weight		
Iron (ton)	48	67
Copper (ton)	11	15
PM (ton)	6	9
Total (ton)	65	91

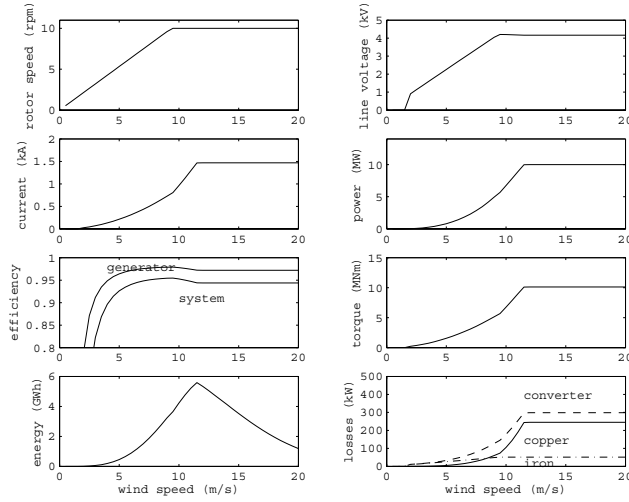


Fig. 7 Characteristics of a turbine with pitch control, a rated torque of 10 MNm, a rated rotor speed of 10 rpm and a rated power of 10 MW

B. Active speed stall control with speed limited

In the active speed stall control with speed limited, the power is limited to 10 MW in a safe way, namely by limiting the rotor speed to 7.2 rpm, so that the generator power never exceeds 10 MW. Therefore, the power ratings of generator, converter and cables are all 10 MW. Fig. 8 depicts the steady-state operation characteristics of the turbine with this control concept. At low wind speeds, the turbine is operated at maximum aerodynamic efficiency up to the rated speed of 7.2 rpm. At high wind speeds, this control concept keeps the speed at 7.2 rpm. The annual energy yield reduces of this control concept is 20 % lower than the pitch control as described in Table 4.

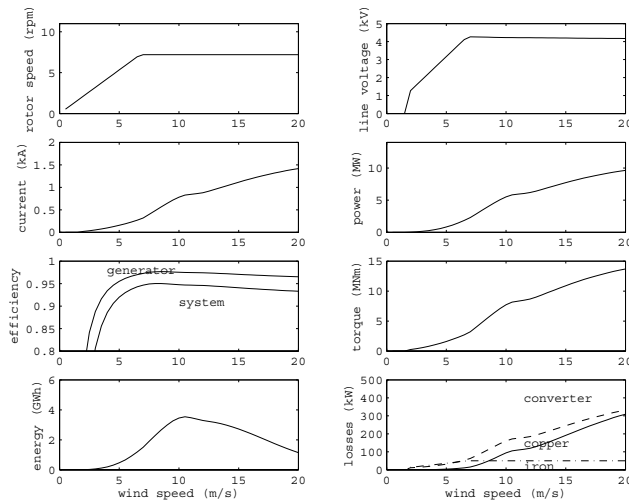


Fig. 8 Characteristics of a wind turbine with active speed stall control, a rated torque of 14 MNm, a rated rotor speed of 7.2 rpm and a rated power of 10 MW

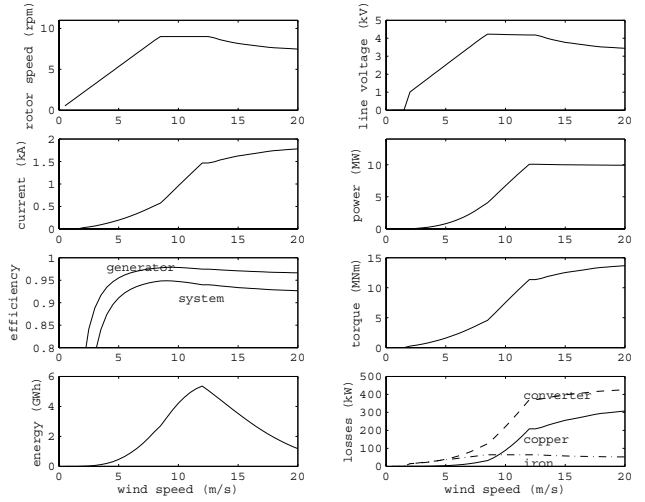


Fig. 9 Characteristics of a wind turbine with active speed stall control, a rated torque of 14 MNm, a rated rotor speed of 9 rpm and a rated power of 10 MW

C. Active speed stall control with power limited

In the active speed stall control with power limited, the power is limited to 10 MW assuming that the wind speed changes are very slow, or we know them sufficiently long before their happening. The converter rating and the generator rating are 12.6 MW because the generator and the converter would be able to generate 12.6 MW if the speed would be kept at 9 rpm. Because the power is limited to 10 MW, the cables can probably just be dimensioned for 10 MW. Fig. 9 depicts the steady-state operation characteristics of the turbine with this control concept. At low wind speeds, the turbine is operated at maximum aerodynamic efficiency up to the rated speed of 9 rpm. At high wind speeds, this control concept keeps the speed constant, until the power level of 10 MW is reached. Then the speed is reduced to limit the power to 10 MW. In order to keep the power at 10 MW at decreasing speeds, the torque has to increase. The annual energy yield of this control concept is described in Table 4. It is comparable to the pitch control concept.

D. Active speed stall control with torque limited

In the active speed stall control with torque limited, the generator and the converter are able to make 14 MNm torque, and therefore, it would be nice to use them up to this torque level. In this case, the generator, the converters and the cables have to be rated for 12.6 MW. Fig. 10 depicts the steady-state operation characteristics of this control concept. At low wind speeds, the turbine is operated at maximum aerodynamic efficiency up to the rated rotor speed of 9 rpm. At high wind speeds, this speed is kept constant, until the torque level of 14 MNm is reached. Then the speed is reduced to limit the torque to 14 MNm. In order to keep the torque at 14 MNm, the speed has to decrease, and therefore also the power decreases. The

annual energy yield of this control concept is 6 % higher than the pitch control concept as described in Table 4. However, this control concept can only be used if the rotor speed is reduced before the wind speed increases. If the turbine works at rated conditions and the wind speed increases instantaneously to twice the rated value, the torque will increase to about 20 MNm, which is not possible for a generator system rated at 14 MNm.

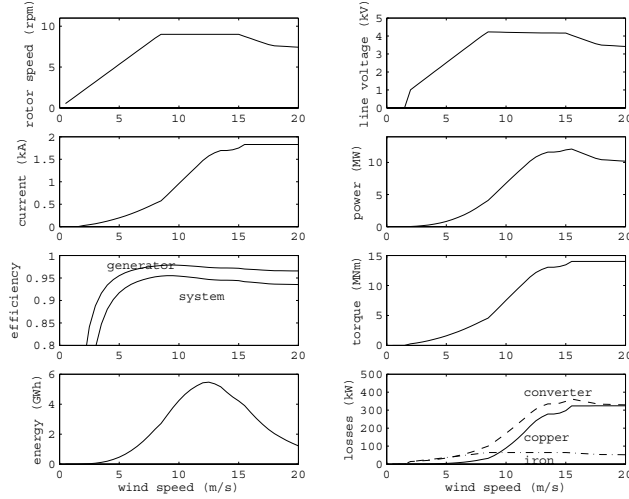


Fig. 10 Characteristics of a wind turbine with active speed stall control, a rated torque of 14 MNm, a rated rotor speed of 9 rpm and a rated power of 14 MW

Table 4 Cost and energy yield for different control concepts

Generator system	Pitch control	Active speed stall control		
		Speed limited	Power limited	Torque limited
Ratings				
Generator torque (MNm)	10	14	14	14
Generator power (MW)	10	10	12.6	12.6
Converter (MW)	10	10	12.6	12.6
Cable power (MW)	10	10	10	12.6
Cost (kEuro)				
Generator active material	462	640	640	640
Converter	400	400	452	504
Annual energy (GWh)				
Copper losses	1.01	0.81	0.96	1.07
Iron losses	0.36	0.39	0.45	0.45
Converter losses	1.42	1.21	1.62	1.56
Total losses	2.79	2.31	3.03	3.08
Energy yield (GWh)	48.4	38.8	48.2	51.1

V. CONCLUSIONS

10 MW direct-drive PM generators are roughly designed in case of the pitch control and the active speed stall control with limited power, torque, and speed. These different wind turbine concepts are compared and assessed considering size, weight, cost, loss, and energy yield of the generators. When changing from pitch control to active speed stall control, a considerable increase in generator system cost is necessary because the generator system rating has to be increased substantially. To be able to design these generator systems with active speed stall control, more research is necessary.

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