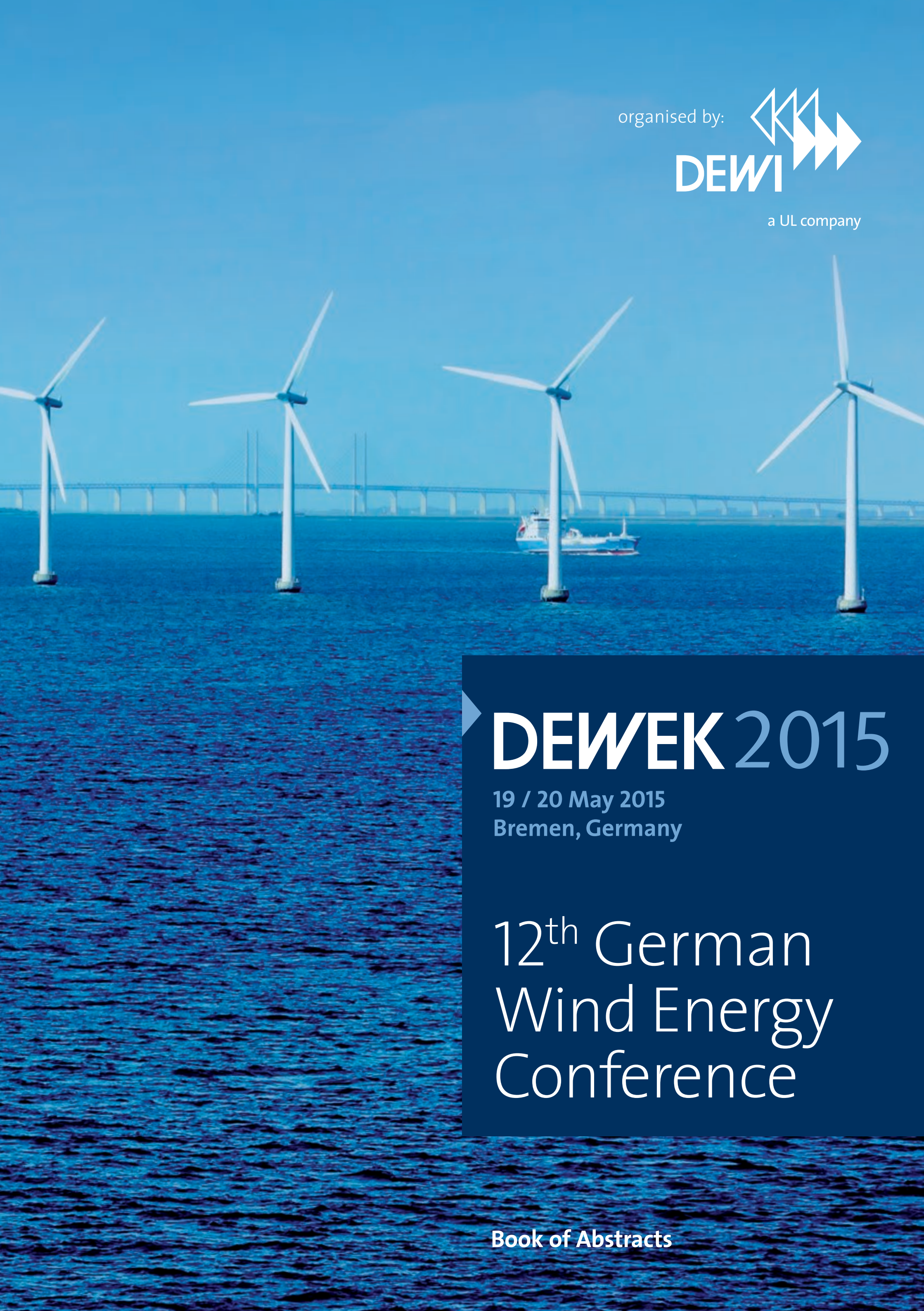

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MULTI-MEGAWATT WIND TURBINE DRIVE TRAIN WITH MULTIPLE HIGH-SPEED GENERATORS

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1. Motivation

High-speed electrical machines offer an increase of power density and cost reduction. Since there are no applications of this technology in wind turbines generators (WTG) so far, an alternative 6 MW WTG drive train with six high-speed (n = 5000 min-1) generators (Fig. 1) will be developed to analyze the potential of high-speed electrical machines in WTG. The proposed drive train configuration combines the advantages of WTG concepts with multiple generators with the high-speed technology of electrical machines.

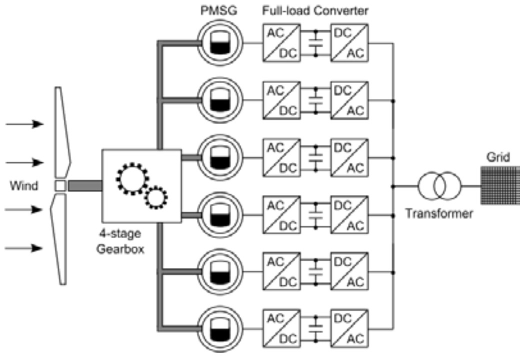

Fig. 1: Drive train configuration

2. Drive Train Configuration

The gearbox used in the proposed drive train configuration needs a higher ratio compared to conventional WTGs. This leads to additional gear stages with new challenges for gears, bearings and the lubrication system. Furthermore the power split for multiple generators leads to an advanced complexity as well as to an increase in weight and material compared to conventional gearbox concepts.
On the generator side the targeted higher speed results in an increased power density, which brings a considerable weight- and size reduction of the generators. This reduces the amount of magnetic active material and leads to a decrease of investment costs.
The design with multiple equal generators enables the utilization of more identical and at the same time smaller and lighter parts, to achieve a better economic efficiency in production and improvements in maintenance. A certain redundancy of the system is given as well, since energy will always be produced, even in case of a malfunction of one generator.

3. Operating Strategy

With a multiple generator drive train concept the operating strategy of conventional WTGs (speed control at partial load and power control under full load) has to be adapted. Here, a special focus is put on the partial load range, since at both, high and low wind sites, about 70 % of the time the average wind speed comes up to the range of partial load operation.
To operate the WTG during partial load in order to permit an optimal efficiency, the rotor speed is adjusted so that an optimum tip speed ratio opt is reached. The use of multiple generator concepts offer the possibility to shut down generators at partial load individually. Thus, the remaining machines will operate in higher power ranges and so at higher efficiencies. Moreover, it is possible to use at different times different generators, so that each generator has a shorter working time than the WTG is in operation.

In this paper first investigated concepts for the gearbox and generator configuration for the WTG will be presented. The main focus is on the operating strategy which will be simulated for different operating conditions to discuss the potential of load and efficiency optimization of this alternative drive train design.

Category: 02

MULTI-MEGAWATT WIND TURBINE WITH MULTIPLE HIGH-SPEED GENERATORS

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Summary

In this research project a new drive train design for a 6 MW wind turbine (WT) will be developed. Thereby the multiple generator concept of WTs will be combined with the high-speed application of electrical machines. Six generators with a rated power of 1 MW at a rated speed of 5000 rpm will be used. This work focuses on the dimensioning of the gearbox, the generators and the development of an operational strategy for such a concept.
For this drive train concept a four-stage gearbox configuration is developed. The first stage is designed as a spur gear stage with a sixfold power split followed by three planetary stages per gear train. This configuration is characterized by a low weight, as well as a large number of identical parts. These factors enable a very modular gearbox design. A coupling is located behind the power split. The power is only reunited on the electrical side, so that the power/ torque flow in the gearbox is determined by the connection and disconnection of individual generators. Thus, the generators can be operated in the optimum operating range with regard to their capacity or efficiency. Connecting and disconnecting individual gear trains and generators during partial load enables an efficiency increase for the developed concept of up to 7 %. This leads to an idealized yield increase of approximately 1.15 % for an exemplary low-wind site with an average wind speed of 5.3 m/s.

1. Introduction

A higher operating speed of electrical machines leads to a higher power density and a reduction of weight and size. This saves magnetic active material, which leads to a significant cost reduction of the electrical machines.
The electrical power in the new drive train concept is intended to be produced by multiple high-speed generators. The power distribution reduces the loads in all parts of the drive train.
The implementation of the multiple generator concept in WTs results in a design with many identical parts, which are smaller and more lightweight than the gearbox and generator components of conventional concepts, due to the power split. Using many identical parts leads to an increased efficiency and quality in serial production and optimized maintenance concepts. The smaller and lighter parts enable on-board repairs and services of the nacelle, without the use of large mobile cranes. Downtimes during WT operation can thus be reduced.
Another advantage of the concept with multiple generators is the higher redundancy. The full energy yield can still be achieved during partial load operation, even if one generator fails. During full load operation only a small energy loss is recorded until the generator is repaired.

2. Drive Train Configuration

During the design of the drive train concept the focus is set on the gearbox and the generators. For the main bearing a conventional four-point bearing concept is used. The nacelle frame is a classic WT main frame, which is modified for the mounting of the new gearbox configuration and the generators.
The developed gearbox concepts for the high-speed multi-generator drive train are designed according to the structure of conventional WT gearbox configurations. The gearbox is made up of a combination of planet and spur gear stages. To restrict the solution space in the design process of the planet gear stages, only the two-shaft operation mode (driven planetary carrier, output over sun gear) will be taken into account. Using planetary gear stages, high transmission ratios with a compact design and high power densities can be realized. To implement the power split to six output shafts or generators, a spur gear stage is used.
Since the intended rated speed of the generators for strong- and low-wind WT configurations is 5000 rpm, the gearbox needs a ratio higher than 1:400. To realize this ratio four gear stages are used. In order to develop a modular configuration, the gearbox concepts consist of standard and independent gear stages, joined together through a coupling. In case of a malfunction the defect gearbox component can

thus be completely replaced and the downtime of the WT can be reduced. Moreover, with this modular design it will be possible to use different lubricating oils and different lubrication procedures for each of the four gear stages. Under these conditions four gearbox concepts were developed. They consist of three planetary stages (P) and a spur gear stage (S). The concepts differ in the position of the spur gear stage and thus the power split in the gearbox (Fig. 1).

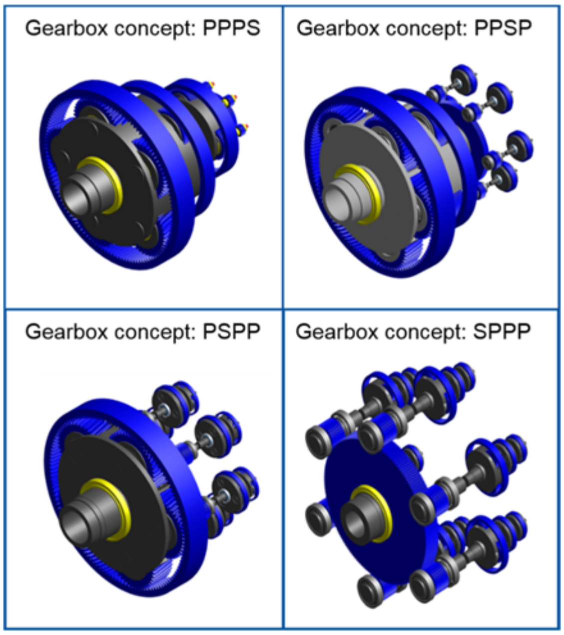


Fig. 1: Gearbox configurations

The PPPS and SPPP concepts should be particularly mentioned. The use of planetary gear units in the first three stages leads to a compact gear design with a low modularity. The concept with power split in the first stage stands in direct contrast to this structure. For this concept six individual 1 MW gear trains, each with three planetary stages, are arranged after the first stage. This leads to a very modular gearbox structure, increases the number of identical parts and reduces the mass of the individual components (Table 1).

Table 1: Comparison of gearbox concepts

Gearbox concepts	PPPS	SPPP
Weight	≈ 47 t	≈ 40 t
Size (width × length)	3.4 × 3.4 m	4.2 × 3 m
Total number of parts	90	370
Number of different parts	28	31

Besides advantages of modularity and weight, the SPPP gearbox concept offers also the greatest potential to improve the capacity utilization of the components and the increase in efficiency during partial load operation. This is due to the possible integration of switchable couplings in the gearbox immediately after the first gear stage.

For the development of the generator with a rated power of 1 MW and a rated speed of 5000 rpm three electrical machine topologies are analyzed: the squirrel cage induction machine (SCIM), the electrically excited synchronous machine (EESM) and the synchronous machine with permanent magnet (PM) excitation (PMSM).
The results of the initial analytical design indicate that the SCIM has the highest power density and the EESM the highest efficiency, but the differences are relatively small in comparison to the PMSM. This aspect shows that the accuracy of an analytical investigation is insufficient. However, it is known that a significant increase of the efficiency of the PMSM can be expected if an arrangement with V-shaped buried magnets (V-PMSM) is used, which is why a V-PMSM is initially chosen for an in-depth numerical design. In order to determine the dimensions and the efficiency map of the V-PMSM design as accurately as possible, an existing generator geometry is scaled to the required power of 1 MW and designed numerically with the help of the finite element method (FEM). The geometric dimensions of the machine yield a total volume of magnetically active material of 0.087 m^3, as well as a power density of 11.5 MW/m^3. The maximum efficiency determined for the V-PMSM is 98.27 % (Fig. 2).

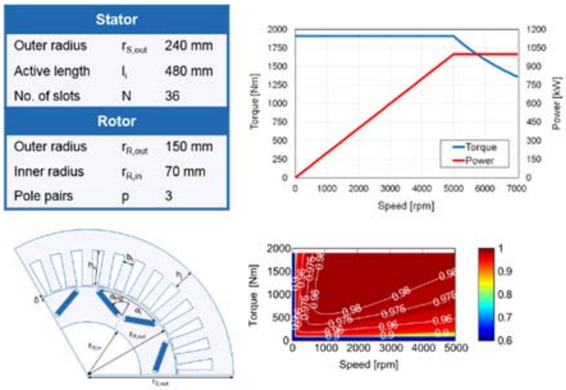


Fig. 2: V-PMSM configuration and efficiency

To compare the different drive train concepts regarding their efficiency, simulation models were created, where the main bearing, the different gearbox structures and the V-PMSM are considered. The calculation of the power losses is based on [1] for the bearings, on [2] and [3] for the gear meshing and on [4] for the seals. The results show a rise of the efficiency curve from the partial to the full load range (where P/P_{Rated} = 100 %), for all drive train configurations (Fig. 3). The simulation results show realistic curves, but there is a difference in the entire operating range of less than 1 %. The drive train concept with power split in the third stage (PPSP) has the highest efficiency, 93.7 % at full load. The concepts with the power split in the first (SPPP) and the last stage (PPPS) show an almost identical characteristic over the entire operating range, with a maximum efficiency of about 93.5 % at full load. The efficiency of the concept with power split in the second stage (PSPP) is about 0.25 % lower.

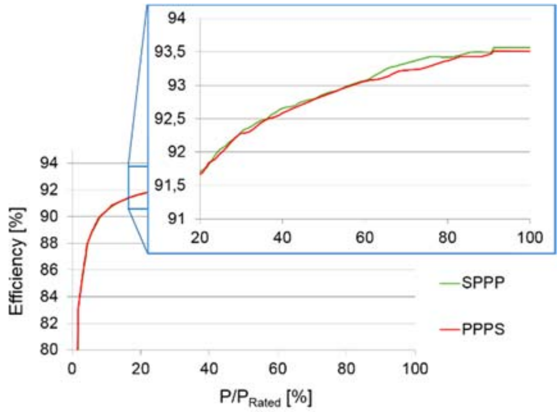
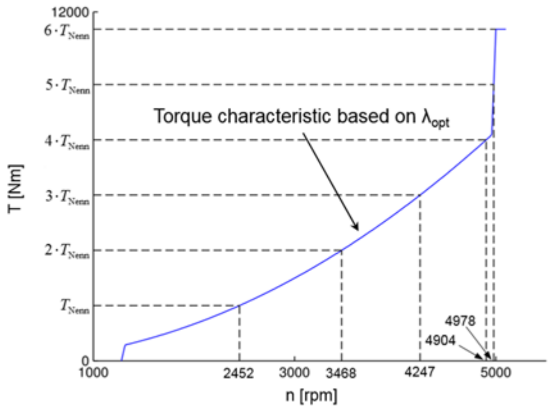


Fig. 3: Results of the efficiency calculation

The expected result, that the gearbox concept with most rotating components (SPPP) has the lowest efficiency curve and the concept with the least components (PPPS) scores best, is not met.
This can be explained by the use of different bearings and small differences in the transmission ratio of the various gearbox configurations, which resulted during the dimensioning of the concepts. In particular, the discrete changes in size of the used bearings lead to different power losses that affect the efficiency results.

3. Operating Strategy

A drive train concept with multiple generators offers the possibility to switch off individual generators during partial load operation, so that the remaining machines can work at their rated operating point and in their optimum efficiency range. Due to the connection and disconnection of individual generators, the utilization of the generators can be optimized and the efficiency can be increased. The decoupling of total gear trains by using switchable clutches in the gearbox can offer further potential for increasing the efficiency during partial load operation.
A major challenge is the coupling during operation of the WT, due to very high torques at low rotational speeds or high torques at high speeds, depending on the position of the coupling in the gearbox. Other requirements, such as space limitations or required switching frequencies, also have to be regarded. Moreover, the high loads are contrasting with the requirement of a maintenance-free system or very rare maintenance intervals. In the presented gearbox structures six identical couplings are used after the power split. The synchronization between the input and the output side of a coupling can be realized in two ways. On the one hand, the speed difference between the input and the output side is automatically eliminated through the slip torque of the coupling. This can lead to high coupling loads and strong heat dissipation. A second option is offered in this case by the generators. They can also be operated as motors and are thus able to adapt the output speed to the drive speed. This constitutes a pre-synchronization, which has the advantage of reduced coupling loads, depending on how precisely the output speed can be adjusted to the drive speed, before the coupling engages.
While at full load the operating strategy is the same as that of conventional WTs, it has to be changed during partial load operation, given the possibility of connection and disconnection of individual gear trains. For the proposed drive train concept with six generators the partial load range has to be divided into six individual operating ranges. Each of these areas must be provided with both a variable speed control and a pitch control in order to protect the WT during short-term changes of the wind speed.
Fig. 4 shows the torque characteristic of the WT rotor based on the optimum tip speed ratio λ_{opt}. The torque characteristic is plotted over the generator speed and the inevitable switching points of the individual generators during partial load operation are pointed out. When the rated torque T_{Rated} of a generator is reached, another generator must be connected. This leads to the indicated switching points and the corresponding duty cycles of the generators. Individual generators must therefore be connected before they reach their rated power, for the given drive torque characteristic. With one generator for instance, the WT can be operated only up to about 500 kW until another generator has to be connected.



$$\frac{P_{G,i}}{P_{Rated}} = \frac{n_i \cdot T_{Rated}}{n_{Rated} \cdot T_{Rated}} = \frac{n_i}{n_{Rated}}$$

$$P_{Rated,1} = 1MW \quad n_1 = 2452\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,1}}{P_{Rated,1}} = 49\%$$

$$P_{Rated,2} = 2MW \quad n_2 = 3468\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,2}}{P_{Rated,2}} = 69\%$$

$$P_{Rated,3} = 3MW \quad n_3 = 4247\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,3}}{P_{Rated,3}} = 85\%$$

$$P_{Rated,4} = 4MW \quad n_4 = 4904\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,4}}{P_{Rated,4}} = 98\%$$

$$P_{Rated,5} = 5MW \quad n_5 = 4978\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,5}}{P_{Rated,5}} = 99.5\%$$

$$P_{Rated,6} = 6MW \quad n_6 = n_{Rated} = 5000\,\mathrm{min}^{-1} \Rightarrow \frac{P_{G,6}}{P_{Rated,6}} = 100\%$$

Fig. 4: WT torque characteristic with inevitable switching points of individual generators

This switching procedure has been added to the efficiency calculation model to show the potential of increasing the efficiency during partial load operation. The moments of connection and disconnection of several generators are defined by reaching a multiple of the rated torque (T_{Rated} = 1900 Nm) of the generators. In the drive train model, the gear trains which are not required, can also be decoupled and switched separately with the generators. This behavior simulates the use of a coupling after the spur gear and therefore after the power split in the gearbox. The results of this efficiency simulation for different drive train configurations are shown in Fig. 5. The red curves indicate the efficiency during partial load operation without the switching procedure and the green curves the efficiency when the described switching procedure is used. The results show a significant efficiency increase in the lower range of the partial load operation, due to the connection of individual drive trains. As soon as all generators are switched on (at approximately 83 % rated power), the efficiency curve is the same as in the case where no switching procedure is used.

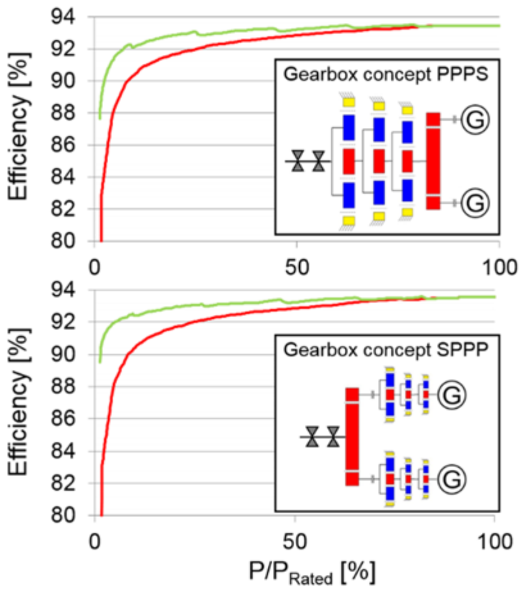


Fig. 5: Efficiency curves for different drive train configurations, without (red) and with (green) switching procedure

The greatest efficiency increase (more than 7 %) by using this switching procedure is reached by the drive train concept with power split in the first gear stage (Fig. 6). For this concept three planetary stages per gear train are decoupled and the highest number of parts is thus disconnected from the power flow, when compared to the other concepts.
The efficiency increase leads to a higher electrical output power of the WT and to a higher energy yield. In low-wind regions the WT operates up to 70 % of the total operating time at partial load (Fig. 7), which makes the use of this drive train concept with the illustrated switching procedure particularly suitable for this locations.
The increase in energy yield during partial load operation is up to 1.15 % for a low-wind site with a mean wind speed of 5.3 m/s. Besides this income increase, the number of operating hours per generator can be significantly reduced, due to the possibility of their individual connection and disconnection.

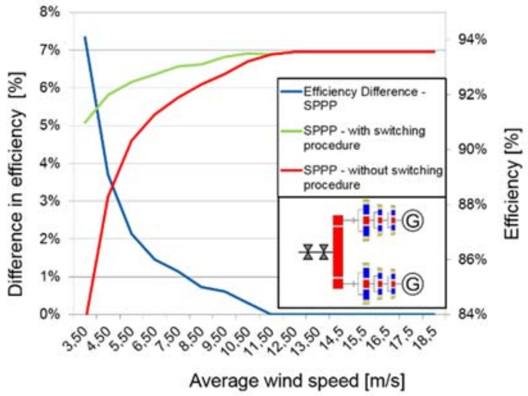


Fig. 6: Efficiency difference (blue) and efficiency curves without (red) and with (green) switching procedure, for the drive train with SPPP gearbox

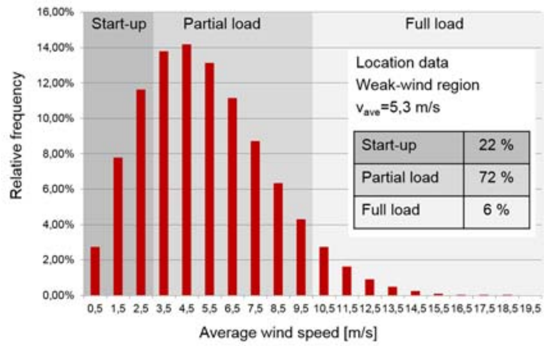


Fig. 7: Wind speed distribution and operating ranges for a low-wind site

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