Technische und wirtschaftliche Bewertung unterschiedlicher Multi-Megawatt Windanlagenkonzepte – Eine alternative Methode

Technical and Economical Assessment of Different Multi-megawatt Wind Turbine Concepts – An Alternative Approach

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EUROPÄISCHE UNION
Europäischer Fonds für regionale Entwicklung

Promoted by the Ziel-2-programme NRW 2007-2013 „Regionale Wettbewerbsfähigkeit und Beschäftigung“ (EFRE)

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1 Abstract

This paper presents an alternative approach used in the technical and economical evaluation of different wind turbine drive train concepts.

A motivation for the purpose the authors set out to achieve, introduces this paper in the second section. In the third section an overview of the established wind turbine concepts is given, starting from the conventional configurations. Subsequently, an evaluation based on the German wind energy market penetration is done and four trendsetting wind energy system topologies are selected. For these concepts the two main components – the gearbox unit and the generator – are systematically investigated. The used assessment methodology is described in section 4. The implementation and the achieved results are discussed in section 5. Finally, section 6 concludes this paper with an outlook.

2 Introduction and Motivation

Wind turbines are energy conversion systems with a complex electromechanical structure, consisting of highly interconnected subsystems, which are constantly exposed to dynamic electrical and mechanical stress.

Test rigs for onshore wind turbines of up to 4 MW are being developed at the RWTH Aachen University to facilitate the understanding of the entire wind turbine system and to help improve their design.

At the same time new alternative drive train concepts are being investigated, in order to increase the technical and economical efficiency of wind turbines. For this purpose a fundamental theoretical consideration and assessment of the existing market-relevant drive train concepts, based on a value-benefit analysis, was carried out.

3 Studied Wind Turbine Configurations

This section presents a brief review of today’s conventional onshore upwind large-scale wind turbine concepts, without exhausting all possibilities, and gives a somewhat more detailed overview of the established concepts – regarding their penetration on the German wind energy market – that are used to apply and verify the assessment methodology proposed in the following sections. Hereby the focus is set on the gearbox and generator as the two main components of the drive train. Power electronic converters are also mentioned.

3.1 Established Wind Turbine and Generator Concepts

The most commonly applied wind turbine (WT) concepts can be classified, according to their speed control ability and their aerodynamic power regulation method, into four basic categories [EARN11], [HANS04], as shown in Figure 1:

- Constant speed wind turbines, with a speed variability of only 1 – 2% above the rated speed.
- Narrow range variable speed wind turbines, which allow a variability of up to 10% above the rated speed.
- Limited range variable speed wind turbines, with a speed range of -30 – 30% around the rated speed.
- Wide range variable speed wind turbines, for which speeds up to 3-times the rated speed are possible.

It can be seen that for these wind turbine topologies four basic electrical generator concepts are commonly used: the squirrel cage induction generator (SCIG) for constant speed wind turbines, the wound rotor induction generator (WRIG) for narrow range variable speed wind turbines, the doubly-fed induction generator (DFIG) for limited range variable speed wind turbines and the synchronous generator for wide range variable speed wind turbines. The latter concept is widely spread as an electrical excited configuration with a wound rotor (WRSG), but can also be found having a permanent magnet excitation (PMSG).

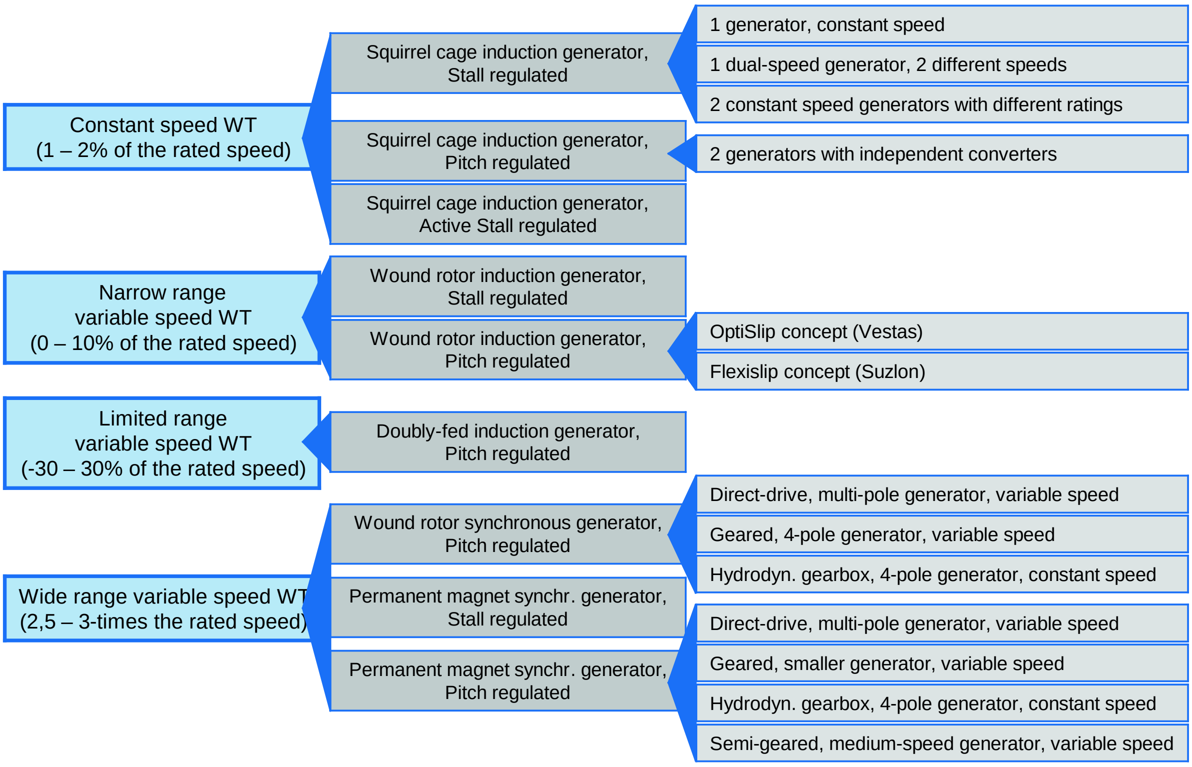

Figure 1: Conventional wind turbine concepts [EARN11]

From these basic concepts different variations have been developed over time (some examples are listed on the right in Figure 1): one dual-speed SCIG or two SCIG with different power ratings (both concepts with stall control), direct-drive gearless wind turbines with a multi-pole WRSG or geared wind turbines with a 4-pole WRSG (both concepts with pitch control), semi-geared wind turbines with a medium-speed PMSG (with pitch control) etc.

Table 1 gives an overview of the generator and gearbox technologies used in these concepts, as well as of several manufacturers that implement them in their wind turbines. This overview is exemplary and by no means exhaustive.

The change of concept in the early 2000s from the simple, robust and inexpensive, yet electrically rigid (from the viewpoint of the grid) wind turbines with SCIG, to the improved and grid-friendlier variable speed solutions was based on both technical and economical grounds. Wind turbines were still a large capital expenditure at that time, despite many grants and subsidies provided by most European governments for the development of the wind industry. The revenue from wind generated electricity had to be increased, which in turn meant that more installed electrical power per turbine was required. Variable speed concepts became therefore essential [NEWT06]. From the technical point of view, constant speed wind turbines exhibit a number of drawbacks when compared to the variable speed concepts, mainly the uncontrollable reactive power consumption, high mechanical stress on the drive train (due to the fixed speed operation, wind speed turbulences are converted into torque fluctuations) and limited power capture and quality control [HANS04].

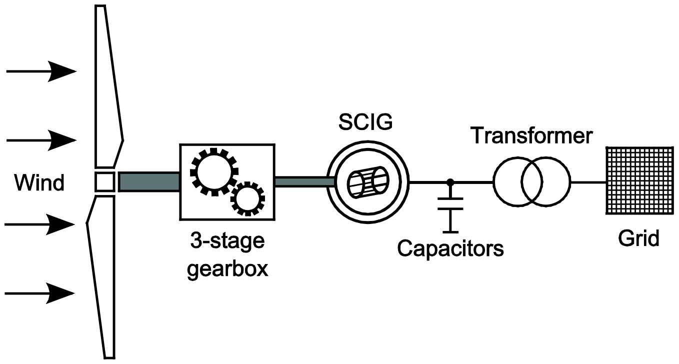

Figure 2: Constant speed WT with SCIG

A constant speed wind turbine as shown in Figure 2 mainly consists of a rotor and a SCIG connected through a gearbox. The stator winding of the generator is directly connected to the grid. With the harvested electrical power the generator speed varies as much as the slip allows it and is therefore not constant. However, due to the small slip variations (1 – 2%), this configuration is commonly referred to as a *constant* or *fixed speed* wind turbine [SLOO03]. For the compensation of the reactive power, which is always drawn by the SCIG from the grid in order to build up its magnetic field, capacitor banks are implemented. Also, soft starters can be implemented for a smoother grid connection during the turbines start-up [EARN11], [HANS04]. This concept won't be regarded any further, being rather obsolete and not used by manufacturers in modern turbines, due to the disadvantages previously mentioned.

Wind turbine concept	**Aerodynamic power regulation**	**Wind turbine manufacturers**
SCIG Very narrow speed range (1 – 2% above rated speed)	Stall, pitch or active stall control 1 or 2 speeds (or 2 generators)	REpower (GE), 600 / 750kW Suzlon (IND / GE), 0.35 / 1 / 1.25MW Nordex (GE), 0.25 / 1.3MW Siemens (GE), 2MW, *Combistall* Siemens (DK), 1.3 / 2.3 / 3.6MW
WRIG Narrow speed range (0 – 10% above rated speed)	Stall or pitch control	Suzlon (IND / GE), 2.1MW, *Flexislip* Vestas (DK), 0.6 – 3MW, *OptiSlip*
DFIG Limited speed range (-30 – 30% around rated speed)	Pitch control	Vestas (DK), 0.85 / 1.8 / 3MW, *OptiSpeed* Gamesa (SP), 0.85 / 2MW Fuhrländer (GE), 1.5 / 2 / 2.5MW Nordex (GE), 1.5 / 2.5MW Acciona (SP), 1.5 / 3MW GE Wind (US), 1.5 / 3.6MW Repower (GE), 1.5 / 2 / 5MW Bard (GE), 5MW
WRSG Wide speed range (2.5 – 3-times the rated speed)	Pitch control Direct-drive gearless WT with multi-pole generator	MTorres (SP), 1.65MW Enercon (DE), 0.8 – 7.5MW
	Pitch control WT with gearbox	Made (SP), 2MW Kenersys (IND), 2MW
	Pitch control WT with hydrodynamic gearbox and constant speed generator	Windflow (NZ), 500kW, 2 rotor blades
PMSG Wide speed range (2.5 – 3-times the rated speed)	Pitch control Direct-drive gearless WT with multi-pole generator	Leitwind (IT), 1.2 / 1.35 / 1.5MW Mitsubishi (JP), 0.3 / 0.6 / 2MW Avantis (GE), 2.5MW ScanWind (NOR), 3.5MW Lagerwey (NL), 2 / 2.5 / 2.6 / 3MW Siemens (DK), 3 / 6MW
	Stall control Direct-drive gearless WT with multi-pole generator	Jeumont (FR), 750kW
	Pitch control WT with gearbox	Clipperwind (US), 2.5MW (4 x 660kW) Vestas (DK), 3MW
	Pitch control WT with hydrodynamic gearbox and constant speed generator	DeWind (GE), 2MW
	Pitch control Semi-geared WT with medium-speed generator	WinWinD (FIN), 1/ 3MW Fuhrländer (GE), 3MW Areva Multibrid (GE), 5MW

Table 1: Exemplary overview of different drive train concepts and of several manufacturers that implement them in their wind turbines [EARN11]

A variation of this concept is the narrow range variable speed wind turbine shown in Figure 3, with a similar topology. The only significant difference is the use of a WRIG instead of a SCIG. Unlike in the case of a SCIG, the rotor of a WRIG does not consist of cage bars, but has copper windings that are connected to an external variable electronically controlled resistance, through either a system of slip rings and brushes (Suzlon *Flexislip*) or through optical fibers, where the optically controlled converter is mounted directly on the rotor shaft and the signal coming from the optical fibers is passed over via opto-couplers (Vestas *OptiSlip*). The size of the resistance determines the speed variability, which is usually up to 10% above the rated synchronous speed and even 16% in the case of Suzlons *Flexislip* [EARN11], [TSIL09]. When compared to a SCIG, the WRIG offers relatively improved grid elasticity and is less sensitive to grid instabilities, due to its higher slip, which results in an increased damping ability of the rotor dynamics. This also allows for a better power factor and provides better efficiency. As a drawback it can be noted that the slip power in the rotor is dissipated as heat losses in the variable resistance, leading to the reduction of the overall power output [EARN11].

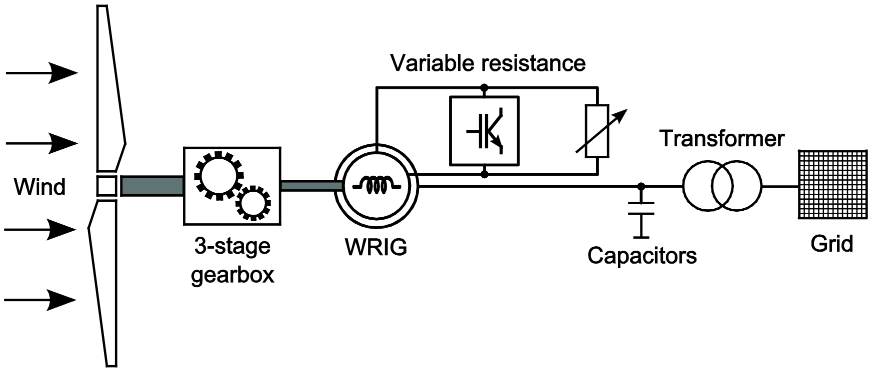

Figure 3: Narrow range variable speed WT with WRIG

The low voltage ride-through (LVRT) behavior of the two aforementioned concepts (with SCIG and WRIG, respectively) is dominated by the direct grid connection and the restricted slip variability. In case of a voltage dip the torque of the generator decreases significantly and leads to a fast acceleration of the rotor. This results in rotor instability, if the voltage is not restored to its normal level or if the accelerating mechanical torque is not reduced below the available electromagnetic torque of the generator fast enough. Also, the slip increases and thus the absorbed reactive power, which basically prevents the fast recovery of the voltage. This effect is not so pronounced for WRIG, because of the slightly higher slip variability. A possible countermeasure would be to supply the reactive power through static compensation devices (STATCOMs), but this is rather complicated and expensive [TSIL09]. The improvement of the LVRT capability of wind turbines is also one of the reasons that lead to the development of concepts with higher speed variability.

Limited range variable speed wind turbines with DFIG (see Figure 4) are the most common configuration of wind turbines on the wind energy market. While the stator is directly grid connected, the rotor windings are connected to the grid via two back-to-back voltage source power electronic converters.

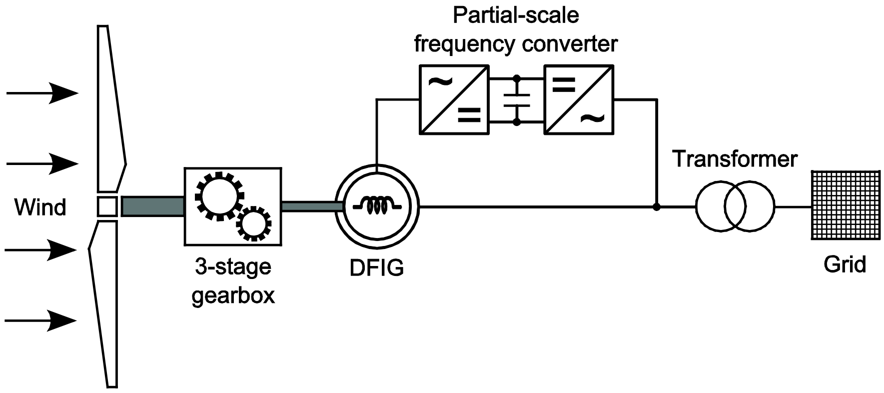

Figure 4: Limited range variable speed WT with DFIG

The basic operation of the two converters can be summarized as follows: the grid-side converter controls the active power flow between the rotor windings and the grid, depending on the operation point. Active power is either being injected into the grid in super-synchronous mode (when the slip is negative) or respectively absorbed by the rotor windings in sub-synchronous mode (when the slip is positive). The rotor-side converter excites the rotor windings at variable frequency, thus determining the rotor speed, and regulates the injection of reactive power into the grid, in order to maintain a unitary power factor operation of the wind turbine. This variable speed operation allows for the maximization of the power coefficient during operation at different wind speeds. The power rating of the partial-scale converter is directly dependent to the operating slip and thus to the speed range the generator has to operate. As the speed range variability of this concept is typically ±30% of the rated speed, the converter is also dimensioned at about 30% of the turbines rated power [ANDR11], [TSIL09].

The smaller power rating of the frequency converter, when compared to full-scale converters, makes this wind turbine concept a very attractive variable speed solution from an economical point of view. In addition the generator is relatively simple and cost effective to manufacture, an aspect that further helps to keep the capital costs as low as possible. Technical advantages of this concept are also worth noting. The dynamic control of the generator, for instance, provides a system with considerable improved transient behavior, when combined with the pitch control of the rotor blades. The wind turbine is thus capable of operating in more turbulent wind conditions. The speed range variability is of course wide compared to that of a wind turbine with WRIG and, unlike in the case of a WRIG where the slip power in the rotor is burned off in the controllable resistance, the converter in the rotor circuit of a DFIG is able to capture this energy. Furthermore, almost all modern DFIG-based wind turbines feature fault ride-through (FRT) capabilities, being able to actively support the grid during low frequency events. On the other hand, LVRT is still an issue with this concept, because of the high currents which could be induced in the frequency converter during voltage dips. A so-called crowbar circuit is implemented in the rotor circuit, in order to avoid this [SALL10], [TSIL09]. The main disadvantage here is the high shock loads that occur in the mechanical components such as the gearbox, especially after the fault clearance. The assembly of slip rings and carbon brushes is also a drawback of the DFIG, since they require regular maintenance [NEWT06], [HANS04], [EARN11].

The last of the four discussed wind turbine concepts is the wide range variable speed wind turbine, which comprises a synchronous generator – electrically excited (with a wound rotor, WRSG, see Figure 5) or with a permanent magnet excitation (PMSG, see Figure 6) – and a full-scale frequency converter, which fully decouples the generator from the grid. This concept can be equipped with a gearbox or have a direct-drive gearless configuration (indicated by the dotted line). In case of a WRSG the excitation is provided via a controllable power electronic rectifier, which supplies the rotor windings with the necessary direct current.

The direct-drive gearless topology is mostly known due to Enercon, a company that exclusively manufactures this kind of turbines, their main characteristic being the bulky low-speed high-torque multi-pole WRSG. The main advantage advocated by the manufacturers in favor of this concept is the absence of a gear unit, which reduces failures and lowers maintenance problems, increasing the total turbine availability. On the downside, this requires a fully rated power electronic converter, which further adds to the cost and weight issue of these turbines. However, being decoupled from the grid, electrical turbulences have no direct effect on the generator. When compared to a DFIG, current and torque variations during voltage dips are thus lower. At the same time, the higher power rating of the full-scale converter allows for a better LVRT capability, being able to produce more reactive current during voltage dips than the partial-scale converters used with DFIG configurations [TSIL09], [POLI06], [EARN11], [NEWT06].

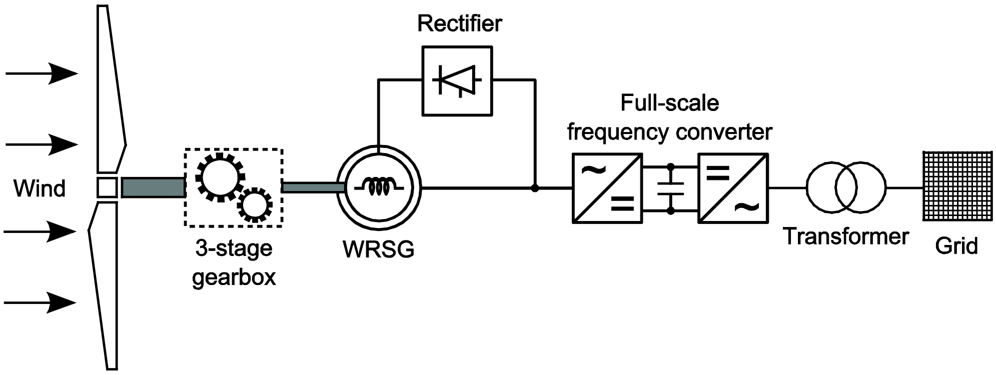

Figure 5: Wide range variable speed WT with WRSG

Synchronous generators with a permanent magnet excitation have also become a viable solution for the application in wind turbines (see Figure 6), due to the low permanent magnet prices. A high increase (of more than 800%) in the permanent magnet prices was registered until 2011, with prices continuously decreasing ever since. Using a permanent magnet excitation generally results in a lightweight design of the generator (roughly a factor two in magnetic active material). At the same time, the absence of the rotor windings and of the rectifier used for the electrical excitation in the WRSG, yields lower total losses. However, careful design of the generator is required to ensure that during grid faults the resulting over-voltage does not damage the converter or that it results in the demagnetization of the permanent magnets [POLI05], [NEWT06]. The use of a full-scale converter, that completely decouples the generator from the grid, is an advantage for the gearbox unit as well, since grid turbulences are not forwarded as mechanical loads. On the other hand, a full-scale converter further adds to the weight and costs of a wind turbine.

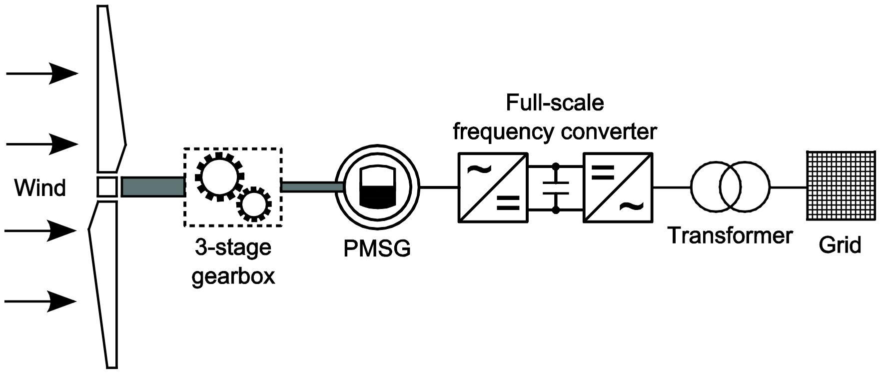

Figure 6: Wide range variable speed WT with PMSG

The main disadvantage of the synchronous generators used in direct-drive wind turbines is that with higher power levels and lower speed they become larger and more expensive. Different manufacturers are therefore embracing an alternative concept, derived from the one depicted in Figure 6: the wide range variable speed wind turbine with a single- or double-stage gearbox and a medium speed PMSG (see Figure 7).

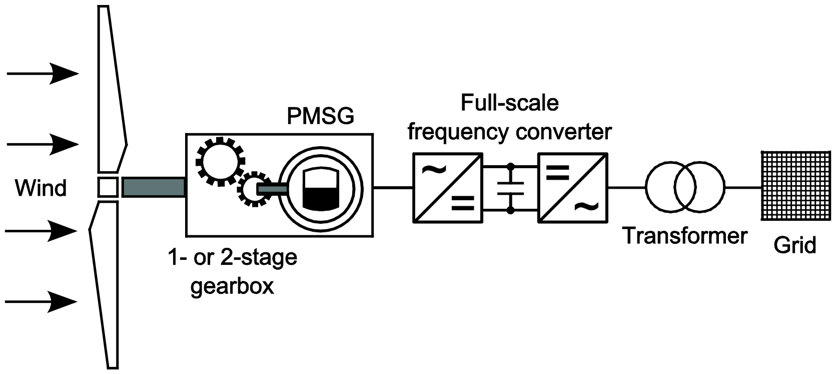

Figure 7: Wide range variable speed WT with a single- or double-stage gearbox and a medium-speed PMSG

This concept, commonly known under the name *Multibrid*, is implemented in wind turbines from different manufacturers, such as Areva or Fuhrländer. Gearbox manufacturer Winergy and generator manufacturer The Switch (in cooperation with gearbox manufacturer Moventas) are successfully marketing this concept under the name *HybridDrive* and *FusionDrive*, respectively. This “hybrid” configuration brings significant advantages regarding generator costs and efficiency, when considering the entire system, through the integration of the generator and the gearbox unit. It has been thus proposed to use a single-stage gearbox in combination with a DFIG as well [POLI06].

Next to the generator, the gearbox unit (see Figure 8) is the second most important component of a wind turbine’s drive train and shall be discussed briefly in the following.

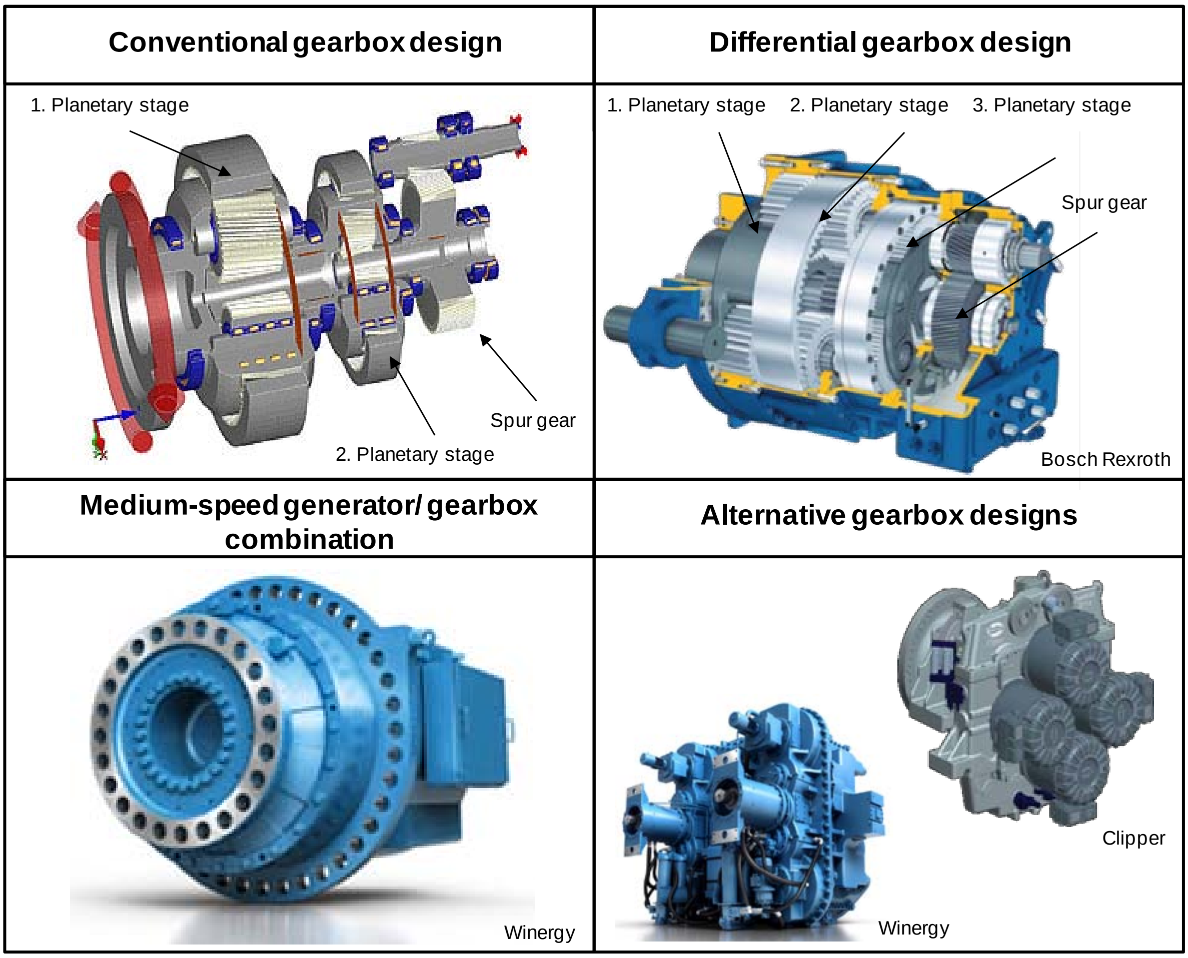

Figure 8: Established gearbox concepts for multi-megawatt wind turbines

The conventional configurations of gearboxes in the area of multi-megawatt wind turbines are designed with two planetary stages and one spur gear stage. In the lower power ranges commonly 3-stage gearboxes with one planetary stage and two spur gear stages are used. The gear ratios for conventional gearboxes are over 60, in order to translate the slow speed on the rotor side to the high speed of the generator. The power flow as well as the number of installed planets can vary from one manufacturer to the other and for different model series. Also in medium-speed drive train concepts of wind turbines planetary gears are used. Depending on the nominal generator speed the gearboxes are usually composed of two or one planetary gear stages. The drive train concepts are usually designed to be very compact and highly integrated, in order to eliminate the coupling between the gearbox and the generator. Thus the generator is flanged directly to the gearbox, or in some cases both components are assembled in a single housing.

Apart from the mentioned gearbox concepts, there is a series of alternative designs, such as the mechanical power split to multiple output shafts or the use of pure spur gears. The transmission of the speed and torque with hydraulic gearboxes is also in the development and prototyping phase.

In conclusion of this section, the main features of the different wind turbines concepts, as discussed in the technical literature, are briefly summarized [BANG08]:

- The DFIG based wind turbine with a conventional gearbox is an advantageous solution regarding weight and cost issues.
- Considering the electrical energy yield, the losses and the reliability, the direct-drive gearless wind turbines are more powerful when compared to the geared concepts, especially the PMSG configuration.
- The wide range variable speed wind turbine with single- or double-stage gearbox and PMSG has the highest energy yield to cost ratio.
- According to their capital cost, the different configurations can be arranged as follows (from highest to lowest): (1) direct-drive wind turbine with WRSG, (2) direct-drive wind turbine with PMSG, (3) wind turbine with single- or double-stage gearbox and PMSG and (4) wind turbine with conventional gearbox and DFIG.

3.2 German Wind Energy Market

In order to determine the most relevant wind turbine concepts, based on their market penetration, a German wind energy market survey was conducted. The analysis, which is hereby briefly summarized, is based on market data from the German Wind Energy Institute (DEWI) and concept evaluation from different wind turbine manufacturers (Internet data). The main focus was set on determining what wind turbine concepts and power ratings are relevant for the onshore upwind large-scale section.

Figure 9 shows the erected wind turbines in Germany from 2007 till 2011 on a percentage basis, regarding their power rating. It can be seen that approximately 80% of the wind turbines have power ratings between 2 and 3MW, with a definite trend towards 3MW turbines in the last years.

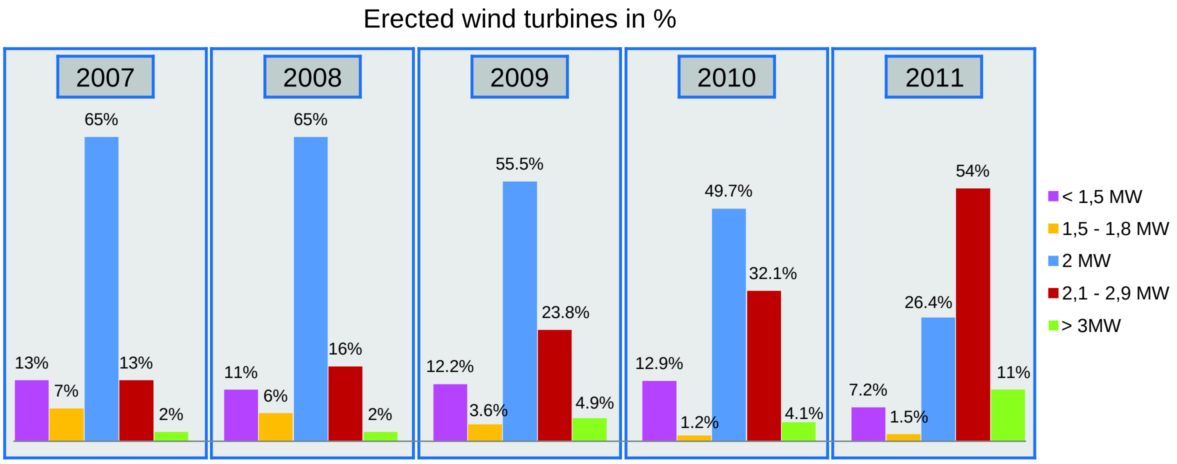

Figure 9: Power ratings of the erected wind turbines in Germany between 2007 and 2011 [DEWI]

The manufacturer-dependent development of newly installed wind turbines between 2007 and 2011 is depicted in Figure 10. Regarding their market share the manufacturers can be arranged as follows: (1) Enercon, (2) Vestas, (3) REpower , (4) Siemens and (5) Fuhrländer.

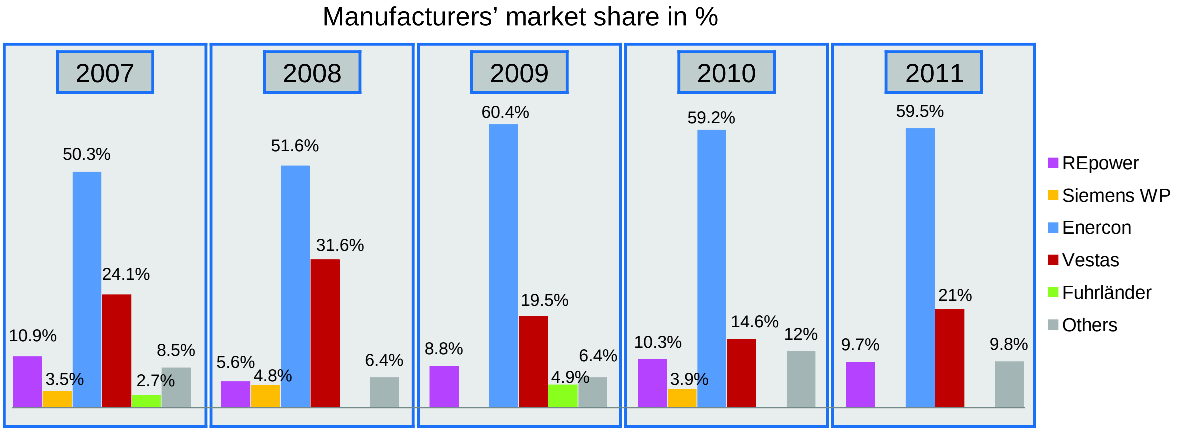

Figure 10: Wind turbine manufacturers and their market share in Germany between 2007 and 2011 [DEWI]

It can therefore be concluded that the wind turbines that are established on the German wind energy market can be divided, according to their basic drive train concept, into four categories:

- Geared wind turbines, built with a multi-stage gearbox and a high-speed generator (most commonly a DFIG).
- Direct-drive wind turbines, without a gear unit and with a low-speed multi-pole WRSG.
- Direct-drive wind turbines, without a gear unit and with a low-speed multi-pole PMSG.

- Semi-geared wind turbines, which combine the advantages of the previous concepts and mainly consist of a single or double-stage gearbox and a medium-speed generator (PMSG).

This four concepts represent the base on which the assessment methodology, proposed in the following sections, is implemented and verified.

4 Methodology

In most design studies of the past years, the Cost of Energy (COE) of the entire wind turbine system is being used as a benchmarking reference in the comparison and evaluation of different wind turbine concepts [POOR02], [BYWA05]. Production and material costs of the components of a drive train are thereto ascertained or calculated according to the available data. In some cases the level of detail and the input data can vary significantly.

As opposed to the above-mentioned studies, the approach considered here is based on a value-benefit analysis and separately regards different assessment criteria according to technical and economical aspects [PAHL05]. The main components of several conventional and well-established drive train concepts – from direct-drive to semi-geared and geared wind turbines – are compared to one another and rated on a structural component level.

The evaluation is hereto based on a scoring system, which allows for a more direct comparison of the components. Furthermore, weighting factors are included for the various assessment criteria. The components of the drive train can hereby be looked upon, independent of the complete wind turbine system. The sum of the several valuations is an indication of the global value of the drive train.

With the help of this methodology a system-dependent relation between the different components, as well as breaking or weak points of a specific drive train concept can be determined. Also, the influence on the final end result of the chosen criteria and their weighting will directly become apparent.

During the evaluation on a component level different power ratings are regarded. With higher ratings the importance of particular assessment criteria changes and different end results can therefore be obtained. The focus lies mainly on the evaluation of the two components that have the most influence on a wind turbines drive train: the generator and the gear unit. A possible structure for the assessment of these components according to the value-benefit analysis is shown in Figure 11.

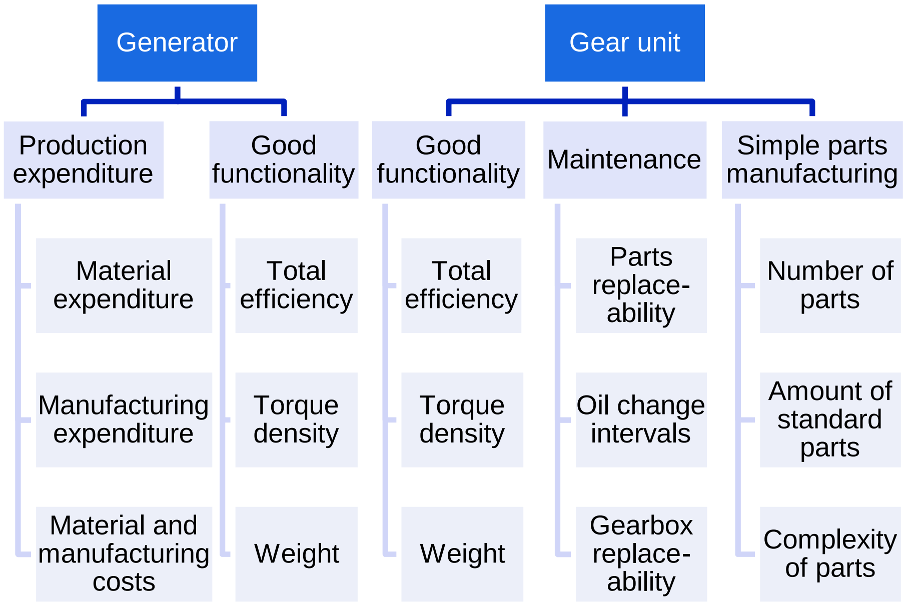

Figure 11: Value-benefit analysis considering the generator and the gearbox unit

4.1 Value-benefit Analysis vs. VDI 2225

When choosing an assessment method for comparing different wind turbine drive train concepts, conventional, established methods as the value-benefit analysis [PAHL05] and the VDI 2225 [VDI2225] are compared to perform the following assessment. The value-benefit analysis uses a scoring system for each rating criterion ranging from zero to ten and for the end result the scores are weighted. The VDI 2225 uses a scoring system ranging from zero to four, where the individual rating criterion should be approximately equally weighted.

If there is no quantitative data available for the individual rating criterion, then better results can be achieved by using the value-benefit analysis because of the broken down scoring system and the inclusion of weighting factors in the assessment. Since the information to compare different drive train concepts depending on the manufacturers data, previous studies and experiences, is not always quantifiable, the assessment method is hereby carried out based on the value-benefit analysis. The rating criteria are defined for each component depending on the data and can be extended in this approach by new knowledge or better data. Using the following method, in addition to the result of the assessment, the influence of subjective weighting factors as well as the influence of subjective scores for each criterion can be identified and illustrated.

4.2 Assessment Approach

The assessment approach is shown in Figure 12. At first the user of this approach has to divide the drive train concept in the main components and has to select the significant components to be used in the assessment. Following this, different rating criteria are to be considered for the selected drive train components. Depending on the available data, a higher number of assessment criteria and thus a more detailed approach can be chosen. Furthermore, the criteria can be arranged in different levels. The weighting factors for each criterion are to be determined with the help of paired comparison. Hereby, all criteria are compared to one another, except themselves. The result is a matrix clearly indicating the weighting factors, where the main diagonal is empty.

Following this, a value between zero and ten is assigned to the regarded component for each criterion, based on quantitative data or subjective experiences (with ten being the highest value). The total assessment value for each component is then calculated by summation of the weighted rating factors of all criteria. Once the assessment on a component level is completed, combining the components to different drive train concepts is possible. The summation of all values for each component constitutes the end result of the assessment for a given drive train concept. The higher the end result is, the better the rating of the drive train concept based on this method will be.

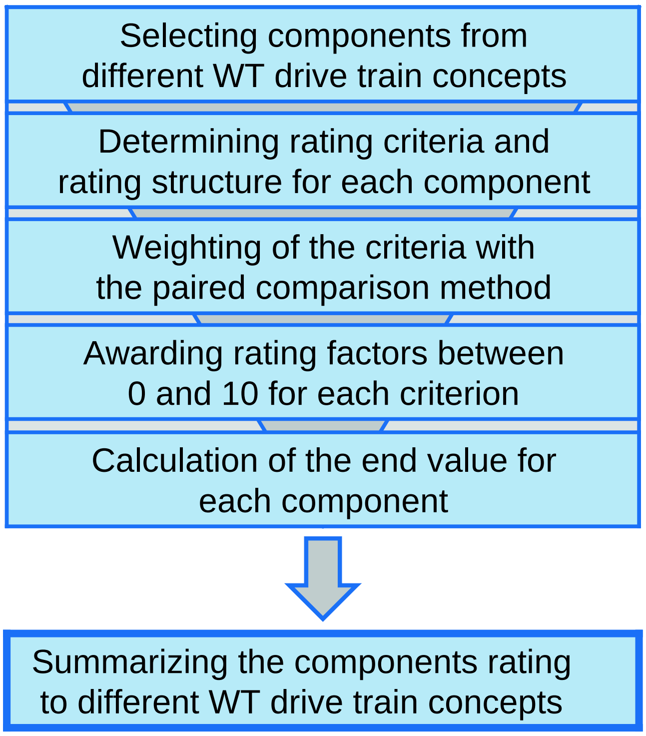

Figure 12: Workflow diagramm of the proposed assessment approach

5 Implementation and Results

In the following the four relevant drive train concepts that were chosen in section 3.2 are subjected to the previously described assessment procedure. In this example only the two main components of a wind turbine drive train – the gearbox unit and the generator – are being regarded.

5.1 Generator

In Table 2 the rating criteria for the different generator types used in the direct-drive (with WRSG and PSMG), semi-geared and geared wind turbine concepts are shown. The regarded assessment criteria are the specific weight, the efficiency and the torque density from the technical point of view and the overall cost from the economical point of view. Furthermore, an estimate is given for the economic viability of the concepts based on know-how and experience.

	Weighting factor		**Specific weight**	**Efficiency**	**Torque density**	**Criterion weighting factor**
Technical	0,4	**Specific weight**	X	2	2	33,33%
		Efficiency	2	X	2	33,33%
		Torque density	2	2	X	33,33%

	Weighting factor		**Cost**	**Experience (know-how)**	**Criterion weighting factor**
Economical	0,6	**Cost**	X	3	75%
		Experience (know-how)	1	X	25%

Table 2: Rating criteria and weighting factors for WT generators

The weighting of the two aspects, technical and economical, is 0,4 and 0,6, respectively and in order to establish reasonable weighting factors for each criterion, the paired comparison method is used. Hereby efficiency, torque density and specific weight are equally distributed. The torque density is a crucial factor, according to basic growth laws for electrical machines. The specific weight of the generator, especially of the magnetic active materials (permanent magnets, iron and copper windings), is reflected directly in the cost of the generator. The efficiency reflects the energy yield of the generator.

When regarding the economical efficiency of the different generator concepts, the two chosen criteria – actual cost and experience – are weighted in the same way. The cost of a generator can be determined based on the weight of the active materials and specific raw material prices. Information on this is sufficiently available in the technical literature and the calculations found in different sources indicate the same trend. In most of the cases this reflects the experience of the authors.

Based on the criteria in Table 2 the four proposed generator concepts in section 3.2, namely the WRSG for direct-drive wind turbines, the PMSG for direct-drive and for semi-geared wind turbines and the DFIG for conventional geared wind turbines, are compared to one another assuming the scoring pattern given in Table 3.

	DFIG, geared WT	**WRSG, direct-drive WT**	**PMSG, direct-drive WT**	**PMSG, semi-geared WT**
Specific weight	9	2	4	8
Efficiency	8	6	8	9
Torque density	7	8	9	9
Cost	9	3	4	8
Experience (know-how)	9	5	5	8

Table 3: WT generators: Scoring of different assessment criteria

At this point it should be noted that a scoring value of 10 can only be given for all regarded criteria, of both technical and economical nature, if the wind turbine would be without a generator and the entire energy from the wind would be harvested without any additional electromagnetic losses or without adding more weight to the overall nacelle mass and increasing the costs. Since this is of course never the case, it is only obvious that a scoring value of 10, unlike in the case of the gearbox unit, can never occur for the generator.

On the contrary, if the direct-drive wind turbine is the most advantageous concept because of the lack of a gearbox unit, it turns out this is also the cause of its main drawback, namely the specific weight. When compared to the medium-speed PMSG or the high-speed DFIG, the specific weight of a direct-drive WRSG can be up to 8 times higher than the specific weight of the other two concepts [LI08], [POLI06]. Thus, the poor rating in Table 3 is assumed. The direct-drive wind turbine with PMSG has a much lower specific weight than the WRSG concept (it is about 40 – 45% lighter [LI08], [POLI06]), due to the use of high energy density PM excitation. Furthermore, in the case of a semi-geared wind turbine with PMSG the specific weight is even lower and not much higher than that of the DFIG, because this concept also has a single- or double-stage gearbox. The two latter concepts are therefore given similar scoring values for the specific weight criterion.

When regarding the efficiency of the different generator concepts, one must take the electromagnetic and mechanical losses into account. Hereby, an overview like the one given in Table 4 helps illustrate the loss mechanisms that occur in the stator and rotor of electrical machines.

		Electrically excited synchr. machines (e.g. WRSG)	**PM excited synchr. machines (e.g. PMSG)**	**Asynchr. machines (e.g. DFIG)**
Stator	**Copper losses ($P_{Cu,St}$)**	$P_{Cu,St} \sim I^2_{St}, R_{Cu,St}$	$P_{Cu,St} \sim I^2_{St}, R_{Cu,St}$	$P_{Cu,St} \sim I^2_{St}, R_{Cu,St}$
	Iron losses (P_{FeSt})	$P_{hysteresis} \sim B^2_{max} \cdot f$ $P_{eddy\ current} \sim B^2_{max} \cdot f^2$ $P_{additional} \sim (B \cdot f)^{1,5}$	$P_{hysteresis} \sim B^2_{max} \cdot f$ $P_{eddy\ current} \sim B^2_{max} \cdot f^2$ $P_{additional} \sim (B \cdot f)^{1,5}$	$P_{hysteresis} \sim B^2_{max} \cdot f$ $P_{eddy\ current} \sim B^2_{max} \cdot f^2$ $P_{additional} \sim (B \cdot f)^{1,5}$
Rotor	**Copper losses ($P_{Cu,Ro}$)**	$P_{Cu,Ro} \sim I^2_{Ro}, R_{Cu,Ro}$	–	$P_{Cu,Ro} \sim I^2_{Ro}, R_{Cu,Ro}$
	Iron losses ($P_{Fe,Ro}$)	$P_{hyst} \sim B^2_{max} \cdot f$ $P_{eddy} \sim B^2_{max} \cdot f^2$ $P_{add} \sim (B \cdot f)^{1,5}$	$P_{hyst} \sim B^2_{max} \cdot f$ $P_{eddy} \sim B^2_{max} \cdot f^2$ $P_{add} \sim (B \cdot f)^{1,5}$	$P_{hyst} \sim B^2_{max} \cdot f_{slip}$ $P_{eddy} \sim B^2_{max} \cdot f^2_{slip}$ $P_{add} \sim (B \cdot f_{slip})^{1,5}$
	Magnetic losses (P_{magnet})	–	$P_{magnet} = f(I_{St}, f, \Delta B)$	–
	Mechanical losses (P_{mech})	$P_{mech} \sim n^2$	$P_{mech} \sim n^2$	$P_{mech} \sim n^2$

Table 4: Loss mechanisms and their dependencies in different electrical machines

In the stator of electrical machines copper and iron losses mainly occur, independent of the electrical machine type. Copper losses ($P_{Cu,St}$) are proportional to the square of the stator current (I^2_{St}) and to the resistance of the stator winding ($R_{Cu,St}$). The stator iron losses consist of hysteresis, eddy current and additional losses [MÜLL08]. Hysteresis losses are proportional to the square of the magnetic flux density and to the frequency of the stators magnetic field ($B^2_{max} \cdot f$). Eddy current losses are proportional to the square of the magnetic flux density and to the square of the frequency of the stators magnetic field ($B^2_{max} \cdot f^2$). And finally, the additional losses increase with the 1,5th power of the product between magnetic flux density and frequency of the stators magnetic field ($(B \cdot f)^{1,5}$).

In the rotor of electrical machines four loss mechanisms can be distinguished: copper losses, iron losses, magnetic losses and mechanical losses. Copper losses ($P_{Cu,Ro}$) only occur in WRSG and DFIG, since these machine types both have a rotor winding. Iron losses ($P_{Fe,Ro}$) consist here as well of hysteresis, eddy current and additional losses, but are dependent of the slip in the case of a DFIG [MÜLL08]. Magnetic losses are eddy current losses that only occur in the permanent magnets of a PMSG and are dependent of the load current, the frequency and the change of the magnetic flux density ($f(I_{St},f,\Delta B)$). Finally, mechanical losses are mainly friction losses that occur in every rotating machine and increase with the square of the rotational speed (n).

As shown in Table 4, the main difference between the loss mechanisms of the different generator types lies in the rotor. In a PMSG for instance, no copper losses occur in the rotor, since there is no winding present. Also, the losses dependent on the rotational speed (iron, magnetic and mechanical losses) are lower in a PMSG used in a semi-geared wind turbine than those of a DFIG, since the speed of the PMSG is about ten times lower than that of a DFIG. This advantage is also noticeable for a direct-driven PMSG, where the typical speed is very low (about ten times lower than that of a medium-speed PMSG). Furthermore, a PMSG highlights better efficiency also when compared to a multi-pole WRSG of a direct-drive wind turbine, whose copper losses are much higher because of the high amount of copper used. However, due to the very low speed, the WRSG has lower iron losses than a DFIG. Thus, for the efficiency of the different generators the scoring as given in Table 3 is chosen.

In order to determine the torque density for the three generator types, an estimation of the torque, based on the rated power and speed [LI08], [POLI06], can be realized. In the case of a 3MW wind turbine for instance, the input torque for a direct-drive WRSG or PMSG with a rated speed of 15min^{-1} is approximately 1910kNm. For a medium-speed (90min^{-1}) PMSG the torque is about 318kNm and for a high-speed (1200min^{-1}) DFIG it is about 24kNm. Dividing the torque by the generators volume, calculated from stator radius and stack length [LI08], [POLI06], yields following torque densities: $81{,}1\text{kNm/m}^3$ for the direct-drive concept (with WRSG or PMSG), $78{,}2\text{kNm/m}^3$ for the medium-speed PMSG and $57{,}4\text{kNm/m}^3$ for the DFIG. It can be seen that, based on data from technical literature, the torque density of the medium-speed PMSG is smaller than that of the direct-drive concept. However, recent developments in the field of medium-speed PMSG have shown that these configurations have long surpassed the direct-drive technology in terms of torque density. Thus, the PMSG concept receives a higher rating in Table 3.

The scoring values given for the cost criteria of the different generator concepts in Table 3 reflect the trend indicated in various sources, namely that the direct-driven WRSG or PMSG are much more expensive than the other two concepts (which are very close to one another in terms of cost). This is due to the high amount of copper and permanent magnets, respectively, used to provide the needed excitation. The difference, however, is here less pronounced than in the case of the specific weight. Furthermore, the medium-speed PMSG is becoming a strong competition in terms of cost for the geared wind turbine concept with DFIG, with the prices of permanent magnets constantly decreasing. Thus, the rating given to this concept based on experience is the same as the one for the DFIG (see Table 3).

Summarizing the ratings in Table 3 through a simple final calculation yields the ranking of the four generator concepts, as shown in Table 5. As expected, the DFIG concept has the higher overall rating, due to the positive scoring both technically and economically. It is followed closely by the medium-speed PMSG concept, ranked second. Both direct-drive concepts have received inferior scoring, mainly because of their high specific weight and cost, despite their satisfactory technical features.

	DFIG, geared WT	WRSG, direct-drive WT	PMSG, direct-drive WT	PMSG, semi-geared WT
Technical (0,4)	7,92	5,28	6,93	8,58
Economical (0,6)	9	3,5	4,25	8
Total	8,57	4,21	5,32	8,23
Ranking	**1**	**4**	**3**	**2**

Table 5: Ranking of WT generators

5.2 Gearbox

In the following, different gearbox configurations used in wind turbine concepts are compared to one another in a similar manner as previously discussed for the generators (see Table 2 and 6 for comparison). Thus, in Table 6 the rating criteria for the main component gearbox are shown.

	Weighting factor		Specific weight	Efficiency	Torque density	Criterion weighting factor
Technical	0,4	**Specific weight**	X	2	2	33,33%
		Efficiency	2	X	2	33,33%
		Torque density	2	2	X	33,33%

	Weighting factor		Cost	Experience (know-how)	Criterion weighting factor
Economical	0,6	**Cost**	X	3	75%
		Experience (know-how)	1	X	25%

Table 6: Rating criteria and weighting factors for WT gearboxes

The rating criteria are divided on a first level in an economic and a technical aspect. The technical area is then weighted with a value of 0,4 and the economical with 0,6. These values are based on a subjective decision by the user of this approach. In the technical area three criteria are considered – the specific weight, the torque density and the efficiency – which allow for a qualitative description of the drive train concepts. To determine the weighting factors for each criterion, the method of paired comparison is used. An example for a possible comparison matrix is shown in Table 7, wherein the classification is subjective. The economic criterion is further divided into costs and experience (know-how) criteria, which are also weighted according to a paired comparison.

	Geared concept, two planetary stages and one helical stage	**Direct-drive concept, gearless**	**Semi-geared concept, one or two planetary stages**
Specific weight	5	10	7
Efficiency	5	10	7
Torque density	5	10	7
Cost	5	10	6
Experience (know-how)	8	10	5

Table 7: WT gearboxes: Scoring of different assessment criteria

In the following, the main component gearbox is rated with the discussed criteria for the four different concepts: direct-drive (for both the WRSG and the PMSG configuration), semi-geared and geared. The scores are awarded based on available data. The grading is in this case as well subjectively dependent on the user of the assessment method. In the direct-driven drive train concept no gear for speed or torque conversion is needed. Nevertheless, this drive train concept is listed in the component assessment in order to ensure a consistent basis for all compared concepts in the overall result. The absence of any gearbox whatsoever is considered in the assessment of this concept as ideal and for all rating criteria the maximum scoring value (10) is chosen (see Table 7). This means that the using of no gearbox is the best solution when assessing the component gearbox.

Because of the lack of viable data, the values for the gearbox systems when regarding semi-geared and conventional drive train concepts are awarded at this point based on logical, technical contexts of different gearbox variants. In the semi-geared concepts single- or double-stage planetary gears are used. The rating parameters for the different criteria are also summarized in Table 7. For each criterion – specific weight, efficiency and torque density – the value of 7 is given. Because of the smaller, compact design of these gearbox configurations, the specific weight is lower and the efficiency and the torque density are higher than those of conventional gearbox units. This feature of all gearbox systems for semi-geared concepts is taken into account through a subjective approach.

On the other hand, the high-ratio gearboxes are rated for each of the three given technical criteria with a value of 5. When compared to the semi-geared gearbox concepts, these conventional three-stage gearbox topologies are inferior, because of the additional spur gear step. The cost assessment criterion is rated for the semi-geared concepts with a value of 6 and for the conventional versions with a value of 5. Due to higher transmission ratios, more components and materials are needed for the conventional gearbox designs. This increases the cost compared to the medium-speed gearboxes.

For the experience (know-how) rating criterion a value of 8 is awarded for the conventional and a value of 5 for the medium-speed gearbox designs. The experience accumulated for conventional transmission systems is very high. They have been used for a long time and are successfully applied in different wind turbine concepts and thus dominate the wind energy market. Medium-speed gearbox concepts represent a more recent development in the field of wind turbines and have only been used occasionally so far.

The overall result for the component gearbox is given in Table 8. The sum of the weighted criteria determines the ranking of the different concepts. With the help of this method first the results of the technical and economical assessment can be individually considered. With additional weighting factors for technical and economical assessment the total results for each concept can be determined. A higher value yields in a higher ranking. Hereby, the direct-drive concept without a gearbox unit is rated with a value of 10, because of the aforementioned reasons. The semi-geared concept (one or two planetary stages) is ranked second, because of the better rating regarding specific weight, efficiency and torque density.

	Geared concept, two planetary stages and one helical stage	**Direct-drive concept, gearless**	**Semi-geared concept, one or two planetary stages**
Technical (0,4)	5	10	7
Economical (0,6)	5,75	10	5,75
Total	5,45	10	6,25
Ranking	**3**	**1**	**2**

Table 8: Ranking of WT gearboxes

Subsequently, this component ranking will flow into the overall assessment of the different wind turbine drive train concepts, resulting in a scoring-based classification of the regarded concepts (see Table 9).

However, a conclusive and final ranking of the aforementioned drive train configurations is here difficult to achieve. This is mainly due to the lack of a data base with solid, verifiable information. The necessary experience for a comprehensive assessment is also missing, when investigating the direct-driven PMSG or the medium-speed PMSG with single- or double-stage gearbox for instance, because this are still rather novel concepts (compared to the already established direct-drive WRSG or geared DFIG).

	Geared concept, two planetary stages and one helical stage, DFIG	**Direct-drive concept, gearless, WRSG**	**Direct-drive concept, gearless, PMSG**	**Semi-geared concept, one or two planetary stages, PMSG**
Generator (0,5)	8,57	4,21	5,32	8,23
Gearbox (0,5)	5,45	10	10	6,25
Total	7,01	7,11	7,66	7,24

Table 9: Overall assessment of the different WT drive train concepts

The previous assessment of the generator and gearbox unit clearly indicates the strong differentiation when looking into particular criteria, as well as the influence of the chosen weighting factors. The impact of these aspects becomes less noticeable once the criteria are summarized and the concepts are investigated on a component level and even less so when the entire system is regarded. This is visible in Table 10, where the resulting overall assessment of the four drive train concepts is almost identical, even though the scoring values awarded to the particular components differ considerably.

Furthermore, other drive train components such as power electronic converters or bearings should also be included in the assessment process, in order to achieve a complete investigation. Nevertheless, the methodology presented here shows the influence of different components, assessment criteria and weighting factors on the end result, while at the same time providing a holistic view of multi-megawatt wind turbine drive train concepts.

6 Conclusions

The proposed approach discussed for the assessment and comparison of various wind turbine drive train concepts is based on a value-benefit analysis and separately regards different criteria according to technical and economical aspects. The main components of several conventional and well-established drive train concepts – from direct-drive to semi-geared and geared wind turbines – are compared to one another and rated on a structural component level.

The evaluation is based on a scoring system, which allows for a more direct comparison of the components. Furthermore, weighting factors are assumed for the various assessment criteria. The components of the drive train can hereby be looked upon, independent of the complete wind turbine system. The sum of the several valuations is an indication of the global value of the drive train.

When compared to the more conventional COE approach, this method gives a different perspective on the different wind turbine configurations and on the main components of the wind turbine drive trains, with all their advantages and drawbacks, while directly indicating the system-based interdependencies between the different components. Even more important, breaking points of a given drive train and the influence on the end result of the different assessment criteria with their weighting factors become directly apparent.

As a result the direct-driven PMSG and the medium-speed PMSG with single- or double-stage gearbox seem to be the most promising concepts. However, this analysis is not exhaustive, since not all drive train components and potential criteria are included. The used data base is also not a complete one and subjective assumptions had to be made. At the same time, the assessment yields a very similar ranking of the four configurations. Therefore, a higher level of detail is mandatory in order to determine the wind turbine drive train concept of the future.

7 References

[ANDR11] Andrei, T.-C.; Salles, M. B. C.; Hameyer, K.
Control and Protection Aspects for Doubly Fed Induction Generators in Wind Energy Systems.
In: Antriebstechnisches Kolloquium (ATK), RWTH Aachen University, 2011, pp. 33-55.

[BANG08] Bang, D.; Polinder, H.; Shreshta, G.; Ferreira, J. A.
Review of Generator Systems for Direct-Drive Wind Turbines.
In: Proceedings of the European Wind Energy Conference (EWEC), Brussels, Belgium, 2008.

[BYWA05] Bywaters, G.; John, V.; Lynch, J.; Mattila, P.; Norton, G.; Stowell, J.
Northern Power Systems WindPACT Drive Train Alternative Design Study Report.
National Renewable Energy Laboratory, Colorado, US, 2005.

[EARN11] Earnest, J.; Wizelius, T.
Wind Power Plants and Project Development.
PHI Learning Private Limited, New Delhi, India, 2011.

[HANS04] Hansen, A. D.; Iov, F.; Blaabjerg, F.; Hansen, L. H.
Review of Contemporary Wind Turbine Concepts and Their Market Penetration.
In: Wind Engineering, vol. 28, no. 3, 2004, pp. 247-263.

[LI08] Li, H.; Chen, Z.
Design Optimization and Evaluation of Different Wind Generator Systems.
In: Proceedings of the International Conference on Electrical Machines and Systems (ICEMS), Wuhan, China, 2008.

[MÜLL08] Müller, G.; Vogt, K.; Ponick, B.
Berechnung elektrischer Maschinen.
Wiley-VCH Verlag, Weinheim, 6. Auflage, 2008.

[NEWT06] Newton, C.
Trends in Electrical System Technology for Wind Turbines.
In: Proceedings of the European Wind Energy Conference (EWEC), Athens, Greece, 2006.

[PAHL05] Pahl, G.; Beitz, W.; Feldhusen, J.; Grote, K.-H.
Konstruktionslehre. Grundlagen erfolgreicher Produktentwicklung, Methoden und Anwendung.

	Springer Verlag, Berlin, 2005.
[POLI05]	Polinder, H.; de Haan, S. W. H.; Dubois, M. R.; Slootweg, J. G. Basic Operation Principles and Electrical Conversion Systems of Wind Turbines. In: EPE Journal, vol. 15, no. 4, 2005, pp. 43-50.
[POLI06]	Polinder, H.; van der Pijl, F. F. A.; de Vilder, G.-J.; Tavner, P. J. Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines. In: IEEE Transactions on Energy Conversion, vol. 21, no. 3, 2006, pp. 725-733.
[POOR02]	Poore, R.; Lettenmaier, T. Alternative Design Study Report: WindPACT Advanced Wind Turbine Drive Train Designs Study. National Renewable Energy Laboratory, Colorado, US, 2002.
[SALL10]	Salles, M. B. C.; Hameyer, K.; Cardoso, J. R.; Grilo, A. P.; Rahmann, C. Crowbar System in Doubly Fed Induction Wind Generators. In: Energies, vol. 3, 2010, pp. 1551-1556.
[SLOO03]	Slootweg, J. G.; de Vries, E. Inside Wind Turbines – Fixed vs. Variable Speed. In: Renewable Energy World, 2003, pp. 30-40.
[TSIL09]	Tsili, M.; Papathanassiou, S. A review of grid code technical requirements for wind farms. In: IET Renewable Power Generation, vol. 3, no. 3, 2009, pp. 308-332.
[VDI2225]	VDI-Gesellschaft Produkt- und Prozessgestaltung (GPP). VDI 2225 Blatt 3: Konstruktionsmethodik – Technisch-wirtschaftliches Konstruieren – Technisch-wirtschaftliche Bewertung. VDI-Verlag, Düsseldorf, 1998.