Abstract. Looking at the upscaling of the rotor diameter not only the loss in power production but the aerodynamic loads arising from yaw misalignment will have an increasing impact on the yaw system design in future wind turbines. This paper presents an overview of yaw systems used in current wind turbines and a review of patents with regards to the yaw system. The current state of the art of yaw systems has been analyzed through a systematic literature review. Further a patent analysis has been done through the European Patent Office. Todays design and strength requirements as per IEC and GL standards will be reviewed and alternative design calculations will be discussed. Over 100 patents have been identified as relevant to the yaw system and have been analyzed. It has been found that most patents are dealing with load reduction possibilities on the yaw system, where fatigue loads seem more of a problem than ultimate loads. Most of these patents concern especially the yaw actuator, which consists of multiple electrical motors, reduction gears and shaft pinions. This is due to the nature of the gearing in the actuator and the gearing between the shaft pinion and the ring gear. This coincides with the patents for yaw brakes, which mostly aim to reduce the fatigue loads during yaw maneuverer and during nacelle standstill. Patents for the yaw bearing are incorporating the reduction of loads through the usage of friction bearings or different bearing arrangement approaches. The paper shows that the conventional yaw system designs are still trying to meet the high requirements regarding the lifetime of a wind turbine and turbulent wind loads. New designs for yaw systems in general are hard to find. Many patents concentrate on control algorithms that depend on additional instruments and incorporate electromechanical systems.

1. Introduction
To reduce the cost of energy of wind turbines and to make them competitive to conventional power plants can be considered as the main goal of wind turbine optimization. The yaw system which is responsible to rotate the nacelle around the tower axis, can contribute to it through the following points:

- Increasing the energy capture through pointing the rotor swept area steadily towards the incoming wind direction and thus maximize the general power input of the wind turbine. A higher energy capture can also be achieved through a better reliability of the yaw system which increases the general availability of a wind turbine.
- Reduction of the structure load by letting the nacelle passively rotate to compensate yaw moments from aerodynamic loads. This leads to potential lower design loads for the yaw system and other wind turbine components.
• Cost reduction of the yaw system itself and also reduction of the operation and maintenance cost and the energy consumption of the yaw system.

A higher energy capture can be achieved by increasing the yaw control sensitivity. This means the yaw system rotates the nacelle based on a smaller yaw error threshold and on the foundation of shorter averaged measured times of the wind direction and speed. Oppositely frequent yawing duties leads to higher accumulated operation loads and energy consumption. A comparison of different yaw control parameters and the resulting numbers of yaw maneuvers based on simulation models can be found in [1]. Yaw stops lead to torsional oscillations on the tower and thus can lead to higher alternating loads on the yaw system if the time between two yawing maneuvers is done without a proper delay [2]. An optimum relation between energy capture and yawing duties depends on the environment condition and the yaw design of the wind turbine. The control system depends also on correct measurements of the wind conditions. Currently the measurements are being made on the nacelle leading to measurements of wind condition disturbed by the rotor and thus leading to false yaw behavior and resulting in lower power production [3]. Reliability studies by [4] show that the yaw system is the second most common mechanical component that contributes to an overall failure rate defined by the number of failures of a turbine in a year with the pitch system being first. Equally to the failure rate of a wind turbine, the yaw system is also the second most mechanical component contributing to an overall downtime of the turbine. This circumstance leads to redundancy system approaches such as possible temporary yaw operation of a wind turbine even when one yaw drive fails to operate[5, 6].

Large wind turbines benefit from an overall reduction cost per rated MW [7], which lead to the development of steadily increasing size of wind turbines over the time [8]. On the downside the increase of rotor diameter leads not only to higher weight induced structural loads but also to higher and more complex aerodynamic loads as the influence of effects of the turbulence on the rotor plane increases thus leading also to higher yaw moments [9].

Soft yaw concepts as researched by [10] can result in fatigue and extreme load reduction of the yaw moment without sacrificing the power production of the wind turbine. Also a reduction in blade flapwise bending and tower base tilting moments had been observed leading to potential lower design loads and thus to lighter components. Regardless from the wind turbine development, load consideration should be made for typhoon situations, above cut-out wind speeds and after emergency stops leading to higher requirements of the yaw system design [11]. Typhoon characteristics as rapid change of the wind direction and a higher possibility of grid failure for example, require increased yawing speeds and also reliable yaw operational functionality above cut-out wind speeds.

A percentage-wise cost distribution of different studies have been put together by [12] where the yaw system takes 1.3 - 5% of the estimated whole turbine cost. A cost trend analysis by [7] shows that the cost trend exponent of the yaw system is the second highest next to the cost trend exponent of the tower, meaning the cost of the yaw system is more influenced by scaling than other components.

In this paper the functions of the yaw system and its different design set ups will be presented first to give an understanding of the diversity of current yaw system components. Hereafter through a patent analysis current issues and development trends of the yaw system will be presented which addresses the mentioned methods to reduce the overall cost of energy. Further design and strength requirements as per IEC and GL standards will be reviewed and alternative design calculations will be discussed.
2. Yaw system

2.1. Functions of the yaw system

In contrast to the function of pointing the rotor swept area towards the wind direction for optimal power input, the yaw system can be used for power regulation above rated wind speeds. This is achieved by reducing the rotor swept area directed to the oncoming wind. A yaw system for rapid power regulation requires high yaw speeds as the decrease in power production in relation to the yaw error is small. Moreover the yaw torque has to overcome high yaw moments due to the large moment of inertia of the nacelle and the rotor [13]. Despite these shortcomings active yaw control is investigated by [14] for a two bladed rotor teeter hinge wind turbine. To enable rapid power control the yaw speed is set about $10^\circ/s$ [5] in contrast to the commonly $0.5^\circ/s$. This is in line with the teeter hinge design which enables reduced yawing moments and also leads to reduced gyroscopic loads.

The yaw system can contribute to a general load reduction by either reducing the fatigue loads or by preventing the wind turbine from extreme loads in extreme wind conditions. Fatigue load reduction can be achieved by damping the yaw movement through hydraulic yaw drives. Simulations by [10] showed a reduction of yaw moment fatigue loads by 40% and extreme loads up to 19%. Prevention of extreme loads during events like wind speeds above cut-out and also in combination with wind turbine operation faults can be achieved by rotating the wind turbine out of the wind. Whereas [15, 16] propose to turn the nacelle in leeward position, [14] proposes to rotate the nacelle perpendicular to the oncoming wind to reduce the structure loads.

On a wind park scale yawing of windward turbines can be used to deflect the wake flow providing the downstream turbines a higher energy yield and thus leading to an overall increase in energy production of the wind park [17]. Simulations by [18] showed potential in an higher overall power production trough yawing but also higher yaw bearing bending moments on downstream turbines most likely because of the resulting partial wake condition. Individual pitch controls can mitigate additional loads resulting from partial wake conditions [19] and can also potentially lead to reduced loads on the yaw system in general [20].

2.2. Yaw component arrangements

Figure 1 shows an example of a yaw arrangement comprising multiple yaw drives, yaw brakes and a yaw bearing. The shown yaw drive consist of an electric motor, a reduction gear and a shaft pinion engaged with a ring gear on the yaw bearing. The yaw brakes apply a braking torque on the brake disc which is mounted between the tower flange and the yaw bearing.

![Figure 1. Example of a yaw system.](image-url)
Apart from the yawing torque transmission options from the nacelle to the tower a main deciding factor for the arrangement of the yaw components are the installation and maintenance possibilities. The attachment of the yaw drives upside down on the tower flange have been proposed by [21, 22]. Reasons for such an arrangement are a better accessibility and the potential to install actuators with large planetary gears without taking space for components installed on the bedplate [21]. The reduced overall weight on the nacelle can lead to smaller cranes needed for the installation of the wind turbine [22]. Another consideration is made about the positioning of the yaw drives relatively to the ring gear. An even stress distribution on the flanks can be achieved by a convex/concave arrangement when the shaft pinions are engaged with an internal ring gear [23]. On the contrary a higher transmission ratio due to a higher pitch circle diameter can be achieved through an external ring gear/shaft pinion arrangement. Because the brake linings of the yaw brakes are wearing parts and have to be changed during the wind turbine lifetime it is favourable for an arrangement on the inner side of the tower for better accessibility. Lubrication between the shaft pinion and the ring gear can access the brake disc if the disc is arranged below the pinion.

2.3. Yaw drives

Opposed to the figure above, hydraulic actuators are also in use. A higher maintenance rate because of leakage issues are stated as reasons why hydraulic yaw drives find less usage in current wind turbines [24]. Advantage over electro mechanical drives as the high power to weight ratio and easy implementation of soft yaw concepts are detailed by [10]. Electro mechanical yaw drives consist usually of an electrical motor with an integrated mechanical brake and a planetary gear. A problem of electro mechanical drives are high load peaks and backlash problems which can occur during start and stop operations. A regulation of the yawing speed and the yawing moment can be achieved with frequency converters. Frequency converters enable controlled start-up operation and can prevent against high load peaks in the reduction gears leading to reduced fatigue loads [25, 26]. A way to eliminate existing backlash is by tightening the yaw drives by inducing an opposite torque through the motors after a yaw operation [27, 28]. Another way is by letting at least one yaw drive operate with a lesser yaw moment generating a counter torque to reduce the backlash [25]. There are also possibilities to use cyclo gears instead of planetary gears as they have less backlash [29].

2.4. Yaw bearing

Usually four point bearings are used as yaw bearings [24, 30] as shown in Figure 1. Double-row four point bearings have the advantages of a better stress distribution and higher lifetime but are also more expensive [30]. In contrast to ball bearings, sliding bearings have braking and damping properties which can make additional yaw brakes unnecessary. Problems can result from the stick slip effect that can cause high wear and sound emissions [31]. The use of a lower and upper bearing arrangement is detailed by [32]. Main advantages are the reduced loads in the bedplate and better bending moment absorption.

2.5. Yaw brakes

The braking forces of the yaw brakes are often hydraulically regulated. During non-yawing operation the maximum brake force is applied. During yaw operation the hydraulic pressure and thus the braking force is reduced but still active to lessen the alternating loads on the gears of the yaw drive. Leakage of the hydraulic can lead to safety issues as it can catch fire and leads to slippery surfaces [33]. Also it can get in contact with the braking surface which leads to lower friction coefficients. These issues result in a higher maintenance and inspection rate. The usage of electro mechanical brakes can avoid these issues but the weight is still higher in comparison.
[34] states a commercial deployment of electro mechanical yaw brakes for a prototype wind turbine and also retrofit usage in yaw systems with leaking hydraulic yaw brakes.

In contrast to the general yaw system design shown in Figure 1, stands the yaw system by [35] which is installed in a prototype wind turbine. A yaw drive consists of two hydraulic cylinders and a brake caliper which is engaged with a brake disc, embodying an integrated yaw actuator and yaw brake unit. As this yaw concept doesn’t inherit any gearing and no relative movement between the yaw brakes and the disc, the mentioned drawbacks like backlashes and sound emission are avoided [36].

3. Patent analysis
To identify technological trends and shortcomings of the current yaw system a patent analysis has been done. The patent research can also serve as a template for prototype design concepts and development choices. As a higher consciousness of intellectual property protection by the wind turbine manufacturers and component suppliers is developed [37] patent databases as provided by the European Patent Office can be used to get more insights on the technological development.

The patent research has been done through a content search on the database of the European Patent Office. 131 patents has been indicated as relevant to the yaw system. For further investigation the patents have been separated in the yaw components. To find current problems and shortcomings of the yaw system the patents have been read with a focus on the issue the invention refers to. These issues have been categorized into problem groups which have been defined as shown in Figure 2. Each yaw component have been classified under a problem group 1 which consist of the points: emission, loads, yield increase, mechanical design and miscellaneous. Next the patents were classified into a sub-level problem group 2.

For example sound emission issues are often found in the yaw brakes because during yaw operation relative movement between the yaw brakes and the brake disc often leads to a stick-slip effect. Lubricant emission can occur in nearly all yaw components. One of the main problem fields are the loads which result from the wind or the operation of the yaw system. Patents put in this problem group mostly lead to a more load optimized design to cope with the fatigue loads or are concepts for load prevention leading to lower ultimate loads. Patents categorized in the problem group mechanical design either decrease the maintenance and installation effort by an accessible construction, modular constructions or by a more simple connection and installation approach. Under miscellaneous patents are categorized which refers to safety systems, test rig constructions or whole yaw concepts which couldn’t be categorized into only one issue.

![Figure 2. Classification structure of the patents analysis.](image-url)
3.1. Analysis and evaluation

The number of patents categorized in the above described problem fields is shown in Figure 3. Almost on every yaw component the highest number of patents refer to load reduction designs and methods. Within the loads category fatigue load issues take the majority. This leads to the assumption that the wind turbulence leading to unsymmetrical and highly dynamical loads on the rotor plane and thus to yaw moments together with the demanded lifetime are the dominating problem in current yaw system design. Especially actuators are still experiencing high fatigue loads mostly in the reduction gears and the pinion shaft. This coincides with the number of patents for brakes which refer to designs and methods to reduce fatigue loads during yawing and non-yawing operation. Also many patents referring to the sound emission during yaw maneuvers which often leads to stick-slip effects [38] have been found. Patents covering yaw bearing designs are mostly about different yaw bearing arrangements which can lead to better load distribution and easier maintenance. The reduction of the ultimate loads and also yield increase are mostly achieved through yaw control. As the wind measurement on the nacelle inhabits many uncertainties, patents relating to yaw control methods based on the measurement of other parameters such as power production or actual yaw loads are becoming more apparent.

Figure 3. Number of patents for the yaw system arranged in sub categories after classification structure shown in Figure 2

In a patent landscape search made by [39] 146 patents regarding the yaw system and yaw control have been found. In comparison to other wind turbine components, the yaw system only makes 0.53% of the named patent landscape which is dominated by patents referring to the rotor blade, control and sensors, generator and drivetrain. These components are also the most
cost intensive parts [40]. Control systems are a cost-effective alternative to increase the energy production and also the load reduction which applies to the yaw control system.

Constructive design concepts for the yaw actuator or the yaw brake were a minority in the patent analysis. Solutions for load reduction on the actuator are mostly based on load regulations methods for the electrical motor. New concepts are bound with high risks and costs which leads to a rather hesitant development.

4. Design methods
Goal of the standards is to ensure the structural and engineering integrity of the wind turbine over its lifetime. The standard IEC61400-1 [41] forms the foundation of the design for the wind turbine. Design parameters are decided upon loads caused by the interaction of the wind turbine and its environment. For the design of the yaw system the loads resulting in the tower top of a wind turbine are considered. The wind turbine and its components are designed for a lifetime of at least 20 years. The standards define design load cases in which external and operation conditions are combined. The frequency in which a certain design case is considered are defined by the standard. For the design of the yaw system components basic standards exist and are referred to by the wind turbine standards but they don’t consider the loads resulting from the interaction of the aerodynamic loads and the wind turbine dynamics. Load calculation of the wind turbine together with its components are therefore a critical subject for future standard revisions [42].

Apart from the aerodynamic loads the design loads are basically put together in dependence from two different operation modes: yawing and standstill. A decisive parameter for the analysis of the fatigue loads of the yaw system is the consideration of the yawing time. The operation of the yaw system is considered to occur during 10% of the turbine’s service life independent of the real wind direction distribution as per the GL and DNV-standard [43, 44].

For a fatigue strength analysis the tower top loads are simulated under different turbulent wind conditions and then cumulated over the lifetime of the wind turbine in combination of the Weibull distribution for a site. The calculated results are represented in form of a load duration distribution (LDD). The LDD represent different load levels and their estimated duration. In regard to the applied design load cases the GL-directive impose the number of occurrences over a year. Usually an average yaw misalignment of ±8° have to be considered during the load cases if smaller yaw errors cannot be verified.

As mentioned for the calculation two different operation modes have to be considered resulting in two different load conditions of the yaw system. During yawing operation gyroscopic torque and changing bearing friction have to be considered. As many yaw concepts are using yaw brakes to reduce the alternating loads on the gears, an additional braking moment has to be calculated. These braking moments, further referred to operation loads, are often higher than aerodynamic loads in low wind speed conditions. In high wind speed situations however it can be distinguished between an aerodynamic load which adds to the driving torque of the actuators leading to an accelerated yawing and an aerodynamic load which contrary further enhances the braking moment during yaw operation leading to a decelerated yawing [25] showcased in Figure 4. If the driving torque is enhanced by the aerodynamic load it can lead to a higher yaw speed and thus to higher gyroscopic torque. A regulation of the yawing speed is usually accomplished by frequency converters.
Especially for yaw concepts which inherit yaw brakes to reduce the alternating loads during yawing, it is difficult to estimate in which wind conditions the aerodynamic loads are higher than the operation loads. With regards to the LDD calculation which is dependent on the wind speed distribution, the transition of the operating loads to the wind speed in which the aerodynamic loads overweight the braking moments are of interest. The influence of the yaw control algorithm should also be taken into consideration.

During non-yawing operations, aerodynamic loads are the decisive factor. Brake moments result usually from the friction of the yaw bearing, the yaw brakes and the brakes in the electric motors. Different situation can be considered during non-yawing operation in which the load distribution on the yaw components differ:

- The torque on the tower top is less than the maximum brake moment of the yaw brakes and the bearing friction. The yaw drives are not loaded.
- The torque on the tower top is higher than the brake moment of the yaw brakes and the bearing friction. The yaw drives are loaded and an additional braking moment originate from the brake motor.
- The torque at the tower top is higher than the braking moment of the yaw system. In this case the nacelle will rotate.

To reduce cost, the yaw system is often underdimensioned. That means that the yaw system is not designed to withstand the extreme design loads and a slippage of the nacelle during extreme
design load cases is tolerated. It’s assumed that during slippage the actuators are loaded with a constant braking moment resulting in a LDD curve shown in Figure 5. This inherits many uncertainties as information about the loads and the dynamics of the wind turbine during slippage is unknown. Further investigation should be done in the behavior of the wind turbine and the loads when the nacelle begins to slip.

![Figure 5. Load duration distribution of the yaw actuator with and without assumed slippage](image)

5. Conclusion
The yaw system influences in many ways the cost of energy of a wind turbine. An overview of the different functionalities and concepts have been presented and discussed. An approach to identify major problem fields through a patent analysis have been presented, indicating fatigue loads being a major issue. Based upon design methods specified by the standards, different considerations and design approaches have been discussed. Fatigue load estimations are heavily influenced by the design methods and careful reconsideration of the design standards should be made as they limit the optimization potential of the yaw system. This work serves as a basis for further research in yaw system design and design methods, which will be undertaken within the research project AZIMUT.

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References
[1] Bossanyi E, Delouvri T and Lindahl S 2013 Long-term simulations for optimising yaw control and start-stop strategies, *EWEA Annual Event 2013*
[2] Mtauweg S 2012 Dynamische Untersuchung des Pitch- und Azimutsystems und der zugehörigen Regelstrategien einer Windenergieanlage mittels Mehrkörpersimulation. Ph.D. thesis Technische Universität Dresden
[3] Pedersen T F, Sørensen N N, Madsen A H, Møller R and Courtney M S 2007 Spinner anemometry - an innovative wind speed measurement concept, *EWEC 2007 Milan*
[4] Wilkinson M and Hendriks B 2011 Reliawind - report on wind turbine reliability profiles Tech. rep. GH
[5] Vries E D 2011 Development of two-bladed offshore wind turbine, *Wind Stats Report 24* 1–4
[6] Nordex 2013 *Platform brochure della generation*
[7] Ashuri T 2012 Beyond Classical Upscaling: Integrated Aeroservoelastic Design and Optimization of Large Offshore Wind Turbines. Ph.D. thesis Delf University of Technology
[8] IWES F 2013 http://windmonitor.iwes.fraunhofer.de
[9] Sieros G, Chaviaropoulos P, Sørensen J D, Bulder B H and Jamieson P 2012 Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy. Wind Energy 15 3–17
[10] Stubkjer S, Pedersen H C and Markussen K 2013 Hydraulic Soft Yaw System Load Reduction and Prototype Results. EWEA Annual Event 2013
[11] Freudenreich K, Demant S, Gehlhaar T, Kopte D, Mcke T A and Schacht S 2013 Assessment of Wind Turbines under Tropical Cyclone Conditions. American Wind Energy Association Conference 2013
[12] Engels W, Obdam T and Savenije F 2009 Current developments in wind - 2009. ECN Report, ECNE-09-96, 2009
[13] Burton T, Jenkins N, Sharpe D and Bossanyi E 2011 Wind Energy Handbook (Wiley) ISBN 0470699752
[14] Caruso S, Jakubowski M and Caioli L 2013 System for minimizing yaw torque needed to control power output in two-bladed, teetering hinge wind turbines that control output by yawing. Patent. WO2013027127A2
[15] Shibata M, Furukawa T, Hayashi Y, Yatomi Y and Tsutsuomi K 2004 Upwind type windmill and operating method therefor. Patent. US20040105751A1
[16] Wobben A 2004 Azimuthal control of a wind-energy turbine during a storm. Patent. US20040105751A1
[17] J W Wagenaar, L A H Machielse and J G Schepers 2012 Controlling wind in ECN’s scaled wind farm EWEA Annual Event 2012
[18] P Fleming, P Gebraad, S Lee, J W van Wingerden, K Johnson, M Churchfield, J Michalakes, P Spalart and P Moriarty 2013 High-fidelity simulation comparison of wake mitigation control strategies for a two-turbine case. ICOMES Conference 2013
[19] Yang Z, Li Y and Seem J E 2011 Improved Individual Pitch Control for Wind Farm Turbine Load Reduction via Wake Modeling. 49th AIAA Aerospace Sciences Meeting 2011
[20] E A Bossanyi 2003 Individual Blade Pitch Control for Load Reduction Wind Energy 6 119–128
[21] Frederiksen T 2011 A wind turbine with improved yaw control. Patent. EP2273104A2
[22] Numajiri T 2011 Wind-driven generator and construction method thereof. Patent. EP2302215A1
[23] Steinhilper W 2008 Konstruktioelements des Maschinenbaus 2: Grundlagen von Maschinenelementen für Antriebsaufgaben (Springer) ISBN 3540766537
[24] Hau E 2008 Windkraftanlagen - Grundlagen, Technik, Einsatz, Wirtschaftlichkeit
[25] Keller H, Wiese-Müller L U and Voß E 2009 Verfahren und Vorrichtung zum Drehen einer Komponente einer Windenergieanlage. Patent. EP2101058A2
[26] Wobben A 1999 Azimutantrieb für Windenergieanlagen. Patent. EP133638B1
[27] Wobben A 2007 Wind power installation with an asynchronous machine for establishing the azimuth position. Patent. US2007012370A1
[28] Nielsen E 1990 Yawing device and method of controlling it. Patent. US4966525A
[29] Nabtesco 2012 Yaw/pitch drive for wind turbines - catalogue
[30] Terrell E J, Needelman W M and Kyle J P 2012 Green Energy and Technology
[31] Wagner J and Wolter D 2011 Erneuerbare Energien Juli 50–53
[32] Hennig J 2011 Yaw bearing system for wind turbine. Patent. EP2402599A2
[33] Zillen H 2002 Arrangement and method for turning a propulsion unit. Patent. US2002197918A1
[34] EMBSystems 2013 Development of electromechanical braking systems for wind turbines. http://www.emb-systems.com/_englisch/historie_en.html
[35] Mervento 2012 Mervento 3.6-118 technical brochure
[36] Holm P 2012 Wind power station. Patent. US20120235420A1
[37] Totaro P 2012 worldwind technology 2 18–21
[38] Stromag 2011 Hydraulische Bremsvorrichtung für einen Azimutantrieb einer Windkraftanlage sowie Steuervorrichtung hierfür. Patent. DE20201001487U1
[39] Totaro P 2013 Reduction of cost of energy (coe) through innovation. EWEA Annual Event 2013
[40] Martin-Tretton M, Reha M, Drusnie M and Keim M 2012 Data collection for current u.s. wind energy projects: Component costs, financing, operations, and maintenance. Contract 303 275–3000
[41] IEC 2005 Windenergieanlagen - Teil 1: Auslegungsanforderungen (IEC 61400-1:2005 + A1:2010). Standards
[42] Grzybowski R and Steingrüber K 2007 Das Getriebe für Windenergieanlagen im Fokus der nationalen und internationalen Normung. Dresdner Maschinenelmente Kolloquium-DMK 2007
[43] Germanischer Lloyd 2010 Richtlinien für die Zertifizierung von Windenergieanlagen. Standards
[44] DNV/Riso2002 Guidelines for design of wind turbines. Standards