US 20140046614A1

(19) **United States**

(12) **Patent Application Publication**

Pettersson

(10) **Pub. No.: US 2014/0046614 A1**

(43) **Pub. Date: Feb. 13, 2014**

(54) **WEAR-MONITORING OF A GEARBOX IN A POWER STATION**

(75) Inventor: **Bo Pettersson**, London (GB)

(73) Assignee: **HEXAGON TECHNOLOGY CENTER GMBH**, Heerbrugg (CH)

(21) Appl. No.: **14/000,156**

(22) PCT Filed: **Mar. 9, 2012**

(86) PCT No.: **PCT/EP2012/054095**

§ 371 (c)(1),
(2), (4) Date: **Aug. 27, 2013**

(30) **Foreign Application Priority Data**

Mar. 11, 2011 (EP) 11157943.9

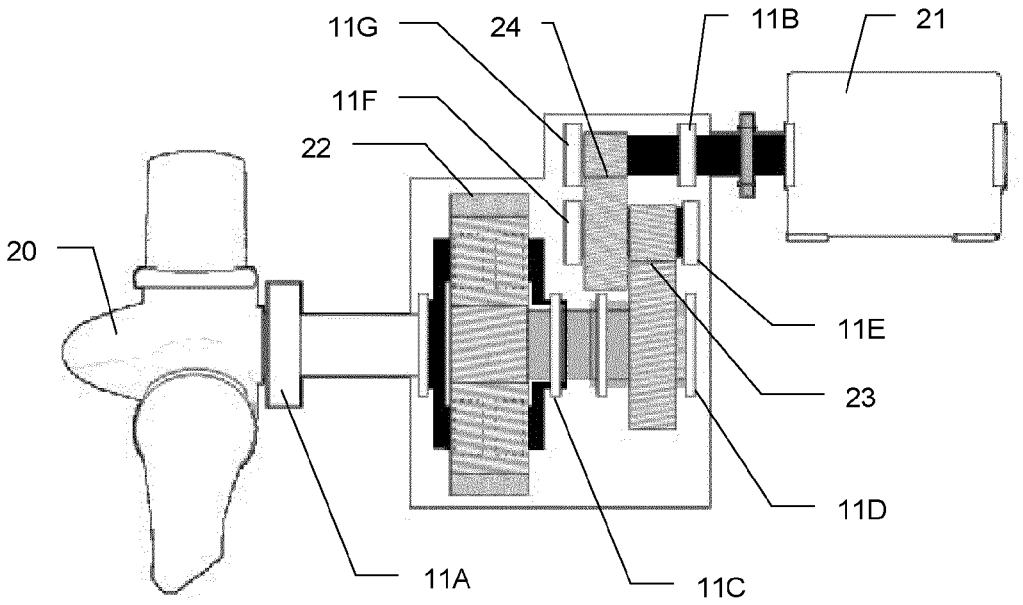
Publication Classification

(51) **Int. Cl.**
G01M 13/02 (2006.01)
G01M 13/04 (2006.01)

(52) **U.S. Cl.**
CPC ***G01M 13/021*** (2013.01); ***G01M 13/04*** (2013.01)
USPC **702/113**; 73/162

(57) **ABSTRACT**

The invention relates to a method of monitoring a wear of a gearbox in a power station, such as a windmill, water-wheel or tidal power station, the gearbox comprising at least two shafts, cogwheels and bearings as components of the gearbox. The method comprises sensing an angular position at the shafts by a rotational shaft encoder and monitoring the wear of the transmission-unit according to differences of the sensed angular positions and generating a condition signal representative of the wear of the gearbox according to the monitored differences. The monitoring comprises an additional sensing of at least one additional degree of freedom, in particular an axial and/or eccentric displacement, of at least one of the shafts caused by wear of at least one of the components of the gearbox, and generating the condition signal according to the displacement and differences in the at least two degrees of freedom.



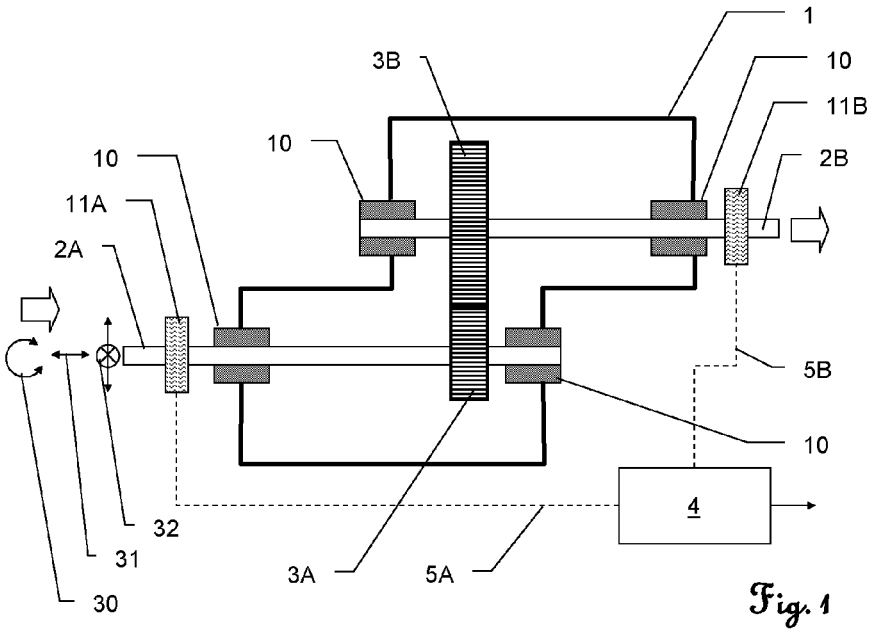

1
3B
10
11B
10
10
2B
11A
2A
5B
10
4
32
31
30
3A
5A

Fig. 1

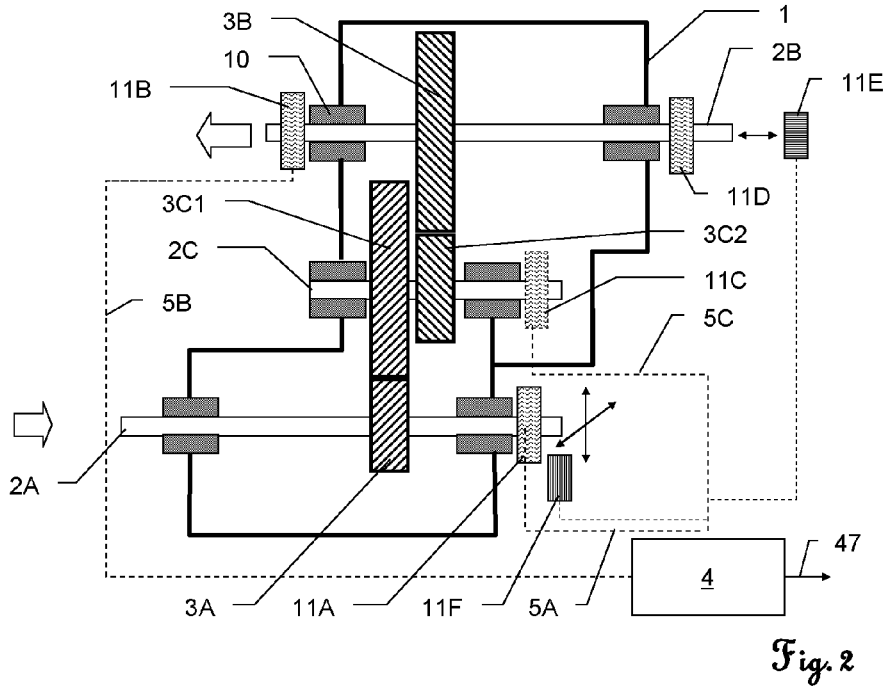

3B
1
10
2B
11B
11E
11D
3C1
3C2
2C
11C
5B
5C
2A
47
4
3A
11A
11F
5A

Fig. 2

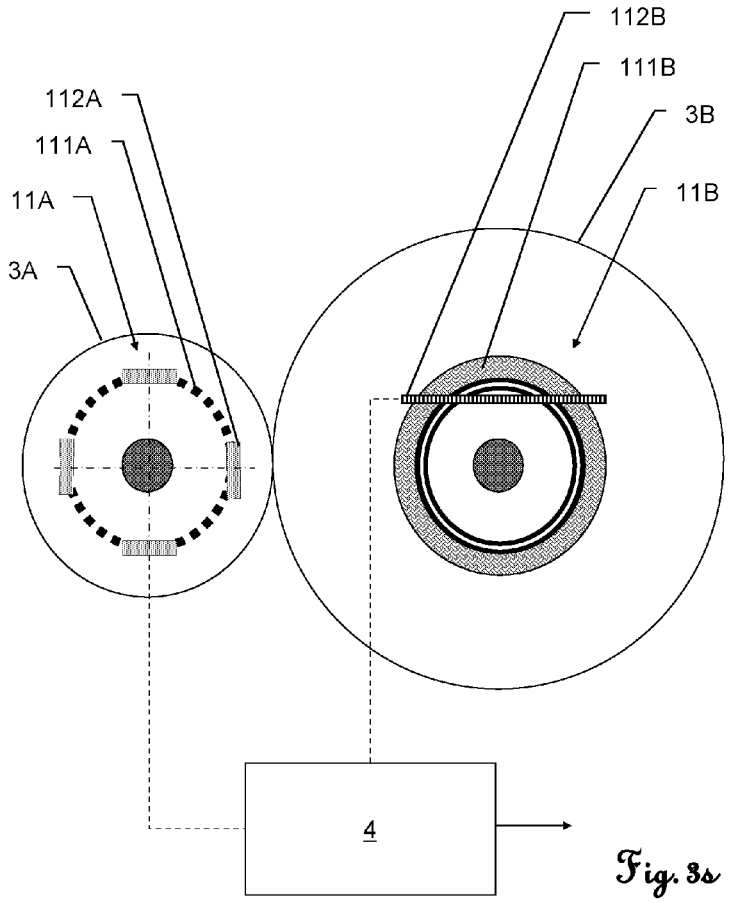

112B
111B
3B
11B
112A
111A
11A
3A
4

Fig. 3a

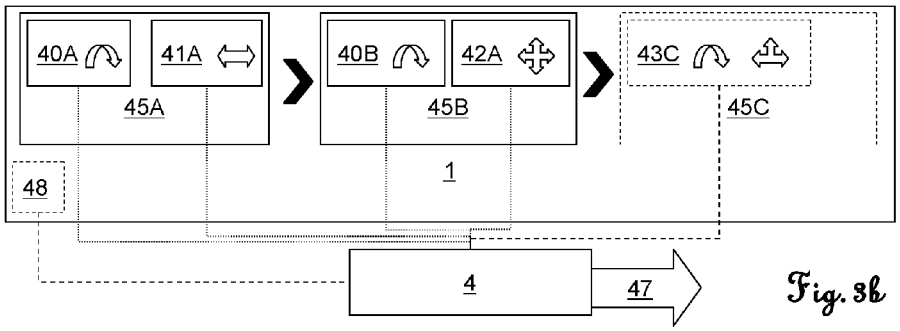

40A
41A
45A
40B
42A
45B
43C
45C
1
48
4
47

Fig. 3b

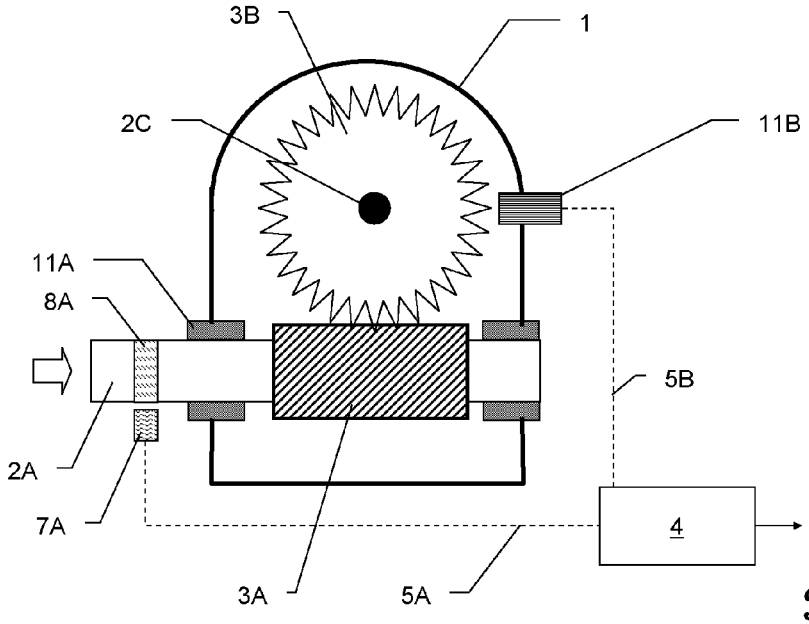

3B
1
2C
11B
11A
8A
5B
2A
7A
4
3A
5A

Fig. 4

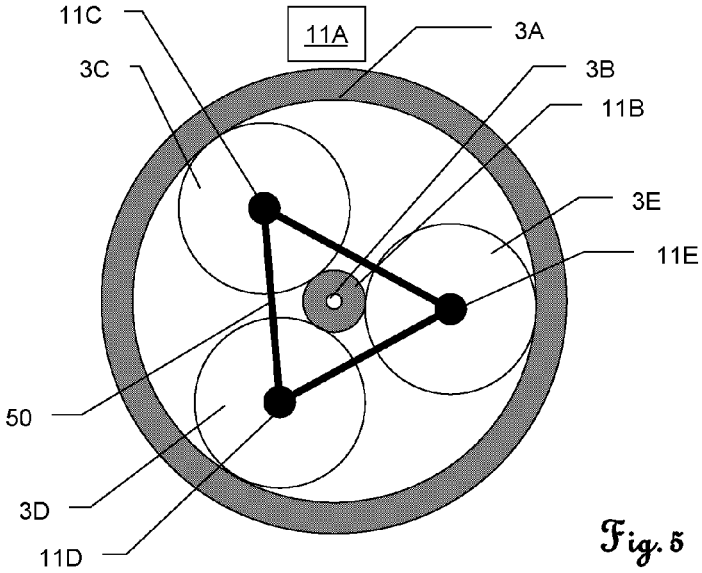

11C
11A
3A
3C
3B
11B
3E
11E
50
3D
11D

Fig. 5

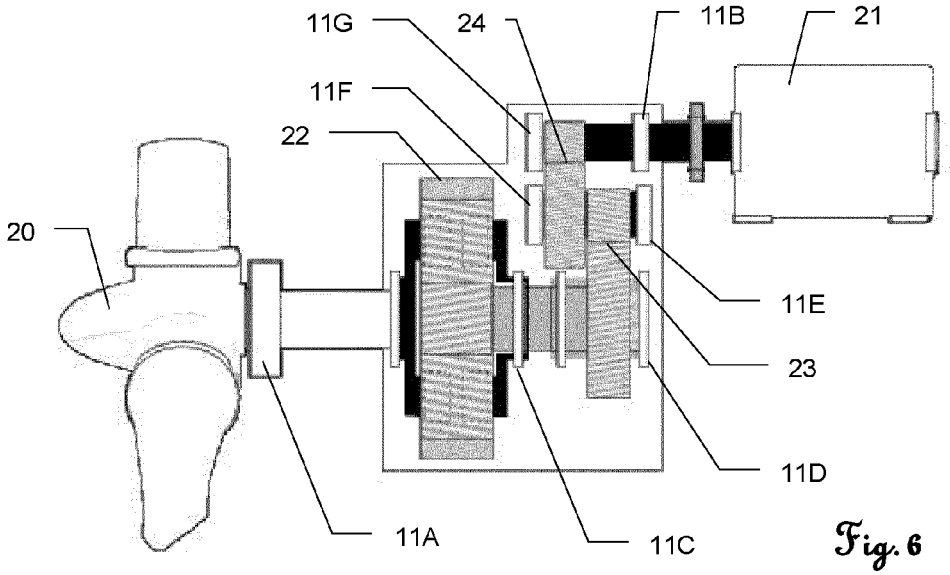

11G
24
11B
21
11F
22
20
11E
23
11D
11A
11C

Fig. 6

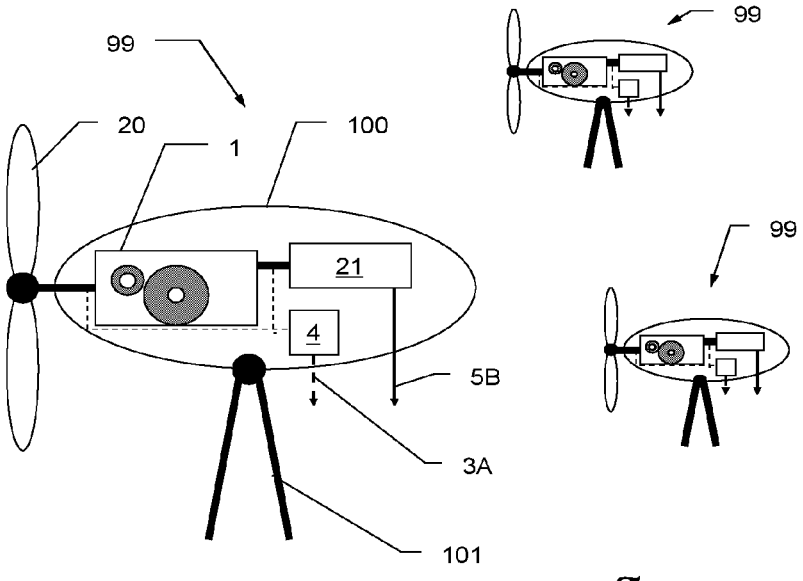

99
20
1
100
21
4
5B
3A
101
99
99

Fig. 7

WEAR-MONITORING OF A GEARBOX IN A POWER STATION

[0001] The present invention relates generally to a method of monitoring a wear of a gearbox in a power station according to the preamble of claim **1** and to a gearbox monitoring device according to the preamble of claim **10**.

[0002] Wind power plants—also referred to as windmills—are a promising source of renewable energy, which is already available on the market. Multiple windmills are often clustered in wind parks or wind farms located in windy areas. The classic design comprises a tower with a horizontally revolvable nacelle at the top, where a rotor with propeller-blades is arranged and where also an electrical generator is located.

[0003] In windmill applications, gearboxes are required to translate the rotor-blade rotation at an operational speed of approximately 6 to 20 revolutions per minute (RPM) to the electrical generator which runs in a range of approximately 900 to 2000 RPM. As spur gears in general allow a gear ratio of up to about 1:5 per stage, multiple gear stages are required to achieve the required ratio of gearing. To reduce the number of stages and gearwheels and also because of efficiency, size, noise and cost considerations, wind power stages can alternatively be equipped with at least one planetary gear stage having a higher gear rate. Also combinations of planetary and spur stages are used.

[0004] Wind power stations often operate in the Megawatt range and are designed for a lifecycle of about 20 years or more. Although the efficiency of such a gearbox is quite high (e.g. about 98%), in view of the Megawatts of power transmitted, the gearbox itself or the oil inside of it has to be actively cooled in many cases. The long lifetime also means hundreds of millions of rotor revolutions and billions of revolutions of the generator. Analogous applications are also gearboxes in other slow running power stations with slowly rotating input shafts which require a gearing up, like waterwheels, tidal power plants, etc. having similar operating conditions than the above mentioned windmills. In addition to the quite long lifetime, the load of such a windmill can vary in a wide range and rapidly, in particular in case of an emergency stop or a flurry, squall or gust of wind. A load control can be achieved by varying the angle of attack of the blades or by a horizontal rotation of the whole nacelle, but those adjustments are slow compared to the possible changes in wind speed. Also, the environmental and climatic conditions in the nacelle are not favourable for running machinery. The above facts show that a windmill-gearbox will require servicing during runtime.

[0005] There are quite sophisticated methods for determining the expectable runtime of a gearbox during the design phase. Those calculations are based on the expected loads and on statistical data and experiences. Due to the uncertainties of the actual load profiles during runtime, manufacturing tolerances and often harsh environmental conditions, those calculations can only be used for determining a preventive maintenances schedule comprising a considerable safety margin. Certain unexpected impacts during runtime, such as peak loads, temperature cycles, manufacturing inaccuracy etc. can cause an early failure which—if not detected in advance—can lead to unexpected gearbox failure like jamming or spinning and all the side effects which might result therefrom.

[0006] In windmills, the gearbox is usually placed in the nacelle, high above ground level, and therefore it is a difficult task to maintain or repair the gearbox or parts of it. It is burdensome to access it, in particular as windmills are often sited in remote areas, on mountains or even offshore. In many cases, a helicopter is required to supply the nacelle with spare parts.

[0007] In particular, as maintenance and replacement of gearboxes can be quite cost-intense, it is a desire to schedule repairs and/or replacements based on a determined actual condition of the gearbox rather than precautionary do those tasks, often well in advance of the end of the actual lifespan.

[0008] A known method to estimate the condition of a gearbox is to analyze the oil inside the gearbox for abrasion, in particular for grazed metal particles. Beside cyclical manual analysis, there are also in-line sensors known. For example, the device presented in KR 2007024230 will provide condition signal and a warning, if the result of the oil-analysis—as indication for worn gearwheels—is critical.

[0009] Another method—which also has been done manually by skilled craftsman for ages—is to "listen" to the sound emitted by the gearbox. In automated systems, this can be done by means of acoustic analysis by a kind of microphone or by means of vibrations or acceleration sensors. The publications US 2008/0234964, CN 101 196 174 or U.S. Pat. No. 5,661,659 refer to wear detection systems for mechanical systems like gearboxes by a structural sound or vibration analysis. The publication US 2007/0118333 discloses an abnormality diagnosis system, wherein the acoustic sensors for detecting an abnormality in the gearbox sounds are comprised in a bearing unit.

[0010] In WO 2004/034010 a method for quality surveillance in manufacturing gearboxes is presented. This is achieved by monitoring two interacting cogwheels by two synchronously sampled rotary transducers attached to the gearwheel shafts after assembly of the gearbox. Therein, the backlash of the gearing is determined by measurements in a forward and backward mode which gives an indication of the quality of the gearbox.

[0011] In U.S. Pat. No. 6,175,793 a vehicle's steering-wheel-gearbox is monitored by a similar angular position sensing means at the input and output shafts of the gearbox and also by a torque sensing unit. By a mathematical cancellation of the torque related torsions, a signal representative of the wear of the gearwheels in the gearbox is generated.

[0012] JP 58 034333 relates to a invariably monitoring of stress conditions at a diaphragm coupling on the basis of the extent of axial displacement, the rotational speed and load of a power plant. This is done by a means for detecting the extent of axial displacement near the fitting part of the diaphragm coupling to a generator shaft. On the basis of the displacement, the rotational speed and load of a power plant, stresses at the diaphragm coupling are calculated and safe operation state of the coupling is judged.

[0013] Although some wear effects can be concluded from the rotational position data, the wear information comprised in the rotational data is incomplete and the evaluation of those data is based on experience. The play or backlash of the tooth of the gearwheels can quite accurately be estimated, but many wear effects in a gearbox can not be concluded from rotational position offsets only. If only angular measurements are analyzed, wear which primarily manifests itself in other effects, not visible in the angular position, is undetectable.

[0014] A more reliable basis for determining the condition of a gearbox is therefore desirable. The above mentioned noise measurement can cover a wider range of wear effects, but it is in general not highly accurate and also comprises guesswork and a setup-specific configuration which is differ-

ent for each instance of gearbox. Also, the desired management of the whole system, comprising an accurate load monitoring and taking into account dependencies from the actual load conditions and a lifespan- or lifetime-management of critical system parts is not feasible by acoustic analysis only. In particular, in big and difficult to access machineries like the ones in windmill towers, false detections are a big cost issue, no matter if false positive or false negative detections are made. In many critical applications, acoustic analysis on its own is not reliable and accurate enough for a stand-alone use.

[0015] It is an object of the present invention to provide an improved lifetime management of a wind power station by accurate and reliable wear monitoring of the gearbox, as one of the most lifespan-critical parts.

[0016] It is therefore an object of the present invention to more reliably monitor a gearbox of a windmill system.

[0017] A further object of the present invention is to provide an improved method and system for monitoring the wear of the whole gearbox during runtime, in particular comprising the whole setup—with gearwheels, shafts and bearings—in the monitoring.

[0018] Another object of the present invention is to allow a more accurate determination of the kind and location of a worn part in the gearbox, in particular providing a condition-state datum for all or at least the most critical components of the gearbox.

[0019] It is also an object of the present invention to cover a wide spectral range of wear indications in the monitoring, in particular also low frequency ranges, starting form DC level.

[0020] The present invention relates to a method of monitoring the wear of a gearbox in a wind power station. The gearbox comprises at least one first shaft, at least one second shaft, cogwheels and bearings as components of the gearbox.

[0021] The method comprises sensing a first angular position—as a first degree of freedom—at the first shaft by a first rotational shaft encoder, sensing a second angular position at the second shaft by a second rotational shaft encoder. Monitoring the wear of the gearbox is done according to differences of the sensed angular positions of the shafts and a condition-signal representative of the wear of the transmission-unit according to the monitored differences is generated.

[0022] The method further involves an additional sensing of at least one additional degree of freedom, in particular an axial and/or eccentric displacement, of at least one of the shafts, in particular caused by wear of at least one of the components of the gearbox, and monitoring the additional degree of freedom as an indication of wear and generating the condition-signal according to the displacement and the differences in at least two degrees of freedom, in particular in at least one angular and at least one linear degree of freedom.

[0023] By analyzing the rotational position of the input and output shaft of the gearbox and comparing those measurements, an indication of the wear in the form of backlash or play as well as teeth abrasion or break can be evaluated. Play or backlash especially occurs when shifting the direction of the rotation. Signal disturbances due to tooth-errors have a rotational periodicity. If the error does not occur on a measured shaft, but for example on an intermediate stage gearwheel, it is scaled by the gear transmission ratio.

[0024] In particular, if the torque-load of the gearbox is also measured and the torque related angular displacement effects are compensated, the above mentioned wear effects are represented by the angular displacement differences of the shafts relative to each other. By incorporation of the knowledge of the materials and shapes of the internal components, the gearbox's theoretical behaviour under load and dynamics can be predicted and the dynamic performance of the gearbox or certain parts of it can be derived and monitored.

[0025] Two angular encoders on a single shaft—with a torque loaded shaft section in-between and in knowledge of the stiffness of the shaft—can be used to determine the torque according to the angular twist or torsion of the shaft under load. Thereby, things like peak torque, how many times the torque has exceeded a certain limit, number of load cycles, etc. can be recorded, evaluated and monitored. This can be done individually for one or multiple axis. By the angular position measurement, the axis's rotational speed is also known, and by torque and velocity, the transmitted power can be calculated. If the power on the input and output shaft is determined, the efficiency of the gearbox—or by two encoders on each axis, even the efficiency of each of the internal stages—can be calculated. Fluctuations on the torsion of a shaft within one revolution can also be an indication of wear. A well running gear will have a smooth, round angular torque distribution, without peaks or singularities. Another source for measuring the actual power and/or torque value can be the electrical output of the generator.

[0026] The encoders can be absolute or relative encoders. For a determination in a long term manner, absolute angular encoders can be used. By this, even in case of non-continuous monitoring or power failure, the offsets of the measured position values are constant relative to each other. By analyzing variations in the offsets of at least two absolute encoders located at different shafts, a variation in the gearing inside of the system can be evaluated, which is an indication of wear, in particular if torque yielding and temperature influences are also measured and mathematically compensated.

[0027] By determining the absolute angular positions relative to the box fundament, either by using absolute encoders or encoders with a precise reference mark at least once a turn, also additional scenarios can be covered. For example, a first revolution of the gears measures an angular profile reference as reference data, in particular with and without load and in both directions of rotation. The reference data can then be used for determining wear or singular effects. Also, in case of a required repair on site, like a broken or heavily worn tooth which requires material to be applied (e.g. by welding, etc.), the reference data can be used to re-establish the reference condition (e.g. by a dedicated grinding of non optimal shaped teeth). Thereby, a smooth angular position profile can be established, without peaks, which would indicate a non optimal meshing of the gearwheels, by in particular reworking the effected sections of the cogwheel.

[0028] Besides the above mentioned modelling of a single shaft, the stiffness of the overall gearbox can also be calculated or experimentally evaluated e.g. in a running in phase. The theoretical, experimental and actual system behaviour can be compared, wherein the resulting differences are representative of the condition of the gearbox and the information gathered thereby can also be used for managing its lifespan.

[0029] In practical use, not only a wear indication of the overall gearbox—such as detectable by structural sound or an input and output encoder only—is of interest, but also where, at which stage or which part of the gearbox the wear problem occurs. A smart arrangement of sensors at many, all, or at least at the most critical system components or their respective shafts, can be used to monitor the whole gearbox precisely.

The monitoring of the gearwheels can be done down to the level of monitoring a single tooth to determine its condition.

[0030] According to the present invention, determining the shaft movement in multiple degrees of freedom, in particular in an additional axial and eccentric direction, can gain additional information of the gearbox's condition and a more accurate monitoring can be achieved.

[0031] On one hand, this can be done by extending the system by combining angular encoders with other axis-sensor-means for example optical, capacitive or inductive displacement sensors.

[0032] Another approach is the use of an encoder which is built to also determine eccentricities and axial shifts. The encoder can be embodied as a capacitive encoder, an optical rotation encoder, magnetic encoder, or other type of encoder with the capability of measuring the angular position and at least one additional degree of freedom. For example, an optical angular encoder with a line sensor or an area sensor for the evaluation of an optical projection of an arbitrary geometrical 2D-pattern can be used, wherein the projected pattern can even be non-radial. Such sensors, evaluation circuitries and the evaluation-software are optimized for determining changes in location and/or scale of the projection. In case of a radial disk comprising a 2D-pattern and a projection in axial direction, a change in location represents an eccentricity, a change in scale represents an axial shift and a pattern evaluation determines the angular position.

[0033] Known sensors in the prior art, which are capable of detecting such effects, are not foreseen for a measurement of the effect itself, but rather to achieve a compensation for a highly accurate angular measurement. The values of the axial and eccentric side effects are not even available at the sensors output in prior art, as they are only used internally for angular measurement correction purposes. Even if such information would be available at a distinct output, it is not obvious to use the latter to monitor different wear effects of a gearbox as it is done according to the present invention.

[0034] Exemplary embodiments of sensors or the underlying principles for determining additional degrees of freedom can for example be found in WO 2008/083797, WO 2008/141817, WO 2007/051575 or EP 1 632 754.

[0035] Bearing failures and bearing wear can also be detected according to the present invention, as those problems manifest mainly in eccentricity or axial loosening. In particular, when helical cut cogwheels are used, axial forces are present. In many cases, the bearings are pre-tensioned and if they loosen over time, this can be an indication of wear. Especially, once the bearings are loosened, an increase of abrasion will occur. If undetected, this can lead to a complete system failure, but if detected and re-stressed, such can be avoided and the overall lifetime can be increased without exchange and with low maintenance effort.

[0036] In addition, it is possible to detect shaft-failures like plastic deformations due to overload conditions, which can also result in eccentric or axial displacements. If the gearbox is kept in operation with such a deformed part inside, after-effects will occur, whereby not only the primary affected part, but also other parts will require maintenance or replacement.

[0037] Especially for slowly rotating gearboxes, a wear monitoring by encoders can be advantageous over a wear monitoring by sound or vibration only, as many error terms to be determined are—due to the slow rotation speed—of low frequency. As sound and vibration analysis is advantageous for higher frequencies, a combination of both wear monitoring principles covers a wide spectral range, which is in particular advantageous if slow and fast rotations have to be covered.

[0038] Also, an accurate monitoring of the actual load-cycles improves the certainty of a lifespan estimation. For example, a gearbox running at low loads, well below the values it was designed for, will achieve an extended lifetime. On the other side, unexpected, harsh impacts can dramatically reduce the remaining lifetime below the expected value. An undetected, slight deformation of an internal part due to a short time overload condition, can result in increased wear, and also affect other components of the gearbox. As a result, even a complete replacement of the whole gearbox will be required. By a simple mending of the slight deformation at first hand, such would have been avoidable.

[0039] Another example which results in reduced lifetime is an unbalance at one of the shafts. This can also be detected according to the present invention, as it is observable by eccentricity effects, in particular by frequency or speed dependent eccentricities.

[0040] The method, the devices and setup according to the invention are described or explained in more detail below, purely by way of example, with reference to working examples shown schematically in the drawings. Specifically,

[0041] FIG. **1** shows an example of a first embodiment of a gearbox with a single stage for illustration of the method according to the invention;

[0042] FIG. **2** shows an example of a second embodiment of a gearbox with multiple stages and an alternative sensor setup according to the invention;

[0043] FIG. **3***a* shows abstracted gearings with exemplary embodiments of sensors which can be used according to the invention;

[0044] FIG. **3***b* shows abstracted block diagram for illustrating the method according to the invention;

[0045] FIG. **4** shows a special embodiment of a gearbox and other examples of sensors which can be used by the method according to the invention;

[0046] FIG. **5** shows a planetary stage of a gearbox to explain the applicability of the method according to the invention;

[0047] FIG. **6** shows an embodiment of a transmission system of a windmill with sensors for the method according to the invention;

[0048] FIG. **7** shows an illustration of a wind farm which is monitored and managed according to the present invention;

[0049] The diagrams of the figures should not be considered as being drawn to scale.

[0050] FIG. **1** illustrates an exemplary embodiment of a single stage gearbox **1** with two shafts, an input shaft **2**A and an output shaft **2**B. Apparently, the gearbox **1** can also be used in a reverse direction by changing the roles of the shafts **2**A and **2**B. The shafts **2**A and **2**B are supported by bearings **10**. The bearings **10** can for example be gliding bearings, roller bearings, air or fluid bearings, magnetic bearings, etc. As this embodiment shows a single stage gearbox **1**, there are two interacting gears **3**A and **3**B, an input gear **3**A and an output gear **3**B comprised within the gearbox **1**. The gearbox **1** can be greased or filled with lubricant such as oil, in particular for the reduction of friction, or a forced lubrication system can be applied which can also cover cooling purposes.

[0051] As a transformation of the speed/momentum ratio is the common purpose of a gearbox **1**, the gears **3**A and **3**B have different diameters and numbers of teeth to achieve the

desired gear and transmission ratio, but also a lateral or angular shift of the output **2**B relative to the input shaft **2**A or a change in rolling direction can be the purpose of a gearbox **1**.

[0052] According to the invention, there are at least two sensors **11**A and **11**B attached to the gearbox **1**. As described above, both of the sensors are capable of detecting the angular position **30** of the shaft **2**A relative to the gearbox's base **1** as a first degree of freedom. At least one of the sensors **11**A, **11**B or an additional sensor is capable of detecting axial **31** or eccentric **32** displacements. In FIG. **1** the sensors **11**A and **11**B are both capable of detecting three degrees of freedom, one rotational **30** around the axis, one axially **31** and one eccentric **32**. A skilled person is aware of the fact that an eccentric **32** error itself can be interpreted as a Cartesian displacement in two dimensions, resulting in an total of four dimensions, three linear and one rotational. Alternatively, an eccentric **32** error can be interpreted as a polar displacement by rotation angle and radius, and as the rotations degree of freedom is covered, only one additional degree of freedom in the form of the radius has to be covered, resulting in a total of three values, one rotational and two linear.

[0053] For a measurement of displacements due to wear, other effects like temperature strain or mechanical strain can be cancelled out mathematically by measurement of the causing effects like temperature or torque and modelling and subtracting the displacements resulting thereof.

[0054] A torque measurement can be done by dedicated means, according to the generator's electrical output or by measuring a shaft's torsion by the angular information from the sensors **2**A and **2**B. By an angular measurement at two ends of one (or more) torque loaded shaft sections, the differences of the measurements, as a twist of the shaft, will be proportional to the torque, in particular once backlash and other effects are cancelled out. By knowing the torque and rotational speed, which can be determined by the angular encoders, also the transmitted power can be calculated.

[0055] Angular displacements in a gearbox are good indicators for detecting torsion of the gears and the shafts and also for determining the backlash. A certain backlash is a necessity for a functioning gear transmission, but too much or too little play is disadvantageous and an indication of a putative reduction of lifetime. Also, a complete failure or at least a partial break off of one or more teeth of a gearwheel is identifiable by an increased backlash, which occurs with a rotational periodicity, each time when the affected section of the gearwheel is in interaction.

[0056] The actual forces and load conditions inside a gearbox **1** are quite complex. For example, the forces of a gear-gear combination in general comprise an axial component—shifting the gears sideways (in particular for helical cut gears), a radial component—forcing the two cogwheels apart and a tangential component—which transmits the actual momentum. Furthermore, some friction forces are also unavoidable. Those forces all burden the gearwheels **3**A **3**B, the bearings **10**, the shafts **2**A **2**B and the housing of the gearbox **1** to achieve force equilibrium.

[0057] The angular-only diagnosis of prior art is per se not capable of detecting axial **31** or radial **32** effects. For example, the radial and tangential forces and—due to the radius of the gearwheel—also the axial forces result in bending moments applied to the shafts and also lateral and longitudinal forces at the bearings **10**. The bending moments result in an eccentricity **32** of the shaft **2**A compared to the theoretical force-free shaft axis. The lateral forces also burden and displace the bearings **10** in axial direction **31**.

[0058] The effects of those forces are also relevant for the condition of a gearbox **1** and influence or indicate the wear of the gearbox **1**, nevertheless those are not detectable and evaluable by rotational only encoders. By analyzing all the forces or rather the effects resulting therefrom according to the present invention, a more accurate analysis of friction, deformation, play, losses and other effects is achieved.

[0059] Also, the bearings **10** can be monitored according to the invention, as they are also subject to wear, sometimes even more than the gearwheels **3**A **3**B. In most cases, bearing-wear does not result in increased play or backlash of the gearwheels **3**A **3**B, but rather in eccentricity or axial play, which is undetectable by a rotational only encoder.

[0060] The figure also shows the measured signals from the sensors **5**A and **5**B and the evaluation unit **4**. To determine the difference of angular position at the same time, the readout of the sensors **11**A and **11**B is, preferably, synchronized. The evaluation unit generates a signal representative of the wear of the gearbox **1** based on the sensed position and displacement information from the sensors **11**A and **11**B.

[0061] FIG. **2** illustrates a multi stage gearbox **1**. The gearbox **1** comprises at least one input-shaft **2**A were a driving torque or momentum is applied and at least one output-shaft **2**B where a driving torque is drawn off, with a changed torque/speed ratio according to the tooth ratio. In between the two shafts **2**A, **2**B, there are a plurality of gears **3**A, **3**B, **3**C**1**, **3**C**2**, in this particular example one further intermediate-stage-shaft **3**C equipped with two cogwheels **3**C**1**, **3**C**2**. Such multi stage gearboxes can be seen as a daisy chain of single stages, wherein the input shaft of one stage merges with output shaft of the previous stage resulting in an intermediate stage, which can also be inaccessible and invisible from the outside of the gearbox.

[0062] The gears are attached to a centric shaft, either rotatable about the shaft by some bearing or coupled to the shaft for the transmission of torque from the gear to the shaft. There are also special gear arrangements known, such as sprockets, worm wheels, spur wheels, planetary wheel drives, etc. which can have a more complex mechanic than simple spur wheels.

[0063] There are also different shapes and arrangements of teeth known for the gears. For example, helical cut gears can achieve more running smoothness and are known to produce less noise in comparison to orthogonally toothed gears, but with the side effect of additional axial forces on the shaft and bearings. In the gears, the teeth are a critical part, as they have to transmit the torque from one wheel to the other. Dependent on the actual shape and accuracy of the shape of the teeth, high punctual loads can occur on the face of the teeth. Furthermore, some friction between two interacting teeth will happen. Although friction can theoretically be avoided by design and be replaced by a rolling motion only, practically at least some friction will always remain due to production tolerances, mounting inaccuracies, thermal expansion, etc. Also, the cyclic changes in the load profile of the teeth can raise fatigue issues and failure.

[0064] The load on the teeth of a gearbox **1** will lead to a wear in the gearbox **1** which can result in damage of a gearbox **1**. Both kinds of total failure, jamming or spinning of the gearbox **1** can also result in severe follow-up damages. The tooth-wear, in particular if undetected, will even increase friction and scuffing, generate more heat, and even lead to a following tooth failure like a cracking, breaking loose or even

breaking out of one or more teeth. In particular, in case of a failure of one tooth, the gearbox will remain working, but with an increased load on the other teeth, whereby those will likely fail as well within a short timeframe. A splintered part of a tooth can also cause jamming if it gets squeezed in between two gearwheels.

[0065] In particular heavy machinery, such as wind power plants, which have to transmit high forces, require corresponding large gears and gearboxes, which are costly and hard to inspect and maintain. Also, the whole machinery has to be halted for error diagnosis and maintenance, resulting in productivity losses.

[0066] An almost torque-independent measurement of the sensors can be achieved by a placement of the sensor on an unloaded end of the shaft as illustrated by the sensors **11**C and **11**D. As the gearwheels **3**B and **3**C**2** themselves have high torsion stiffness due to their geometry, the unloaded ends of the shafts will rotate in conformance with the gearwheel, almost independent of torsional effects by the actual power transmitted by the gearbox.

[0067] The sensor **11**D is an example of an embodiment which uses a dedicated linear position sensor in the axial degree of freedom, indicated by the double-arrow at the sensor **11**E. Sensor **11**A has an accompanied eccentric sensor **11**F indicated by the two degrees of freedom shown next to the sensor **11**F, which measures the same shaft as the sensor **11**A. As mentioned, eccentricity can also be indicated in polar coordinates by angle and radius. As the angular position is already measured, only the radius has to be determined, which can e.g. be done by a radial distance sensing of the circumference of the shaft in one additional (linear) degree of freedom.

[0068] In the shown embodiment, there is also a sensor **11**C at the internal-stage-shaft **2**C. Thereby all the shafts in the gearbox **1** can be monitored and each gearing stage can be evaluated separately. For example, if the intermediate shaft **2**C and/or its gearwheel **3**C**2** is known or expected to be the weakest link in the gearbox, such a direct measurement is advantageous. In particular, the shown sensor **11**C is even located inside of the gearbox **1**.

[0069] In further embodiments, other or more axis of the gearbox **1** could be equipped with sensors for an individual subset of degrees of freedom. For example, in an exhaustive embodiment, each end of each shaft can be equipped with a sensor capable of sensing the rotational, axial and eccentric degree of freedom.

[0070] FIG. **3***a* illustrates a close-up of a gear system with two cogwheels **3**A and **3**B (teeth not shown) with exemplary embodiments of sensors for a measurement in more than the rotational degree of freedom. Sensor **11**A comprises a code-wheel **111**A and four sensors **112**A which are arranged at the circumference of the code wheel. The sensors' arrangement allows a determination of the eccentricity of the code wheel, while the sensors are built in such a way asto determine the axial position according to a scale factor for the code wheels' projection.

[0071] Sensor **11**B comprises a single line sensor **112**B and a code wheel **111**B carrying the code for rotational position determination and also two inner rings for eccentricity and axial position determination by evaluating the scaling and displacement of the projection of the rings.

[0072] There is a variety of other sensor designs capable of measuring the rotational position and an additional linear displacement or a tilt. For example the European patent application Nr. 10157931.6 relates to a measurement of multiple degrees of freedom by one single device. Besides those off-centre sensing principles, there are also central sensing encoders known, like in DE 197 50 474, EP 1 890 113 or DE 39 24 460, which are measuring directly to a shaft's plain end and can also be used according to the present invention.

[0073] The one single sensor for determining at least two degrees of freedom comprises a code carrier **111**A, **111**B and a sensor arrangement **112**A, **112**B, code carrier and sensor arrangement being rotatable relative to each other about an axis of the shaft as a first degree of freedom. The sensing comprises a generation of a code projection, dependent on the three-dimensional displacement of the code carrier (**11**A, **111**B) relative to the sensor arrangement (**112**A,**112**B), onto the sensor arrangement (**112**A,**112**B) and detection of at least a part of the code projection. From the code projection, the angular position of the code carrier (**111**A,**11**B), based on the axis of the shaft is determined.

[0074] Also a displacement value for the at least one additional degree of freedom of the code carrier (**111**A,**111**B) relative to the sensor arrangement (**112**A,**112**B) is determined on the basis of the code projection, in particular wherein an axial displacement of the sensor arrangement relative to the code carrier and/or the eccentricity of the sensor arrangement relative to the code carrier is determined.

[0075] FIG. **3**B shows a block diagram of the method of monitoring a gearbox **1** which comprises multiple stages **45**A,**45**B,**45**C, having at least one corresponding shaft **2**A,**2**B,**2**C and being in mechanical interaction with each other. The stages **45**A,**45**B,**46**C are equipped with sensor means, which can be of different types. As possible examples, angular transducers **40**A and **40**B, axial shift sensor **41**A, eccentricity sensor **42**B and a combined angular, axial and eccentric sensor **43**C is illustrated. The calculation unit **4** for monitoring the gearbox **1** is determining a condition signal **47** from the sensor data, which can comprise a single information or information dedicated to a certain component, stage or subset of the gearbox **1**.

[0076] As mentioned above, a sound/vibration analysis can quite well cover higher frequency ranges, whereby a combination of both wear monitoring principles can be used to cover a wide spectral range. Especially, if slow and fast rotations are present, a combination of positional and sound monitoring can be advantageous. For example, in an embodiment according to the present invention for a windmill or waterwheel gearbox, the input stage—rotating slowly at about 10 RPM—can be monitored by an angular sensing **45**A,**45**B,**45**C, whereas the output stage—rotating fast at about 2000 RPM—can be covered by sound and/or vibration monitoring **48**—in addition or as an alternative to the positional sensing. According to the present invention, also the low frequency wear effects can be monitored, which are not well coverable by sound analysis or are often overlaid by external noise and vibration sources, like a swinging of the whole windmill tower, etc.

[0077] FIG. **4** illustrates a special embodiment of a worm gear, where the shaft **2**A is in particular axially loaded, due to the design of the tooth system **3**A.

[0078] The sensor **7**A and the corresponding code-section **8**A on the input shaft **2**A is embodied with a code on shaft **8**A. The code **8**A can for example be (laser) engraved, etched, printed, glued onto the shaft, and the readhead **7**A is positioned to sense at least part of the code **8**A to determine the angular position. By sensing the distance between the shaft

and the sensor, also the eccentricity can be determined for example optically or capacitively. The code **8**A and the readhead **7**A can further determine the position in axial direction, which information is also evaluated, not only to determine the wear of the gearing but also of the bearings which have to sustain the axial load. Such a system can also be used for a quick retrofitting, as the shaft has only to be stopped for applying the code **8**A.

[0079] In this embodiment, the second sensor **11**B is built as a tooth sensor which is directly sensing the teeth of the cogwheel **3**B. For example, this can be done capacitively or magnetically by a distance evaluation between the sensor and the tooth. A rotating cogwheel will result in a signal with an alternating part representing the teeth and the angular position and an offset, which can for example have a periodicity of one revolution due to eccentricity. Apparently, the above mentioned sensor principles are not limited to worm gears but can also be applied to other gearbox types.

[0080] FIG. **5** illustrates an embodiment of planetary gear stage. In one embodiment, planetary gears have a rotating outer ring **3**A and a standstill planet carrier **50**—to which the planetary wheels **3**C, **3**D, **3**E are attached. Another embodiment is realized by a fixed outer ring **3**A and a revolving planet carrier **50**. The placements of the sensors vary accordingly, as it is preferred to arrange the sensors on the non-rotating components for ease of electrical connection and readout, although rotating sensors connected rotationally or by wireless means can be used otherwise.

[0081] In the shown example, the planet carrier **50** is static, wherefore the planetary wheels **3**C, **3**D, **3**E can be sensed by three sensors **11**C, **11**D, **11**E. Also, the input- and output-shafts or wheels **3**A and **3**B can be sensed by the sensors **11**A and **11**B. Thereby the whole gear can be monitored, although planetary gears are known to be difficult to monitor by acoustic means.

[0082] When the planet carrier is rotating, a sensing of the planetary wheels would require a revolvable electrical connection or some wireless means, but at least the rotation of the whole carrier can be sensed, which will suffer from eccentricity if a planetary wheel is damaged.

[0083] FIG. **6** illustrates another embodiment of a mechanical transmission system of a wind power plant with a rotor **20**, a gearbox **1** and a generator **21**. The gearbox **1** comprises multiple, in particular three stages, whereof the first is a planetary stage **22** and the others comprise helical cut cogwheel stages **23**, **24**. According to the invention, the shafts of the axis are equipped with sensors **11**A to **11**G, of which at least one, preferably all, are capable of sensing rotation and at least one additional degree of freedom, in particular an axial and/or eccentric shift.

[0084] FIG. **7** illustrates a schematic of a wind power plant farm with a plurality of windmills **99** each having a rotor **20** connected to a gearbox **1**. On the other end of the gearbox **1**, there is an electrical generator **21**. All those parts are inside of a nacelle **100** on a tower **101**. The gearbox **1** is equipped with a monitoring device **4** according to the invention for monitoring the wear of the gearbox and lifetime management.

[0085] The monitoring device **4** allows an accurate monitoring or the wear condition of each windmill **99**. By the resulting data, not only the health of the whole windmill **99** can be determined, but also a diagnosis down to the, in particular critical, component level can be done. One example of the advantages of the present invention is that by knowing the required spare parts even before opening the gearbox, the required parts can be sourced in advance of maintenance. Also, statistical analysis like failure trending can be done at a very accurate level.

[0086] Not only a schedule of servicing can be planned based on those data, but also a planning of further load distributions between the windmills in the wind park can be planned to achieve an equalization of service intervals between multiple windmills, allowing to maintain multiple windmills in the same timeframe and not randomly upon the present demand.

[0087] As a load reduction on a half worn gearbox can prolong its lifetime to a certain extent the servicing can be scheduled to a desired timeframe, e.g. calm season according to the weather forecast, but still producing energy (although with a slightly reduced efficiency).

1-15. (canceled)

16. A method of monitoring a wear of a gearbox in a power station comprising at least the following components:

at least a first shaft;

at least a second shaft;

cogwheels; and

bearings,

the method comprising:

sensing a first angular position, of the first shaft by a first rotational shaft encoder;

sensing a second angular position, of the second shaft by a second rotational shaft encoder;

monitoring the wear of the gearbox according to differences of the sensed angular positions of the first shaft and second shaft; and

generating a condition-signal representative of the wear of the gearbox according to the monitored differences,

wherein:

an additional sensing of a displacement of the first shaft and/or the second shaft in at least one additional degree of freedom; and

the displacement in the additional degree of freedom is comprised in the monitoring and generation of the condition-signal as an indication of wear.

17. The method according to claim **16**, wherein the power station is a wind power station, a waterwheel power plant, or a tidal power plant.

18. The method according to claim **16**, wherein the additional sensing of the displacement of the first shaft and/or the second shaft in at least one additional degree of freedom includes an axial and/or eccentric displacement caused by wear of at least one of the components of the gearbox.

19. The method according to claim **16**, wherein the sensing of the angular position and of the displacement at one of the shafts is carried out by one single means, which is sensing in at least two degrees of freedom.

20. The method according to claim **19**, wherein the one single means comprises:

a code carrier and a sensor arrangement, code carrier and sensor arrangement being rotatable relative to each other as a first degree of freedom;

and the sensing comprises:

generating a code projection, dependent on the three-dimensional displacement of the code carrier relative to the sensor arrangement, onto the sensor arrangement and detection of at least a part of the code projection;

determining the angular position of the code carrier from the code projection; and

determining a displacement value for the at least one additional degree of freedom of the code carrier relative to the sensor arrangement on the basis of the code projection.

21. The method according to claim **20**, wherein an axial displacement of the sensor arrangement relative to the code carrier and/or the eccentricity of the sensor arrangement relative to the code carrier is determined

22. The method according to claim **16**, wherein at least two angular positions at different axial locations on each of the first and/or second shaft are sensed and a twist of the respective shafts is determined.

23. The method according to claim **22**, wherein the different axial locations are chosen so that a torque loaded shaft-section is in-between of the axial locations.

24. The method according to claim **23**, wherein the torque load is determined dependent from the angular position differences and a known or presumed shaft stiffness.

25. The method according to claim **22**, wherein the efficiency and/or losses of the gearbox are determined according to the sensed positions and/or displacements and the determined torque load.

26. The method according to claim **16**, wherein the condition of the bearings is monitored according to a sensed axial and/or eccentric displacement of the shafts.

27. The method according to claim **16**, wherein the condition of the bearings is monitored including a loose pre-stressing and/or a radial run-out of the bearings according to a sensed axial and/or eccentric displacement of the shafts.

28. The method according to claim **16**, wherein each of the shafts in the gearbox are sensed with respect to their actual location and/or orientation in at least two degrees of freedom, in particular wherein an angular position and axial and/or eccentric displacements are sensed by the least one sensor on each of the shafts in the gearbox, preferably wherein the sensing is time synchronized.

29. The method according to claim **28**, wherein an angular position and axial and/or eccentric displacements are sensed by the least one sensor on each of the shafts in the gearbox, preferably wherein the sensing is time synchronized.

30. The method according to claim **16**, wherein an additional sound/vibration monitoring of the gearbox is performed.

31. The method according to claim **30**, wherein he positional and displacement monitoring covers the lower frequency range of the evaluated wear indications and the sound/vibration monitoring covers the upper frequency range of the evaluated wear indications.

32. The method according to claim **16**, wherein a managing of the lifespan of the gearbox according to the condition-signal and an allowable load condition to be applied to the gearbox is determined.

33. The method according to claim **32**, wherein the managing of the lifespan of the gearbox according to the condition-signal includes an allowable load condition to be applied to the gearbox is determined by equalizing an expected lifespan of a plurality of power stations in a wind park.

34. A gearbox monitoring device for power stations power plant gearbox, comprising

an angular shaft encoder for a first-shaft and

an angular shaft encoder for an second-shaft,

a calculation unit for monitoring a wear-condition of the gearbox according to signals of the angular shaft encoders, wherein at least one displacement sensor for determining displacements of a shaft of the gearbox in at least one translational degree of freedom, wherein the calculation unit is built in such a way as to determine the wear of the gearbox according to the signals of the angular shaft encoders and at least one signal from the at least one displacement sensor.

35. The device according to claim **34**, wherein the calculation unit for monitoring a wear-condition of the gearbox according to signals of the angular shaft encoders does so by determining the difference of the signals of the at least two angular shaft encoders.

36. The device according to claim **34**, wherein the at least one translational degree of freedom includes an axial or eccentric degree of freedom.

37. The device according to claim **34**, wherein the angular shaft encoder and the displacement sensor are embodied as a single sensor, which is built in such a way to sense at least two degrees or freedom.

38. The device according to claim **37**, wherein the wear-condition of the gearbox is determined according to the angular position signal and at least one axial position signal and/or excentric position signal from the single sensor.

39. The device according to claim **37**, wherein further means for determining a torque-load signal of the gearbox and/or a synchronisation means for capturing the signals at a distinct time are comprised.

40. The device according to claim **34**, wherein the first and/or second shaft has a further angular shaft encoder and a twist of the shaft is determined by the calculation unit according to the difference in relative angular position of the angular shaft encoders.

41. The device according to claim **40**, wherein a torque load signal is generated by the calculation unit according to the twist and the shaft's stiffness.

42. The device according to claim **34**, wherein an intermediate-stage-shaft of the gearbox is equipped with a sensor, in particular all shafts are equipped with at least one sensor.

43. The device according to claim **42**, wherein all shafts are equipped with at least one sensor.

44. A wear monitored gearbox system comprising a gearbox and a gearbox monitoring device according to claim **34**.

45. A computer program product with program code being stored on a machine readable medium, the program code being configured to automatically execute and operate the method of monitoring a wear of a gearbox according to claim **16**.

46. The device according to claim **34**, wherein the power stations include a wind-, waterwheel- or tidal-power plant.

* * * * *