OPTIMISED GEARBOX DESIGN FOR MODERN WIND TURBINES

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Summary:-
Early development of wind turbines in the UK saw the application of gearboxes with novel and advanced design features based on the ideas of Hicks. Unfortunately at the time the full benefit of these design features, the flexible pin and the high speed differential, was not fully appreciated by the wind turbine industry and superficially simpler and lower manufacturing cost industrial based gearbox solutions were generally adopted. Reliability issues with current gearboxes and the need for larger wind turbines operating in sever offshore conditions suggests that the design principles of Hicks are even more appropriate to today's wind turbine industry. This paper outlines the fundamental advantages of the design features that were successfully demonstrated on LS1 3MW wind turbine in Orkney in 1982, are installed in wind turbines operating in extremely high wind conditions in NZ, and currently under going test on a 3.4 MW wind turbine operating in adjures conditions in northern Europe. The true technical and commercial advantage of the flexible pin and differential features can now be demonstrated relative to the performance of current gearboxes and these advantages become even more significant to the total life cycle economics of wind energy generation, when larger power machines are considered for which mass, size, reliability and energy capture are paramount factors. The paper leads on to illustrate the optimized wind turbine gearbox transmission, the MINI-MASS, that provides high reliability, low weight, and can be used in combination with a low cost generator system.

Key words:-Wind turbines, gearboxes, flexible pins, superposition gears. Epicyclic gears.

Introduction

Hicks developed in 1964 a novel method of providing load sharing between the planet wheels of an epicyclic gearbox, the flexible pin, which has been applied to a large variety of industrial aerospace and marine gearboxes from 1964 onwards. (Ref 1 &2) In the early eighties a 3 MW experimental wind turbine was built in Orkney, the LS1, employing Hicks flexible pins and including a high speed differential gear that allowed synchronous operation of the generator.
The full benefit of the flexible pin in providing uniform gear tooth and planet bearing loads combined with the high speed differential device was not understood or fully appreciated by the industry and superficially simpler and lower manufacturing cost gearbox solutions were generally adopted.

Recent developments have seen a Hicks designed gearbox with flexible pins and differential features successfully applied to a 550 KW wind turbine working in very high wind conditions in NZ. A 3.4 MW differential gearbox using a Hicks design is currently on commissioning trials in Northern Europe and 1.5 MW gearbox using a Timken version of the flexible pin as been built by Maag and is under trial on the site of the original LS1 machine.

The authors have taken the well proven Hicks design principles and combined these with the most up to date technology in bearings, electrical machines and suspension ideas to arrive at the MINI-MASS new generation wind turbine transmissions.

Epicyclic Gear Design

Load – Sharing among mesh points.

The basic problem in all epicyclic gearing is to ensure equal load-sharing among the multitude of mesh points. For example, the Stoeckicht system (circa 1940) solves this problem by making the annulus ring flexible, while allowing both it and the sun wheel to float without bearings so that they are supported by their respective mesh points.

Successful epicyclic gears transmitting high powers have embodied similar principles of floating flexibility.

The stability of such systems relies upon straddle mounting the planet spindles in a rigid carrier so that they cannot tilt under the influence of load. Such a carrier is a hollow cylindrical block having rigid webs which form rectangular ports through which the planets project radially to mesh with the annulus. Because of this rigid construction the number of planet wheels that can be carried is limited, and the planet carrier is thus physically large and expensive to manufacture.

In the industrial based gear designs that have been applied to wind turbines to date the full floating members and flexibility principles of Stoeckicht have been removed or compromised making the gear tooth loading far more sensitive to carrier deflection.

The consequence of this approach leads to large, heavy gearbox designs that are sensitive to overloads and misdistribution of load across the bearings and tooth face widths which in turn contributes to a high rate of premature failures.

Flexible Pins

The flexible pin eliminates the need for a straddle mounting and, therefore, enables the maximum possible number of planet to be used subject to tip to tip clearance for any particular epicyclic ratio. Load sharing is achieved by ensuring that the deflection of the planet spindle under its normal load is considerably greater than the manufacturing errors which cause maldistribution; that is, if one planet tends to take more load than the others it will deflect until the others take their share.

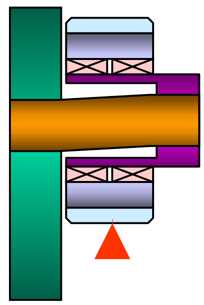

Fig 1

Fig 1 shows that a uniform tooth load, where the centroid of load is symmetrical with the free length of the flexible pin, thus exerting equal and opposite moments on the built in ends of the flexible pin which then remains parallel during deflection.

The most important feature of the flexible pin design is that, as the planet spindle and flexible pin are co-axial, it is capable of deflection in two planes, which makes it virtually self-aligning. This means that the pin is influenced by radial as well as tangential tooth loads, and it is able to compensate for helix errors of different magnitude or sense at the sun and annulus mesh points. If the resultant load of the sun and annulus mesh points is not in the same plane as the mid-point of the unsupported portion of the flexible pin, there are two restoring effects. First, the offset tangential load tips the spindle in the tangential plane in a manner which tends to offset the respective load points an equal amount to either side of the mid-point of the pin. Second, the radial couple resulting from the offset radial load tilts the spindle in the radial plane until the residual couple is reduced to an amount compatible with the angular flexibility of the spindle assembly. In short, there is a complex movement in two planes. This complex movement is in fact beneficial since it promotes a slight crowning effect as a result of the skewed or non-parallel axes.

Put simply the flexible pin is designed to use high deflections to provide uniform tooth loads between planets and across sun - planet and planet - annulus tooth face widths. An added benefit of producing equal loads across the tooth contact face widths is equal loads along the planet wheel bearings, the most critical element of a high capacity low speed epicyclic gear.

Conversely the industrial design of epicyclic gear requires high carrier rigidity relative to the gear tooth stiffness which is impractical and leads to misdistribution of load across the teeth and bearings resulting in premature failure.

Fig 2 illustrates a typical high speed multi planet Hicks flexible pin planet carrier assembly. The impact of using a flexible pin designed epicyclic train employing maximum number of planets, 7, compared with a conventional rigid three planet design increases the torque capacity a factor of 2.33.

Gear Tooth Surface Stress.

A comparison of the gear tooth surface stress on the LS1, the Tjaereborg, and a typical modern gearbox are shown in table 1. If today's designs are considered to be 100% then the interesting comparison is Tajeborg machine was operating at 72% of the gear stress and the LS1 at 55%. The authors recommend gear stresses for wind turbines are based on K factors of 6 to 8, similar to those used on the Tajeborg design.

Date Power Country	1986 3 MW LS1 GB	1987 2.2 MW Tjaereborg DK	2000 1.5 MW typical wind turbine gearbox design today D
K- Factor α SH^2	4	7	13
Gear surface stress ratios	55%	72%	100%

Table 1 Gear tooth K factors & surface stress ratios

Torsional Dynamic Inertial loads

In a wind turbine, the fluid power source, the wind, is an uncontrolled variable unlike other turbines where the power source is fully controlled. This factor presents a significant issue when considering the design of the gearbox and other power transmission components. Instantaneous wind speed will produce instantaneous rotor torque proportional to the wind velocity squared. This instantaneous torque will be applied via the gearbox to accelerating the inertia of the generator which appears large when referred to the turbine shaft via the gearbox ratio squared, see fig 3. Dynamic loads across the gear system created by instantaneous wind speed loads are considered, by the authors, to be a major contributory factor in creating premature gearbox failures.

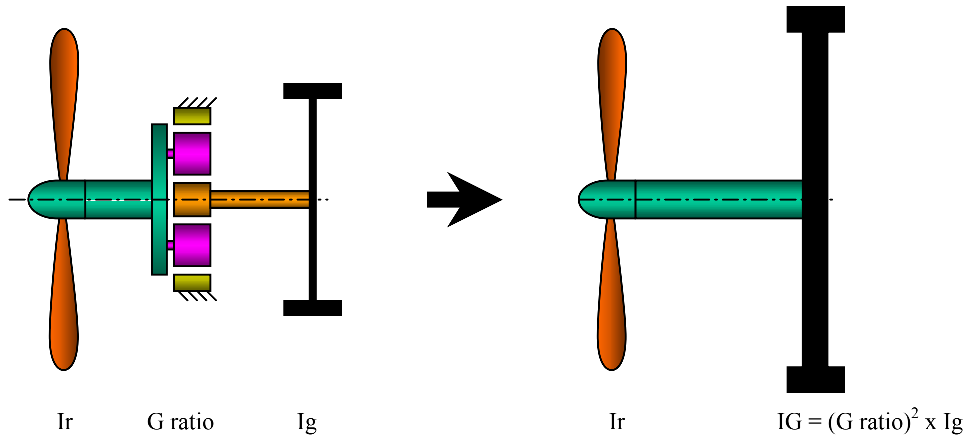

Fig 3 referred inertia of the drive train.

High Speed Differential drive.

A differential gear can be placed at the high speed end of the gear train that provides a number of functions to a wind turbine transmission. The differential is set to limit the maximum torque that can be transmitted by the transmission. Under conditions where the rotor generates an instantaneous excessive torque, this torque is absorbed by the generator operating on full load torque running at a constant speed and component of torque that accelerates the rotor allowing the rotor speed to increase whilst the pitch control adjust the blades to the wind conditions and the rotor speed is then reduced. Under this method of control loads in the gearing system and dynamic loads on the electrical machine can be reduced to less than +-5% of full load torque for rotor speed variations of +-5%.

The LS1 machine employed such a high speed differential gear connected to a constant torque auxiliary generator and a main synchronous generator. A schematic description of the system is shown in fig 4

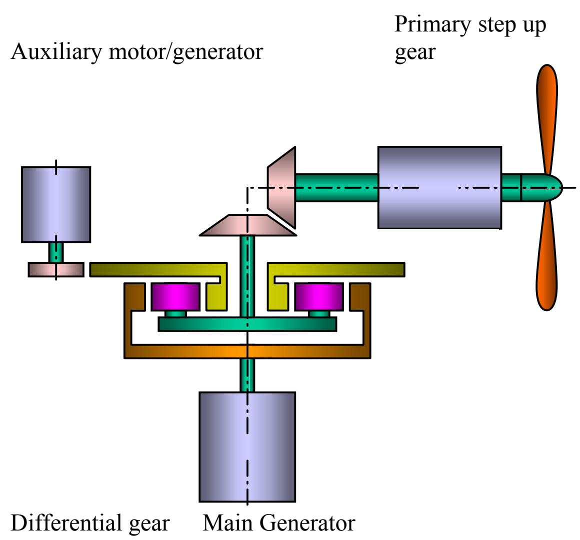

Fig 4 The LS1 differential load control

The rotor speed range over which the differential can be used to provide a constant speed output is a function of both the complexity of the shunt transmission gear system and the power rating of the auxiliary motor / generator. The larger the power ratings of the auxiliary machine then the larger the range of rotor speed over which the generator runs at constant speed.

The range of rotor speed over which the differential is required to work is a function of the total wind turbine system design. To provide transient torque protection on a variable speed generator then a speed range of +-5% is required. Using a fixed speed induction generator or synchronous machine a speed range of +-15% is required.

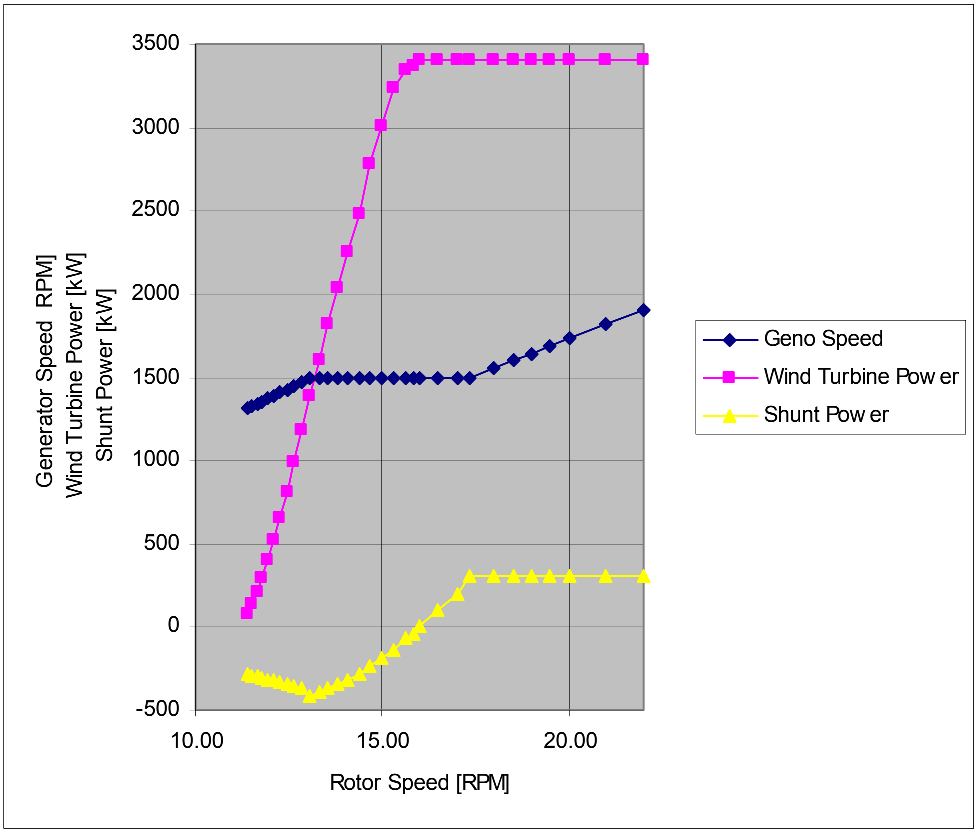

Fig 5 Generator speed, Wind turbine power, Shunt power v rotor speed

In figure 5 a typical characteristic of rotor power, generator speed and shunt power against rotor speed is shown for a 3.4 MW turbine operating in combination with a high speed synchronous or induction generator. The operating envelop obtained when using an auxiliary motor / generator of 400 KW is from 13 to 17.5 rpm on the rotor and 1.5 to 3.4 Mw on the generator.

Above 17.5 rpm is the over speed mode, 17.5 to 22 rpm, were the turbine can over speed in high wind conditions when load is removed and the turbine is in the process of being brought to rest.

The auxiliary motor / generator drive can be provided by an electrical machine or a hydraulic pump motor system. Each system has advantages and disadvantages and final selection would be influenced by the individual customer requirements. An electrical machine was used in LS1 but the technology at the time prevented using the drive through zero speed and into the motor range. Electrical technology as progressed and motors are now available that will hold torque through zero speed.

Main Generators and power conditioning.

When using a differential gear transmission the generator can be a simple fixed speed induction or synchronous machine operating at high voltage. This means that a full load power converter is not required. Additionally all the power transformers and electrical conditioning equipment for connection to the grid can be installed at ground level considerably reducing the weight and space taken in the nacelle. Only a power converter and transformer for the auxiliary motor generator whose rating is 15/20 % of the main generator needs to be installed in the nacelle.

Gearbox Mounting and torque reaction

A MINI-MASS gearbox with the flexible pin and differential feature can be configured to fit the classic twin bearing rotor shaft mounting arrangement and an example of this using a hydraulic shunt transmission is illustrated in figure 6.
A MINI-MASS gearbox can also be configured to fit the new twin taper rotor support bearing system and an example is illustrated in figure 7 where in this case an electrical machine is used to provide the shunt transmission feature.
The authors considered it important that the gearbox is protected from all types of overloads created by the instantaneous wind loads and in addition to the torque protection a torque neutral suspension is proposed that ensures the gearbox experiences only pure torque and this feature is illustrated in figure 7.

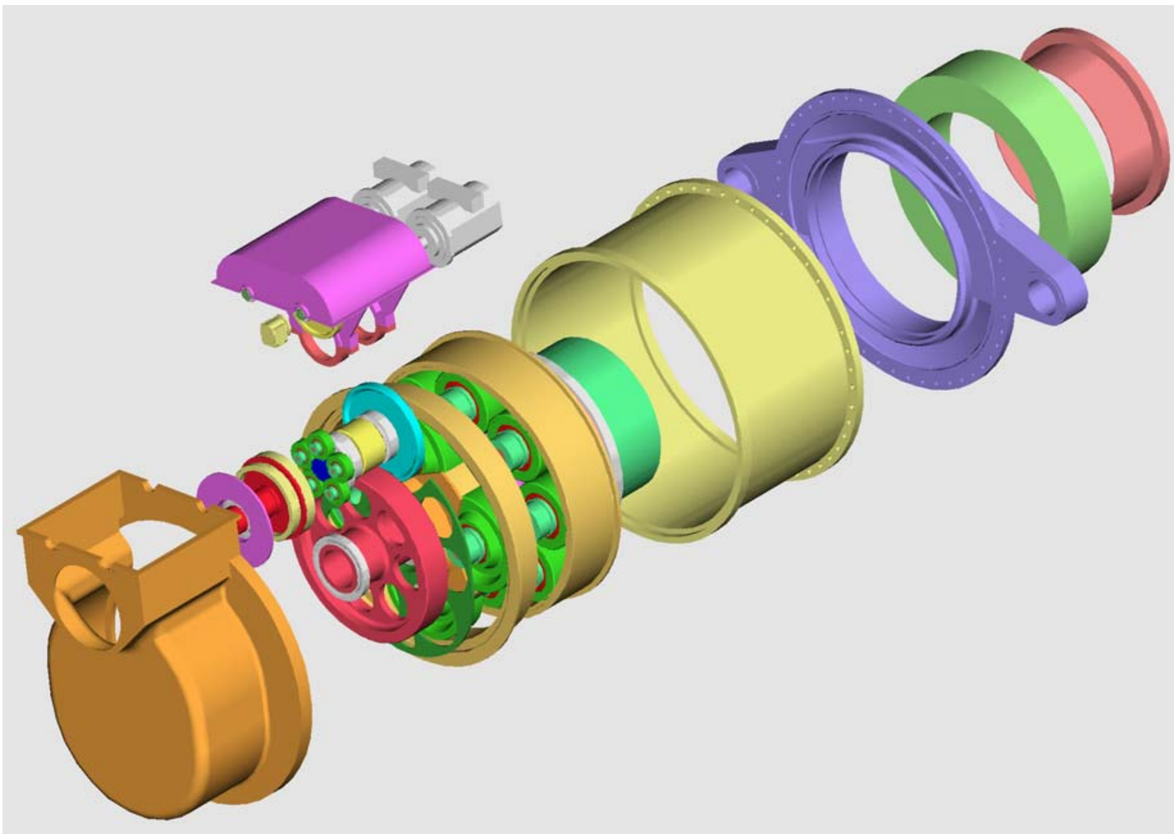

Fig 6 A MINI-MASS gearbox suitable for a classic turbine shaft installation and a hydraulic shunt transmission.

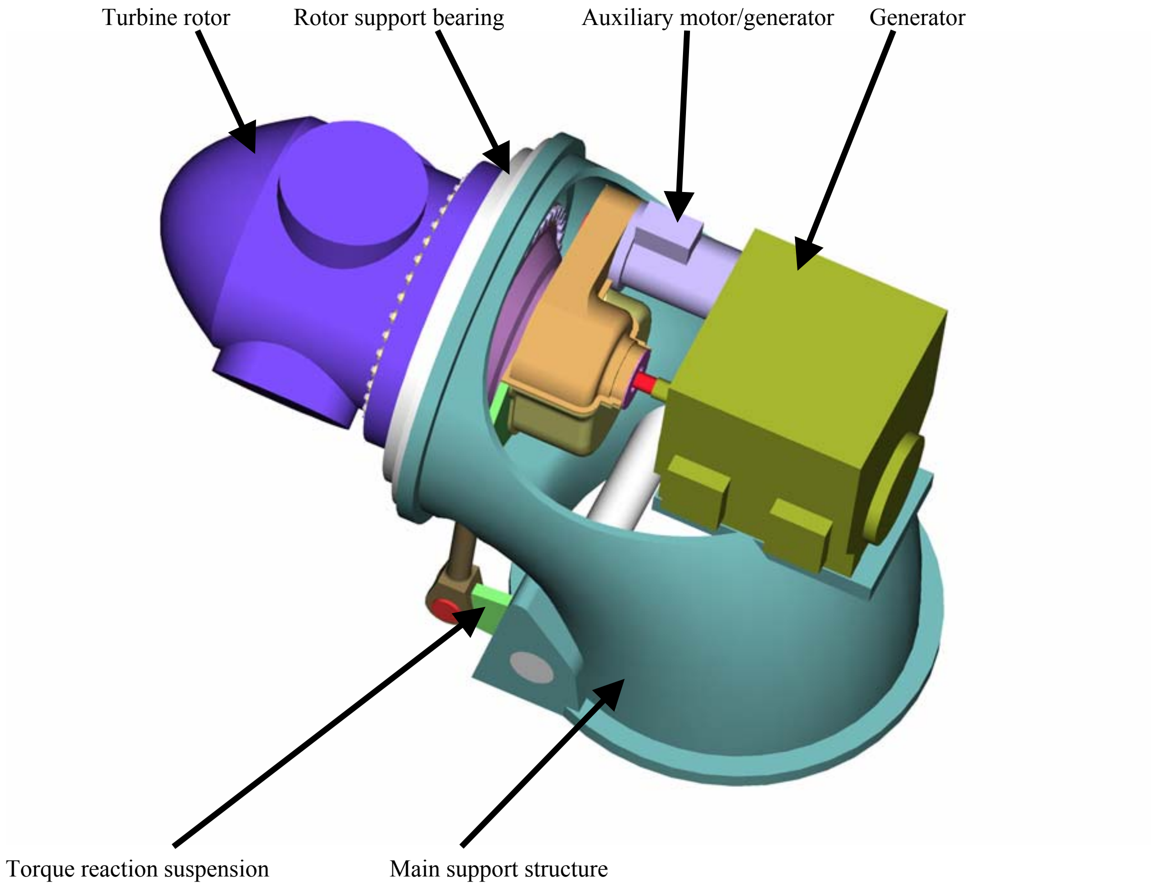

Fig 7 A MINI-MASS gearbox suitable for a twin taper rotor support bearing using an electrical shunt transmission.

OPTIMIZED GEARBOX DESIGN FOR MODERN WIND TURBINES

Optimizes wind turbine gearboxes employs the latest developments in flexible pins with the epicyclic gear train on the first stage employs 8 planet wheels to provide minimum volume gearing with maximum bearing life. A differential gear on the output shaft which can be controlled via a shunt hydraulic or electrical drive provides a mechanism by which the speed of the generator remains constant whilst the speed of the wind turbine varies thus providing torque protection and the use of simple fixed speed generators. Installation of the gearbox is compatible with the new form of twin taper rotor support bearing and this combined with a torque neutral suspension ensures that the gearbox is only subjected to the steady state rotor torque.

Such an OPTIMIZED transmission provides the following advantages.

- Flexible pin technology providing uniform gear tooth, and bearing loading providing high actual bearing life.
- Torque protection of the gear train and rotating elements against wind gusts and grid lockout, resulting in high reliability.

- Considerably reduces the weight of the gear train. 20 tonnes for 3.4 MW 2, meters diameter.
- Allows synchronous or fixed induction generators to be used without full power converters.
- Allows all of the main power electrics and transformers to be placed on the ground further reducing the weight in the nacelle.
- Improves wind energy capture at low speeds by using a more aggressive wind turbine blade pitch and a variable ratio gearbox.

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