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A Preliminary Evaluation of a Multiple-Generator Drivetrain Configuration for Wind Turbines

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A PRELIMINARY EVALUATION OF A MULTIPLE-GENERATOR DRIVETRAIN CONFIGURATION FOR WIND TURBINES*

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ABSTRACT

The recent trend toward large wind turbines has led to very expensive gearboxes that hinder their feasibility. The gearboxes for these wind turbines are more expensive per kilowatt (kW) of rated power than for smaller turbines because the torque increases more quickly than the power when increasing the rotor diameter. Multiple-generator drivetrain configurations can reduce the drivetrain cost for large wind turbines while increasing the energy capture and reliability. The National Renewable Energy Laboratory (NREL) is reexamining the benefits of multiple-generator configurations through the Wind Partnership for Advanced Component Technology (WindPACT) program. This paper qualitatively compares a multiple-generator drivetrain configuration to a conventional drivetrain.

INTRODUCTION

The Problems Associated With Gearboxes

Historically, gearboxes have been problematic for wind turbines. The fluctuating aerodynamic loads are difficult for designers to accurately predict. Thus, designers compensate for unknown loads with large safety factors. In addition, the recent trend toward large turbines has led to very expensive gearboxes. The gearboxes for these wind turbines are more expensive per kW than for smaller turbines because the torque, which is the primary cost driver, increases more quickly than the power for a given increase in rotor diameter. The rotor torque tends to increase as a cube of the rotor diameter while the power only increases with the square of the diameter. This is because large wind turbine rotors operate at slower rotational speeds (to limit aero-acoustic noise) but produce more power.

Gearboxes also require significant maintenance. Most of the larger machines are intended for offshore use where the trend has been toward very low maintenance designs. Some manufacturers have opted to forego the use of gearboxes and manufacture direct-drive machines. However, these machines have a unique set of design and manufacturing challenges. For example, the Enercon E-66/15.66 1.5 MW, wound rotor, direct-drive wind turbine has a 5.3 m generator diameter [1]. These large generators require special construction techniques and present substantial logistical problems.

Recent Multiple-Generator Drivetrain Development

Multiple-generator wind turbines were first manufactured in the early 1990's. NedWind used twin 250 kW generators on its 40 m model and Kenetech used twin generators on its 33M-VS [2]. NREL has begun to reexamine the benefits of multiple-generator configurations through the WindPACT program. The overall objective of the WindPACT program is to develop advanced component concepts that are appropriate for application to utility scale wind turbines.

In February, 2000 NREL issued the WindPACT Advanced Wind Turbine Drivetrain Designs request for proposal in which the multiple-generator drivetrain was described as a concept to evaluate [3]. Global Energy Concepts LLC and Northern Power Systems were both awarded WindPACT subcontracts to investigate advanced wind turbine drivetrains. Both companies developed the idea independent of NREL's internal studies. Recently, a patent concerning multiple generators was issued to Dehlsen Associates LLC who has been independently developing the idea [4].

This report qualitatively evaluates one of the more promising drivetrain embodiments resulting from NREL's internal studies. The WindPACT subcontractor drivetrain reports are forthcoming.

Split-Power Drivetrain Configurations

The first stage makes up the majority of the gearbox cost due to its large size. Most large wind turbines use planetary gear sets or split-power arrangements to provide multiple power paths from the first stage gear, thereby reducing the size of the gear.

The planetary arrangement uses multiple (usually three) planetary gears to transfer the power from the planetary carrier to the sun gear. Although more planets are desirable for load sharing purposes, increasing the number of planets requires higher precision gears and increases the risk of uneven load distribution among the planets.

A simpler gear configuration is the split-power arrangement portrayed in Figures 1 and 2. In this parallel-shaft arrangement, the gear power is distributed among several pinions that are attached directly to medium speed generators.

There are several variations of the parallel shaft, multiple-generator arrangement. One variation entails placing generators on either side of the gearbox and staggering the pinions so that more pinions can be used. Another variation attaches a second gear stage to each pinion and connects the outputs of the secondary stages to the generators. Optionally, pairs of pinions can be used to transfer the power to the second stage in a split-power arrangement to increase the number of pinions.

Another advantage of the parallel shaft arrangement is the ability to incorporate multiple generators. There are several reasons why multiple generators are desirable. NedWind used twin generators to distribute the load among several pinions and to facilitate two-speed rotor operation. This allowed the machines to achieve a higher aerodynamic efficiency than constant speed machines at only a moderate cost increase.

Induction generators can obtain further benefits from multiple-generator configurations. Induction generators operate more efficiently at full load. A multiple-generator wind turbine can operate each induction generator at full load by switching them on individually. Some designers also believe that producing multiple small generators rather than one large generator facilitates mass production.

COMPARISON TO A CONVENTIONAL DRIVETRAIN

The multiple-generator drivetrain configuration has many benefits compared to a conventionally designed turbine. A conventional drivetrain is shown in Figure 3. A conventional drivetrain for an upwind, three-bladed wind turbine consists of a spherical hub connected to the low speed shaft (LSS). The LSS is supported by a three-point-suspension arrangement. Upwind, the shaft is supported by a double spherical roller bearing. The double spherical roller bearing is a locating bearing that resists the rotor thrust loads and the LSS radial loads. A locating bearing is a bearing that locates the rotating part axially relative to the stationary part of the machine. Downwind, the shaft is supported by a pair of tapered roller bearings (which are also locating bearings) incorporated into the gearbox.

The gearbox is supported by a pair of bushings lined with elastomers that allow the gearbox to translate along the LSS axis, permitting thermal expansion of the LSS. The bushings also allow the gearbox to rotate enough to accommodate LSS flexing, and they damp gearbox noise.

The gearbox of most large machines consists of a planetary first stage and two parallel-shaft stages. Although this arrangement is more than 50% heavier than three planetary stages [5], it provides centerline access to the end of the LSS for sliprings. In addition the helical stages are flexible for gear ratio adjustments [6].

Figures 1 and 2 present one embodiment of a multiple-generator drivetrain configuration. This configuration consists of six pinions, each coupled to a medium speed, permanent magnet (PM) generator. The bedplate has been replaced with the maintube, and the LSS has been replaced with a spindle that supports the hub on both ends using bearings. I have grouped the merits of this configuration into three categories relating to the gearbox, generator, and towerhead components. The merits are described below.

Gearbox

Advantages:

1) Reduced Gearbox Mass and Cost
Preliminary estimates indicate that a single-stage, multiple-generator gearbox will weigh up to 80% less than a conventional three-stage planetary gearbox.

There are several reasons for this low weight. In addition to having only one stage, the configuration shown in Figure 2 has twice as many pinions contacting the gear as does a conventional planetary arrangement. On this basis, the gear mass should be less than half that of the planetary stage. In addition, the multiple-generator configuration does not have the added mass of a planetary carrier. Furthermore, the surrounding housing for the multiple-generator concept is lighter than a three-point-suspension because the single-stage gearbox housing is not used to support the LSS.

Determining the optimum number of pinions and the gear diameter is a constrained optimization problem. The number of pinions, pinion diameter, gear face width, gear diameter, and generator diameter are all interdependent. In general, a small diameter gear with a wide face will result in the most affordable gearbox. However, the gear diameter must be large enough to prevent the generators from interfering with the spindle and with each other. Preliminary WindPACT sizing studies indicate that the number of pinions for the minimum drivetrain cost is between six and twelve for a 1.5 MW turbine.

2) High Gear Ratios

Another benefit of the multiple-generator assembly is that higher gear ratios can be obtained compared to a single planetary stage. The increased gear ratio benefits the medium speed, PM generators if they are adequately cooled (torque limited rather than power limited). An adequately cooled PM generator will generate higher voltages at faster speeds, thereby increasing the power density of the design.

Preliminary WindPACT designs indicate that gear ratios of about 15:1 are possible for the first stage of a multiple-generator design. In contrast, planetary gear ratios are typically about 7:1 for each stage. Higher gear ratios are possible because the narrow face width permits small diameter pinions. The pinion diameter is determined by the gear face width and the recommended aspect ratio (the face-to-diameter ratio), which is an indicator of a gear's sensitivity to misalignment. According to American Gear Manufacturers Association specifications, the aspect ratio of spur or helical pinions should be less than 1.0 to achieve good load distribution on the pinion [7].

3) Low Frequency Noise Emissions

The single-stage gearbox may also have a significant noise advantage over a three-stage gearbox. The noise emitted by a single-stage gearbox on a 1.5 MW machine will be at a relatively low frequency. For example, a 1.5 MW machine with a rotor rotation speed of 20 revolutions per minute (RPM) and a 15:1 single-stage gearbox has pinions that rotate at 300 RPM. If there are 20 teeth on each pinion, the gear mesh frequency will be 6,000 cycles per minute, or 100 Hz. In perspective, the human ear is most sensitive between 500 Hz and 4,000 Hz.

4) Increased Gearbox Efficiency

A single-stage gearbox also has an efficiency advantage compared to a conventional gearbox. Gearbox losses on wind turbines are due primarily to tooth contact losses and viscous oil losses. Tooth contact losses for a conventional gearbox, although small for most gearboxes (approximately one-half percent per stage at rated power), will be higher than a single-stage gearbox because of the extra stages. Viscous losses will also be higher for a conventional design because of the high speed churning in the second and third stages. In general, the churning losses are difficult to predict. However, a simple approximation of gearbox efficiency can be obtained by neglecting the tooth losses and assuming that the viscous losses are constant (a fixed percentage of the rated power). A viscous loss of 1% of rated power per stage is a reasonable assumption. Thus the efficiency of a gearbox with "q" stages can be computed using Equation (1) [8]. The resulting efficiencies for gearboxes with different numbers of stages are presented in Figure 4.

$$\eta = \frac{Power_{Out\ of\ gearbox}}{Power_{Into\ gearbox}} = \frac{Power_{Into\ gearbox} - q \times .01 \times Power_{rated}}{Power_{Into\ gearbox}} \qquad (1)$$

6) Increased Gearbox Reliability

The multiple-generator gearbox may also have a reliability advantage. Although the bearing count and gear count for a conventional three-stage gearbox and the single-stage, multiple-generator concept are similar, the multiple-generator gearbox is a much simpler design and has many identical parts. Furthermore, the pinions and pinion bearings are easily accessed and can be replaced in the field.

Another reliability advantage is that the multiple generator configuration does not require a high speed shaft coupling as does a conventional drivetrain. Instead, the generator rotor is mounted directly on the pinion shaft.

Disadvantages:

1) Large Diameter Seal
Lubricating the bearings and gears with oil rather than grease is necessary for an adequate life. The configuration presented in Figure 2 has been designed so that all bearings and gears are lubricated using the same oil lubrication system. Oil leakage may be the primary challenge in many of the multiple-generator configurations. Preventing oil from leaking through the relatively large diameter joint between the hub and gearbox housing (as drawn it has a 1.1 m diameter) may be problematic. Lip seals are inadequate because they require frequent replacement, and the location of the seal requires that the hub be removed from the spindle to replace it. Thus, either a long life mechanical seal or a labyrinth seal will be required. However, it may be difficult to economically manufacture these seals in large diameters.

2) Limited Noise Damping
Although the previous section described noise as an advantage, noise may be a disadvantage instead. Unlike conventional three-point-suspension drivetrains, the multiple-generator configuration shown in Figure 2 does not facilitate placing elastomers between the mainframe and the gearbox because the gearbox housing is pressed onto the spindle to maintain alignment between the gear and pinions. Although the noise from the multiple-generator configuration is low frequency (approximately 100 Hz), it is difficult to prevent the noise from transmitting and resonating through the spindle and tower.

3) Gear Diameter
The gear shown in Figure 2 has a diameter of 1.8 m. Carburizing ovens capable of accommodating gears with diameters larger than 1.5 m are not widely available. This scarcity causes a steep increase in gear manufacturing cost [6].

Generator and Power Electronics

Advantages:

1) Low Cost Generators
Preliminary results from the WindPACT Advanced Drivetrain Study indicate that the PM generators for the single-stage, multiple-generator configuration will cost about the same as the induction generators for a two-stage gearbox. The WindPACT results also indicate that these generators will cost about 12% less than a single PM generator connected to single-stage gearbox and 29% less than a single high speed, doubly fed generator [9]. The reasons for the low PM generator cost can be attributed to recent advances in PM sintering technologies and to the efficient “pancake” generator shape. In addition, the narrow face width of the generator allows the generator rotor to be mounted directly on the end of the pinion without endbells or generator bearings.

2) Increased Generator Reliability
A PM generator should be more reliable than a doubly fed generator because a doubly fed generator uses slip rings to transfer power to and from its rotor. Slip rings are subject to wear and require occasional inspection and maintenance. However, multiple PM generators will likely be less reliable than a single large PM generator because adding generators increases the likelihood that a generator failure will occur.

3) Direct Current Output
The multiple-generator power processing method is still being studied. However, it might be possible to use bridge doublers in the nacelle to full wave rectify the PM generator output to generate a direct current (DC) with a voltage as high as 2.828 times the generator RMS voltage. Sending this higher voltage down the tower would reduce the mass of the tower wires without increasing the generator voltage. In addition, direct current does not suffer from skin effect, which is the tendency of an alternating current to flow on the outer surface of a conductor.

Another possible advantage of the multiple-generator design is a reduction in the capacitor costs. Since each generator is indexed to the gear, it may be possible to reduce the DC ripple to the inverter by staggering the outputs between generators. Since DC ripple is typically reduced by using larger capacitors, this would significantly reduce the size of the required capacitors.

Disadvantages:

1) Power Electronics Cost
The power electronics cost is still a large source of uncertainty for the multiple-generator PM concept. It’s possible that the torque/voltage relationship will vary significantly between generators. This could result in the generators applying different loads on the pinions. If an inexpensive control scheme cannot be arranged, it is possible that the power electronics cost will negate many of the other cost benefits of the multiple-generator configuration. The WindPACT drivetrain groups are still investigating the power electronics costs and control schemes.

Tower Head Components

Advantages

1) Reduced Support Structure Costs
The multiple-generator design facilitates a tubular support structure (maintube) and a spindle type hub. In contrast to the channel-shaped mainframe of a conventional machine, the tubular, thin-walled maintube is a stiff and efficient means of transferring the loads from the rotor to the yaw bearing. In addition, a conventional drivetrain requires a separate support structure for the generator. This generator support structure is not necessary for the multiple-generator configuration because the generators are supported by the gearbox. For these reasons, the maintube will likely be significantly less costly than a conventional mainframe.

2) Reduced Hub Mass
The spindle hub should be less costly than a conventional cantilevered hub. A spindle hub can be roughly modeled as a beam simply-supported at each end. A cantilevered hub can be modeled as a beam rigidly supported by the LSS. The theoretical maximum bending moment of a simply supported beam due to a moment load applied at the center is half that of the cantilevered beam. Furthermore, this peak moment occurs at the center of the beam (where the hub diameter tends to be greatest) rather than at the cantilever support. Thus, on a first-principle basis, a spindle hub should be roughly half the mass of a cantilevered hub. A preliminary finite element analysis indicates that a spindle hub will weigh approximately 35% less than a conventional cantilevered hub.

3) Reduced LSS Mass
There is no LSS per se in Figure 2. The functions of the LSS to transfer torque from the rotor to the gear and to support the hub are now performed by the hub and the spindle. The spindle and a conventional LSS are roughly the same length and are subject to similar loads. On this basis, they should weigh about the same. However, the spindle is subject to a static gravity load rather than a cyclic (1P) gravity load from the rotor mass. Thus, the spindle mass is likely to be driven by stiffness or peak load requirements rather than fatigue requirements. This is likely to result in significant mass savings.

4) Easier Assembly, Transportation, and Erection
The cargo weight of a standard tractor-trailer is 19,000 kg (42,000 lb). Cargo above this limit necessitates overweight permits and becomes more difficult to transport [10]. One option to remain under this limit is to remove the gearbox and generator from the mainframe for shipment. Because the gearbox, hub, and spindle should be significantly lighter than that of a conventional machine, they would likely be assembled at the manufacturing facility and shipped as a unit. In the field, the blades would be attached to the hub. The assembly would then be lifted onto the tower and fastened to the main tube. Because shop assembly is more efficient than field assembly, the assembly costs for the drivetrain should be reduced.

5) Additional Tower Clearance
The trend for large turbines has been toward short, compact drivetrains to reduce the mainframe and LSS mass. However, in order to maintain sufficient tower clearance, the blades have to be stiffer or the nacelle tilt has to be increased. The spindle arrangement and the lightweight drivetrain may facilitate an inexpensive means of increasing tower clearance. An inexpensive rolled section could be inserted between the maintube and the spindle at the flange (see Figure 2). The increased tower clearance would allow lighter, more flexible, blades to be used. However, the increased rotor overhang will increase some of the loads. A detailed loads and cost analysis will have to be performed to determine the feasibility of this arrangement.

6) Amenable to Site Specific Design
Wind turbine manufacturers commonly offer more than one blade length for a wind turbine model to tailor the turbine to a given wind regime. For a slow wind speed site, longer blades are installed to produce more power when operating in slower winds. However, altering the blade length can significantly affect the rotor efficiency and loads.

An alternative approach to changing the blade length is to reduce the cost of the turbine by reducing the turbine power rating. This de-rating can be achieved by reducing the drivetrain and power electronics capacities and the strength of components such as the tower and blade spars. This approach is desirable because it may eliminate or mitigate the need for changing the blade length.

The multiple-generator configuration offers a way to de-rate the drivetrain without significant gearbox or generator changes. For example, one of the six generators and pinions could be removed from the drivetrain in Figure 2 to reduce the drivetrain capacity by 17%. Accordingly, the power electronics capacity, tower, and possibly the blade spar wall thicknesses would be reduced to minimize the turbine cost.

Disadvantages

1) Blade Pitch System Location
Unlike a conventional cantilevered hub, the interior of the spindle hub is not accessible (see Figures 2 and 3). In a conventional hub, the actuators and power supply are located inside the hub. For a spindle hub, the blade pitch actuators and backup power supply must be located on the exterior of the hub as shown in Figure 1. Although these components are located within the spinner, they have less protection from the elements than a conventional hub offers.

CONCLUSIONS

The multiple-generator drivetrain configuration considered in this paper appears to have significant cost reduction potential resulting from increased energy capture, simplified assembly, increased reliability, and reduced mass. However, several aspects require further investigation. Of primary concern is the cost of the power processing method. Drivetrain noise emissions are also a concern since the design does not facilitate damping. Sealing the gearbox and bearings may also prove challenging due to the relatively large diameter seal required between the hub and the gearbox. The WindPACT advanced drivetrain subcontracts will provide a means to investigate these issues further.

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FIGURES

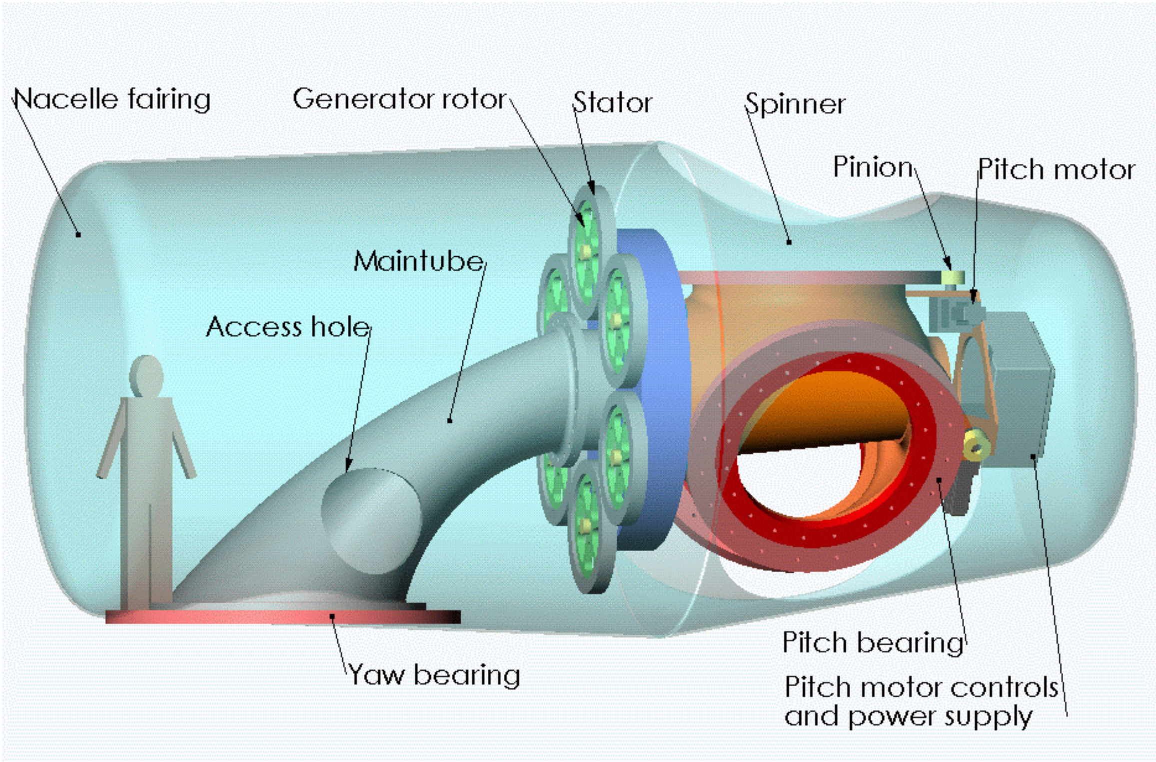

Figure 1: 1.5 MW multiple-generator drivetrain configuration.

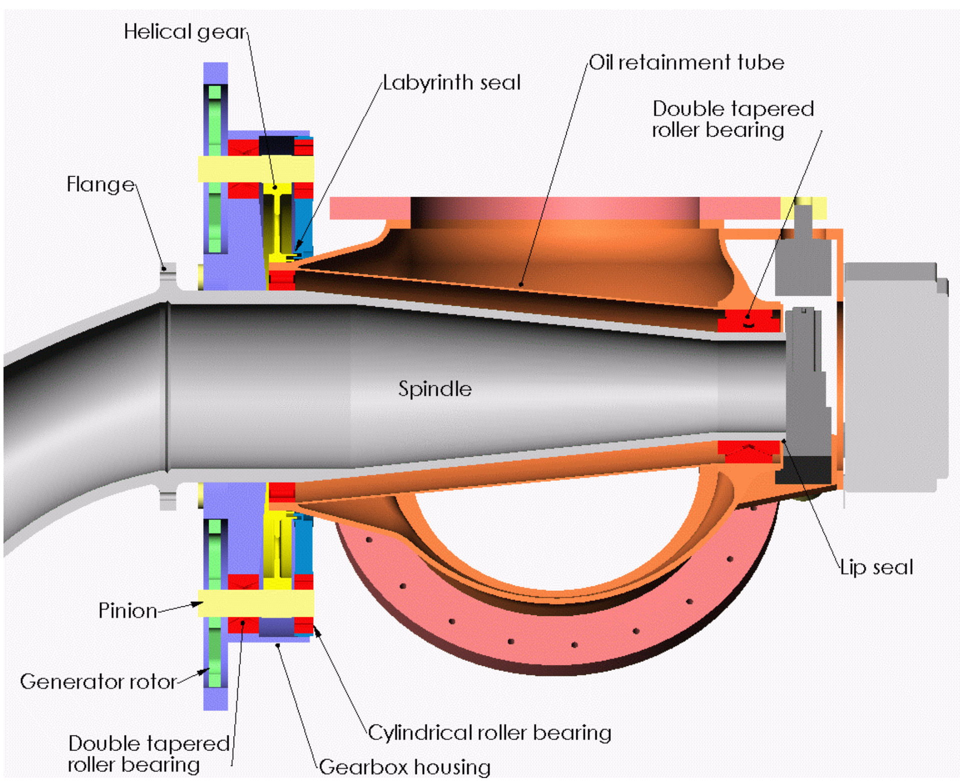

Figure 2: Section view of the multiple-generator drivetrain.

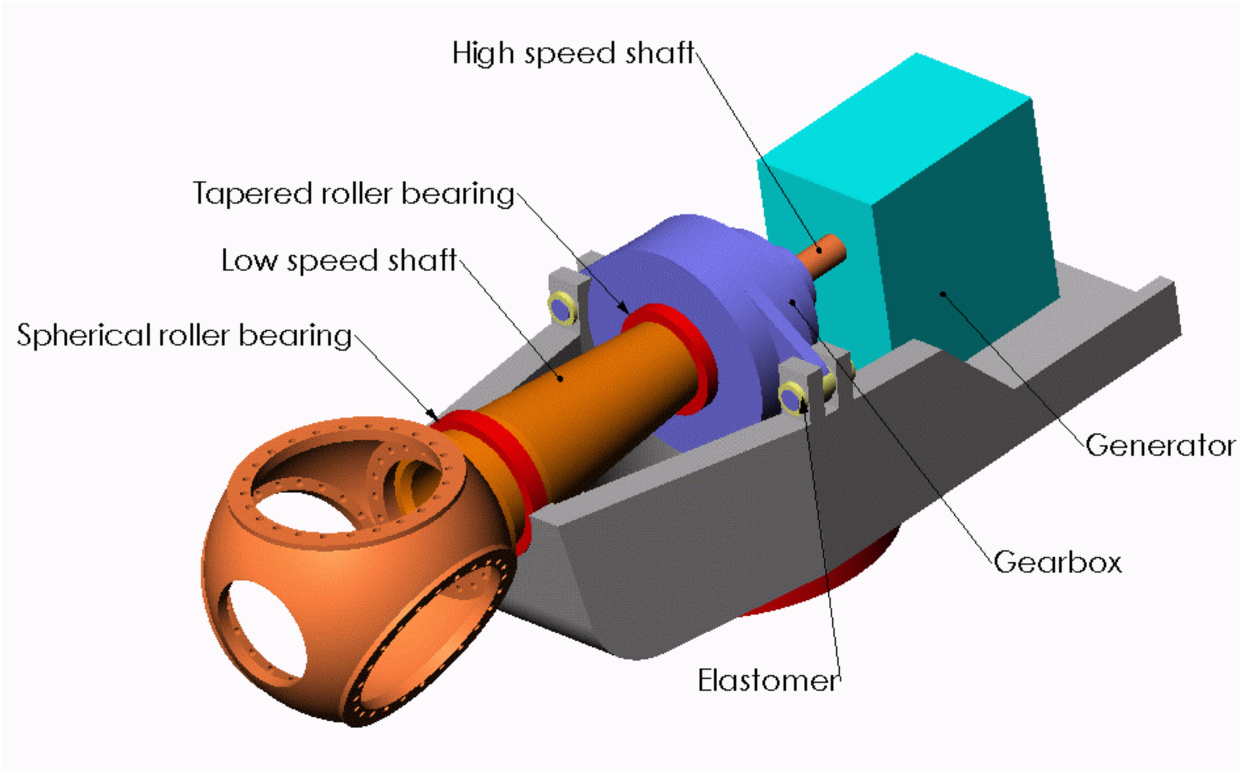

Figure 3: Conventional wind turbine drivetrain.

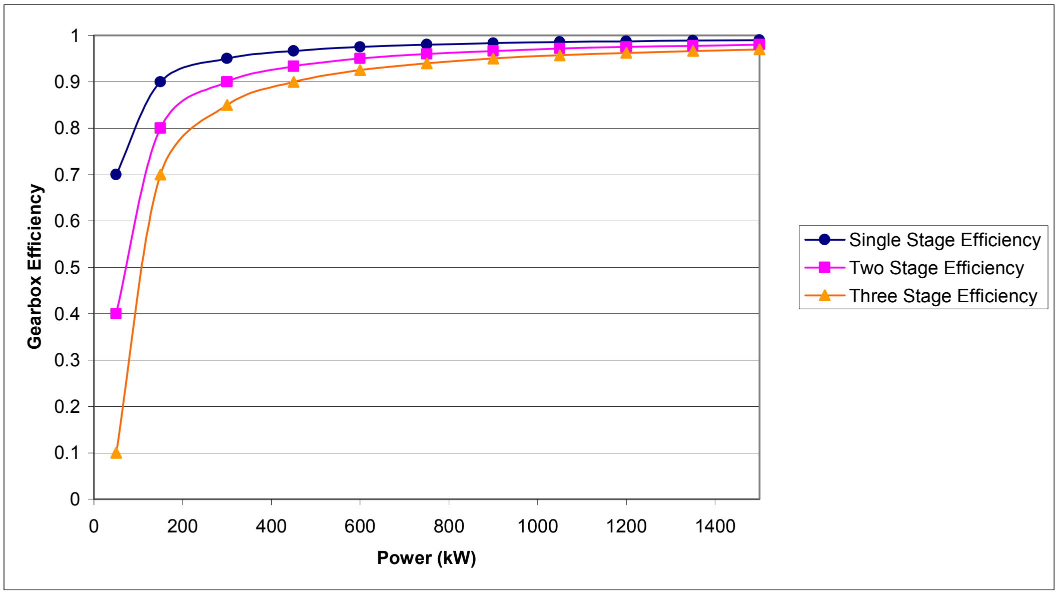

Figure 4: Theoretical gearbox efficiency estimate for a 1500 kW wind turbine.

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