Techno-Economic Comparison of Operational Aspects for Direct Drive and Gearbox-Driven Wind Turbines

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***Abstract*—The majority of wind turbines currently in operation have the conventional Danish concept design—that is, the three-bladed rotor of such turbines is indirectly coupled with an electrical generator via a gearbox. Recent technological developments have enabled direct drive wind turbines to become economically feasible. Potentially, direct drive wind turbines may enjoy higher levels of availability due to the removal of the gearbox from the design. However, this is only a theory: so far not substantiated by detailed analytic calculation. By providing such a calculation, this paper enables us to quantitatively evaluate technical and economic merits of direct drive and gearbox-driven wind turbines.** Q1

***Index Terms*—Markov chain, operational comparison, reliability, wind turbines.**

I. Introduction

WORLDWIDE installed capacity of wind generation is growing significantly and is likely to continue to increase in the future. The twin policy objectives of energy security and climate change mitigation have resulted in economic incentives, which in turn, have driven investment in wind energy. Taking the U.K. as an example, Fig. 1 shows how the installed capacity has grown since 2005—by the end of 2008, the installed capacity broke through the 3 GW barrier [1]. This 3 GW capacity consists of 2276 individual wind turbines (WTs) [2], the vast majority of which are conventional Danish concept, gearbox-driven machines. However, recent technical strides have enabled direct drive machines to become economically feasible.

Since a gearbox is not included in the direct drive concept, it is clear that the reliability and availability of the WT will improve—if it can be assumed that all other factors remain unchanged. On the other hand, it has been reported in the paper that failure rates of electrical components and generators of direct drive wind turbines are significantly higher than those of gearbox-driven equivalents [3], [4]. The purpose of this paper is to establish if there is a technical and/ or economic advantage in deploying direct drive wind turbines instead of gearbox-driven machines. This analysis is based on quantitative modeling of the operation, failure, and maintenance of wind turbine units as proposed in [5]. Such an operational comparison of different wind turbine concepts is not available in the existing literature.

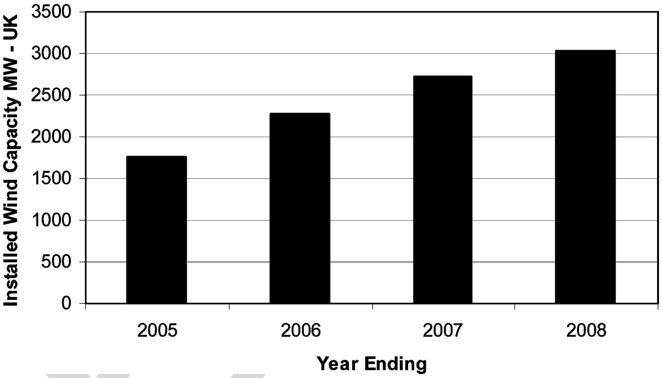

Fig. 1. Recent growth in U.K. wind generation capacity [2].

II. Comparison of Concepts

A. Conventional Danish Concept—Gearbox Driven

The conventional Danish concept comprises a three-bladed upwind rotor, which revolves on the horizontal axis (sometimes called horizontal axis wind turbine, HAWT). The coupling between rotor and electrical generator is indirect and is achieved via a gearbox in order to increase the rotational speed to a level that can drive a relatively small-diameter, lightweight induction generator. A conceptual view of the energy conversion process for such a typical modern wind turbine is outlined in Fig. 2.

The whole wind turbine assembly rotates into the prevalent wind direction on its vertical axis by means of an electromechanical yaw system. Once facing into the wind, control of the mechanical input power is achieved either by aerodynamic design of the rotor (stall control) or by actively changing the angle of attack of the rotor blades to the wind (pitch control) via electrical motors or hydraulics.

The electrical configuration of Danish concept WTs is influenced by mechanical aspects, as one main objective of the WT mechanical design is to minimize the weight at the top of the tower, where the nacelle (containing the generator) is located in modern HAWTs. This means the generator has to be as light as possible and must have a relatively small physical footprint. For this reason, induction generators are employed: induction generators have the added advantage of being more robust than

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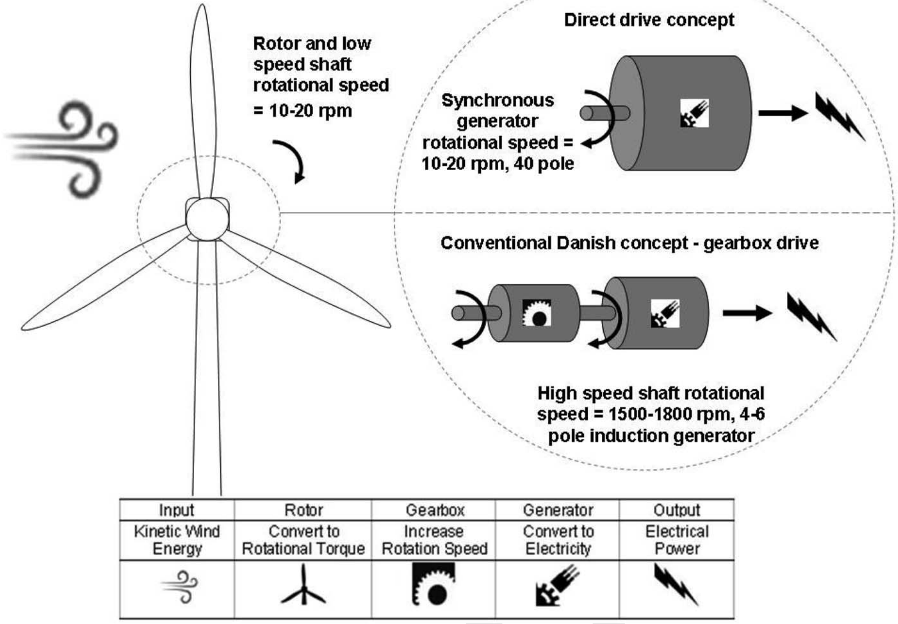

Fig. 2. Process diagram for gearbox-driven and direct drive wind turbines.

synchronous generators and tend to have fewer electrical faults. However, due to the low rotational speed of the wind turbine rotor, a gearbox has to be used to increase the rotation from tens of revolutions per minute at the gearbox input to thousands at the output. The primary reason for this is the low number of induction generator poles.

The older Danish concept WTs that operated at fixed speed employed squirrel cage induction generators; however, newer variable speed technology has resulted in a switch to doubly fed induction generators (DFIG), which are now the dominant wind turbine generator configuration. The reason for the dominance of this configuration is that it represents a good compromise between economy and performance. It is relatively economic because it has only a partial electronic converter rated at ∼30% of the generator output [6], not a full converter.

B. Direct Drive Concept

In a direct drive WT, the main rotor is coupled to the generator input shaft, eliminating the need for a gearbox in the design. In order to generate power at such a low rotation speed, the generator has to have many pole pairs, and usually a synchronous generator is employed. This implies much greater dimensions and weight as compared with an induction generator. In addition, a fully rated electronic power converter is required, which increases the cost of the system.

C. Types of Comparison

There are several examples in the published literature where a comparison is made between the two concepts. For example, Tavner *et al.* [3] focused on how the configuration of the WT generator and converter in different design concepts affected overall WT reliability. The data utilized by the authors had enough detail to enable a direct reliability comparison of three WT concepts: fixed speed with gearbox, variable speed with gearbox, and variable speed direct drive (no gearbox: synchronous generator). The main conclusion was that direct drive systems are less reliable than models with a gearbox because the potential increase in reliability due to elimination of gearbox failures is cancelled out by increased generator, inverter, and electrical system failures.

Interestingly, the authors recognized that overall availability would also be affected by component repair times: In this sense direct drive systems may have an advantage, as mean time to repair (MTTR) for a gearbox is likely to be very much more than MTTR for an electronics subassembly. As yet, no other research has addressed this operational comparison of the two concepts.

Echavarria *et al.* [4] analyzed a similar dataset, which provides some highly relevant information regarding the reliability of the two WT concepts. In particular, the data suggest that generator failures in direct drive WTs are roughly two times the gearbox-driven equivalent (0.22 failures per annum compared with 0.12 suggested by Tavner *et al.* [7]). Similarly, power electronics failures in direct drive synchronous machines are quantified as 1.03 failures per annum compared to 0.661 suggested in [7] for the induction machine equivalent.

Polinder *et al.* [6] examine direct drive and gearbox-driven WT concepts from the viewpoint of design and economic performance. The authors define a typical Danish concept WT with a three-stage gearbox (3GDFIG) and a direct drive machine coupled to a synchronous generator (DDSG). Three other concepts are also defined (DFIG with a single-stage gearbox, permanent magnet direct drive, and permanent magnet single-stage gearbox) but these are not considered in this paper due to the fact that they are not currently deployed in significant numbers.

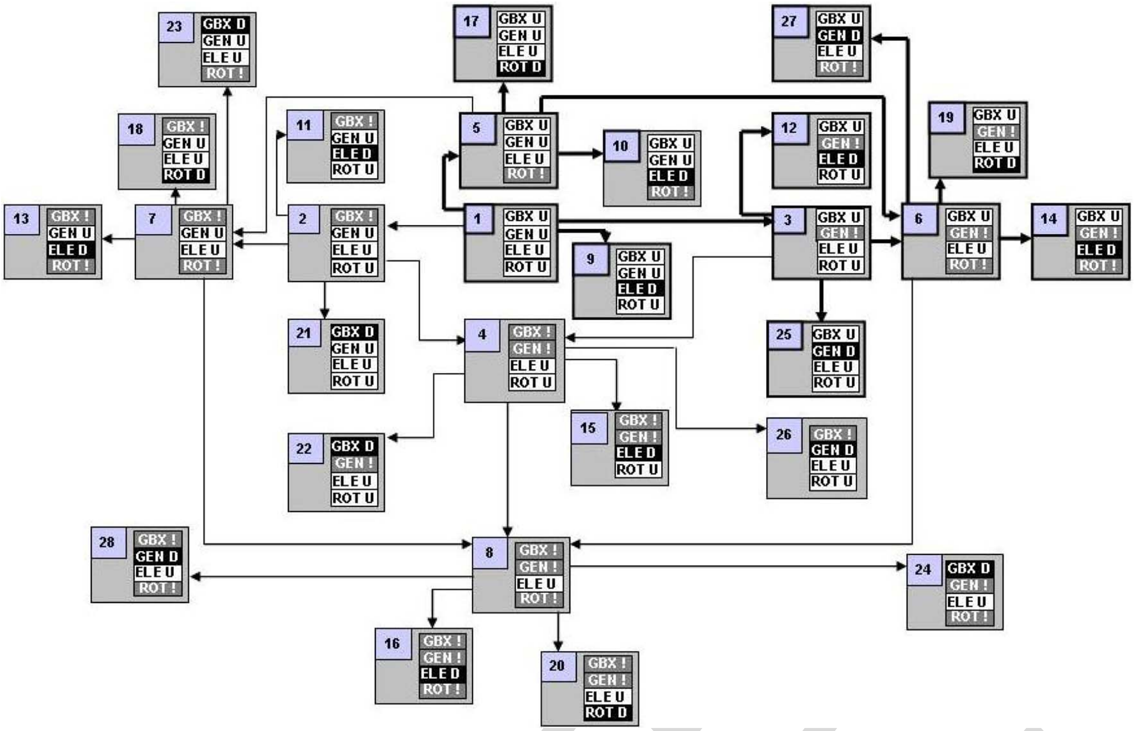

Fig. 3. Markov chain of key wind turbine components. Bold arrows and boxes indicate direct drive system.

The authors again highlight the need for further work to better understand the reliability and availability benefits of adopting different WT design concepts—a requirement which this paper aims to meet.

III. MODELING OF WIND TURBINE CONCEPTS

A. Physical Modeling of Wind Turbine Components

In order to build an accurate operational model, the key physical components of the WT must be identified and a suitable mathematical representation decided upon. It was reported in [5] that using a combination of failure rate data, downtime estimates, and expert opinion, the key components of a gearbox-driven WT could be identified as follows:

1) gearbox (GBX);
2) generator (GEN);
3) rotor blades (ROT); and
4) inverter, electronics, and control (ELE).

In terms of the mathematical representation, a Markov chain solved via Monte Carlo simulation (MCS) was identified in previous studies as a suitable model framework [5]. The Markov chain representation has been very successfully applied to power systems infrastructure deterioration and failure modeling, including wind turbines [8], [9]. The main problem with these analytically solved models is that the introduction of constraints, such as weather-constrained maintenance, makes obtaining a solution rather difficult. Although not computationally efficient, MCS methods overcome this difficulty and have been applied to similar problems in the past [10], [11]. Since the problem considered is essentially a planning problem, the time required to get the solution is of little importance.

It has been assumed that three states are sufficient to capture the deterioration and failure processes of the GBX, GEN, and ROT. ELE failures are assumed to be instantaneous and, therefore, require only binary representation. When all four components are modeled in a single Markov state-space, the total number of states is 54. This is cut down to 28 by assuming that degradation and failure events of different WT components cannot happen concurrently. Furthermore, for a GBX, GEN, or ROT failure to occur, the system must transit through the deteriorated (intermediate) state before outright failure.

The possible Markov states and transitions for the overall WT system are visualized in Fig. 3. The three possible deterioration levels are indicated as fully up (U), deteriorated (!), and down (D).

All 28 states and transitions are possible for the case of gearbox-driven WTs. The obvious physical difference when modeling a direct drive WT is that there are no gearbox states. Thus, the bold arrows in Fig. 3 refer to the transitions and states that represent direct drive WTs, as a 12-state subset.

The arrows in Fig. 3 represent transition probabilities (e.g., probability of transition from state *a* to state *b* is $p_{a,b}$), whose magnitude must be estimated. These probabilities depend only on the current state of the system (s) at current time t_k. Equation 1 expresses this "memory-less" property of a Markov chain

$$p_{a,b} = p(s_b, t_{k+1} | s_a, t_k) \qquad k = 1, 2, 3, \ldots . \qquad (1)$$

Furthermore, the transition probabilities are constant in time: This is the "time-stationary" property. The magnitude of all transition probabilities from one state (a) to all others in the

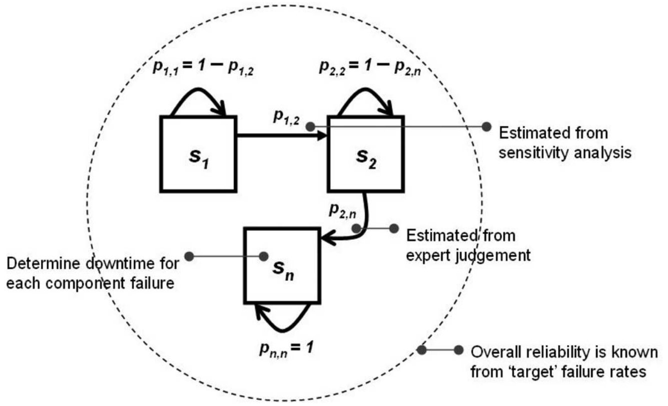

Fig. 4. Parameter estimation for Markov chain.

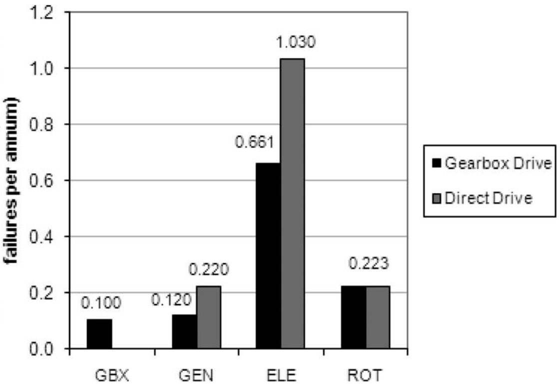

Fig. 5. Reliability for gearbox-driven and direct drive wind turbines.

system must sum to unity. This is shown in (2)

$$\sum_b p_{a,b} = 1 \qquad a = 1 \ldots n \tag{2}$$

where *n* is the total number of system states. For convenience, the transition probabilities for the whole system are expressed in a transition probability matrix (TPM). For the case of the system in Fig. 3, the TPM is shown in (3). Note that only the possible transitions (indicated in Fig. 3. with arrows) need to be estimated—all other probabilities are equal to zero

$$\mathrm{TPM} = \begin{bmatrix} p_{1,1} & p_{1,2} & . & p_{1,28} \\ p_{2,1} & p_{2,2} & . & . \\ . & . & . & . \\ p_{28,1} & . & . & p_{28,28} \end{bmatrix}. \tag{3}$$

The TPM values are estimated based on the partial information available, as illustrated in Fig. 4. A good estimate of the overall reliability ("target" failure rate) is known from the work of Tavner *et al.* [7].

Similarly, downtime estimates can be made for the outage of the key components [5]. The probability of an outright failure in a deteriorated condition ($p_{2,n}$) can be estimated based on expert opinion of times to failure. The remaining parameters can then be estimated by conducting sensitivity analyses (previously reported in [5]).

B. Data for Physical Model

The study of Tavner *et al.* [7] provided estimates of component failure rates based on populations of Danish and German WTs. The German population was larger (over 4,000 machines) and the population consisted of more modern WTs. Therefore, the German figures are used to fit the gearbox-drive WT physical model.

On the other hand, Echavarria *et al.* [4] suggest modifications to the GEN and ELE failure rates for direct drive machines. Taking this into account, the target failure rates for both WT concepts can be visualized in Fig. 5.

Downtimes for the failure types are as follows: GBX—30 days, GEN—21 days, ELE—1 day, and ROT—30 days. They are based on domain knowledge elicited in [5]. Using this information, the TPM parameters were estimated based on the iterative procedure devised in [5]. The procedure is based on sensitivity analysis estimation of the unknown parameter $p_{1,2}$ (see Fig. 4).

The Markov chain has been defined for both gearbox-driven and direct drive concepts. In the following sections, other aspects of operational modeling—which are common to both concepts—are discussed.

C. Energy Yield Modeling

There are two main components to the energy yield model. These are the wind speed model and the power curve model. The wind speed (WS) model previously used by the authors [5] was based on a single parameter autoregressive process, or AR(1). This is displayed in (4), where μ is the mean of a wind speed time series, ϕ is the autoregressive parameter and the process is driven by a Gaussian white noise function ε_t.

$$\mathrm{WS}_t - \mu = \phi\,(\mathrm{WS}_{t-1} - \mu) + \varepsilon_t\,. \tag{4}$$

The dataset used to fit the model was sourced from a supervisory control and data acquisition (SCADA) system of a U.K. wind farm. Estimation of ϕ and ε_t was achieved by linear least squares, while classification of the model was based on inspection of the autocorrelation and partial-autocorrelation functions.

The power curve model is based on a manufacturers' datasheet for a 2 MW WT [12], which is sampled and the theoretical equation for the power (*P*) in the wind (5) is matched to the data samples by modeling the coefficient of performance C_p

$$P = \frac{1}{2}\rho\pi r^2 v^3(\times C_p). \tag{5}$$

In (5), ρ is air density (kg/m^3), *r* is the rotor radius (m), and *v* is air velocity through the WT rotor (m/s). The re-created power curve is shown in Fig. 6 and has cut in, rated, and cut out wind speeds of 4, 14, and 25 m/s, respectively. It is assumed that both WT concepts adhere to the same power curve.

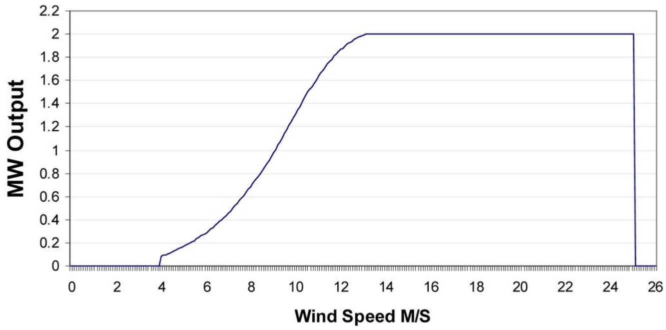

Fig. 6. Power curve for 2 MW wind turbine [12].

D. Maintenance Modeling

It is assumed that a six-monthly periodic maintenance plan is adopted for both WT concepts. The assumptions in the maintenance model are that maintenance actions restore the WT to the fully up state (state 1 in Fig. 3) and that each maintenance visit involves a one-day outage. The model can easily accommodate condition-based maintenance (CBM), but since maintenance paradigms are not the focus of this paper, this possibility is neglected.

If a component failure occurs, a maintenance team is dispatched immediately. There is a probability that a component replacement is necessary (replacement factor $\beta = 0.6$) or that it can be repaired ($1-\beta = 0.4$). This is based on an analysis by Ribrant and Bertling [13] who highlighted that around 60% of gearbox failures require a replacement rather than a repair action. Similar figures have not been published for the other WT components; therefore, due to the lack of data, they are assumed to have the same probabilities of repair and replacement as the gearbox.

If the component can be repaired, it is restored instantaneously to a functional state. If a replacement is required, downtime lasts as follows: GBX–30 days, GEN—21 days, ELE—1 day, and ROT—30 days. This is based on the experience of a wind farm operator. Furthermore, maintenance actions are constrained by wind speed as in [5]. This means that nacelle-related replacements need wind speed conditions of less than 10 m/s, while rotor maintenance cannot be conducted in wind speeds over 7 m/s.

E. Costs and Revenue

It is of interest to compare the economic merits of the two WT configurations. Therefore, a cost model has been built which generates revenue from energy yield and incurs maintenance and replacement costs.

Polinder *et al.* provided costs for gearbox-driven and direct drive wind turbine components rated at 3 MW [6]. Figures can be derived for 2 MW machines of both types assuming that the cost varies linearly with the rating. These costs are provided in Table I. The rotor cost was not provided in [6] and so the value derived previously by the authors of this paper is adopted [5]. In the case of a component replacement, the full cost in Table I is incurred. In the case of a repair, it is assumed that only 10% of this cost is incurred (repair cost factor $\alpha = 0.1$).

TABLE I
COMPONENT COSTS FOR WIND TURBINE CONCEPTS

Component	Gearbox driven	Direct drive
	Cost £	
GBX	121,733	N/A
GEN	177,066	313,740
ROT	210,000	210,000
ELE	22,133	66,400

Besides the costs of the components themselves, the cost of labor and equipment hire has been included. Andrawus [14] showed that skilled labor for WT repairs costs around £50/h. It has been assumed that three crew working an 8 h shift constitute one maintenance action. Therefore, the cost of labor (C_{LAB}) is £1200 per action. Similarly, hire rates for telescopic cranes (C_{EQ}) needed to perform nacelle component lifting operations have been quantified by industry sources [15] as £1500 per week. Lost revenue due to downtime is also taken into account (R_{LOST})—this is wind speed-dependent. These costs are combined with the component costs (see Table I) to calculate replacement (6), repair, (7) and O&M cost (8)

$$C_{\mathrm{replace}} = \beta\lambda \left(C_{\mathrm{CAP}} + C_{\mathrm{LAB}} + C_{\mathrm{EQ}} + R_{\mathrm{LOST}}\right) \tag{6}$$

$$C_{\mathrm{repair}} = (1-\beta)\,\lambda \times \left(\alpha\, C_{\mathrm{CAP}} + C_{\mathrm{LAB}} + C_{\mathrm{EQ}} + R_{\mathrm{LOST}}\right) \tag{7}$$

$$C_{\mathrm{O\&M}} = C_{\mathrm{replace}} + C_{\mathrm{repair}}\,. \tag{8}$$

The revenue model for the WT is based on the energy yield in each one-day simulation interval. Using equations (4) and (5), this energy yield *Y* can be calculated as the power (see Fig. 6) multiplied by a time interval Δt. The energy yielded in a year is then calculated by summing the output over all individual days in the year.

The revenue stream *R* can then be calculated by applying equation (9). MP represents the market price for electricity and renewable obligation certificates (ROCs). For this paper, $\mathrm{MP}_{\mathrm{elec}}$ and $\mathrm{MP}_{\mathrm{ROC}}$ are set to £36 and £40 per MWh, respectively. Although in reality, electricity and ROC prices fluctuate, the annual mean is adequately represented by the figures presented as

$$R = Y\left(\mathrm{MP}_{\mathrm{elec}} + \mathrm{MP}_{\mathrm{ROC}}\right) - C_{\mathrm{O\&M}}\,. \tag{9}$$

It is important to note that any differences in yield between the two WT concepts will be related to the reliability and downtime (see Fig. 5 and Section III-D) of the two WT concepts, rather than to the differences in the electrical design. This is because the same power curve (Fig. 6) has been used for both WT concepts.

Polinder *et al.* showed that the theoretical difference in yield between a 3 MW direct drive machine (DDSG) and a typical 3 MW DFIG (DFIG3G) is +150 MWh [6], if the detail of the electrical machine design is taken into account. Assuming this difference scales linearly with WT rating, it means that for the 2 MW machines considered in this paper, the direct drive machine yields roughly 100 MWh more per annum than the

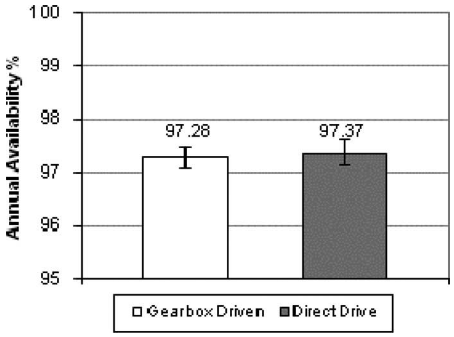

Fig. 7. Availability comparison of wind turbine concepts.

DFIG. Applying (9) and neglecting the O&M cost, this translates to £7600 more revenue per annum for the direct drive machine. Therefore, the annual revenue for the direct drive machine has been boosted by £7600 per annum in the studies that follow.

F. Program Operation

The models outlined in this section were coded in FORTRAN 95, with the SCADA database interface for the wind speed model written using f90SQL [16]. The statistical programming language R was used to fit the wind speed model defined in (4). The resultant capacity factor of the wind turbine based on the simulated wind speed and power curve is just under 30%.

The confidence limit L of the simulation results can be measured by applying (10). Taking the Student-t distribution, and setting the level of confidence to 95%, it means that L can be specified, provided that the number of samples (N) and standard deviation (σ) of the quantity are known. L is shown in the results as confidence bands that specify the accuracy of the results

$$L = \pm \frac{2.045 \times \sigma}{\sqrt{N}}. \qquad (10)$$

IV. RESULTS

A. Operational Comparison of Concepts

Two comparisons are made in order to benchmark the operational merits of the two WT concepts: a technical comparison and an economic comparison. The first result in Fig. 7 compares the overall availability of the two concepts.

It can be seen that despite removing the gearbox from the design, the direct drive concept has similar overall availability to the gearbox-driven machine. Although the availability is marginally better for the case of the direct drive machine, the confidence limits show that this technical benefit is uncertain. It should be noted that grid availability is not included in this paper.

The second result, displayed in Fig. 8, shows the revenue generated (9) for both concepts. This shows that the gearbox-driven design has a much larger economic benefit than the direct drive concept.

The contribution to the revenue of increased energy yield due to avoidance of downtime is negligible in the case of Fig. 8 (direct drive machine avoids loss of ∼6.35 MWh more energy than gearbox-driven, economic benefit = £482 per annum). Therefore, the large disparity in revenue (∼£44 000 per annum) must be due to incurred repair and replacement costs. The large increase in cost and failure rate for the generator in particular (see Table I and Fig. 5) appears to economically handicap the direct drive concept.

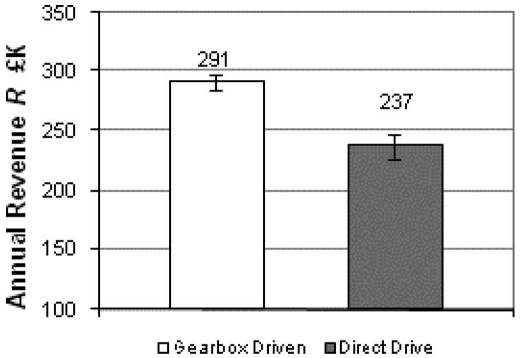

Fig. 8. Economic comparison of wind turbine concepts.

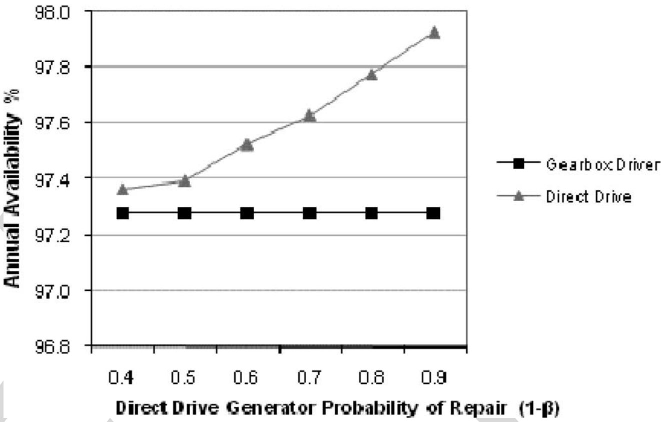

Fig. 9. Availability improvement of direct drive wind turbine as a function of generator reparability.

B. Operational Impact of Generator Reparability

One possible explanation of the superior economic performance of the gearbox-drive concept is that a replacement factor (β) of 0.6 per failure (see Section III-D) may represent a pessimistic view of the "reparability" of a WT synchronous generator. Indeed, it has been reported elsewhere [3] that the increase in generator failure rate for the direct drive concept is related to electrical failures rather than mechanical failures. Electrical faults will be less likely to involve a complete component replacement; therefore, the robustness of the conclusion drawn from Fig. 8 is tested by modeling different levels of reparability for the direct drive generator.

The replacement factor β was reduced from the base value of 0.6–0.1, as shown in Fig. 9. This figure shows that the operational availability of the direct drive concept WT can be significantly higher than the gearbox-driven WT, if a high proportion of synchronous generator failures are minor electrical failures rather than severe mechanical failures (e.g., bearing problems).

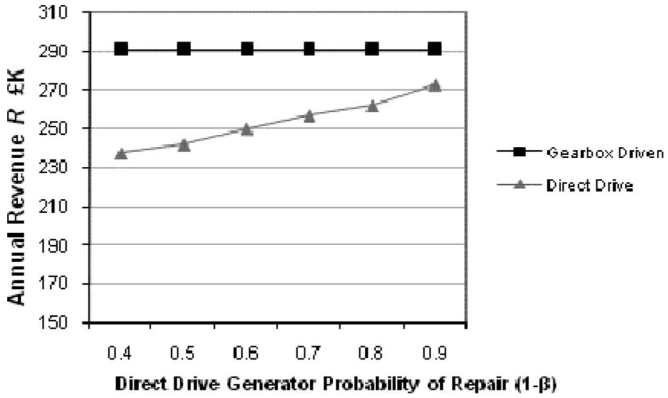

Fig. 10. Revenue increase of direct drive wind turbine as a function of generator reparability.

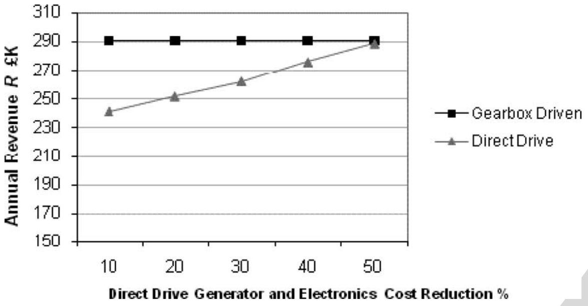

Fig. 11. Revenue increase of direct drive wind turbine as a function of component cost reduction.

The economic impact of this variation is illustrated in Fig. 10. This figure shows that even for an optimistic scenario, the annual revenue of the direct drive WT is still ∼£20 000 less than the equivalent gearbox-driven WT. This aspect of WT component reparability has not received much attention in the literature, but Fig. 10 in particular shows that it is a significant factor when conducting operational modeling of WT concepts. More studies of the type conducted by Ribrant and Bertling [13] will be needed in order to better understand the reparability of different WT components and their effect on operational metrics such as availability and revenue. Analysis of WT failures in the context of repairs and replacements along with their probabilities and costs are crucial for a deep understanding of wind farm operational issues.

C. *Operational Impact of Component Cost Reduction*

In the WT marketplace, there is currently one company that builds 2MW direct drive machines on an industrial scale [17]; however, other large WT manufacturers have identified direct drive machines as an avenue for future production [18]. With more players in the market, it may be possible to significantly reduce the direct drive component cost through a refinement of mass production manufacturing processes. Therefore, it is of interest to review the effect on the economic case for direct drive machines if component costs are lowered. Such a review is provided in Fig. 11, where the GEN and ELE component costs are reduced in 10% steps to 50% of the original Table I values.

The final result shows that if substantial cost reductions in direct drive technology are achieved in the future, this measure may be enough to make the technology cost-competitive with DFIGs. However, very large cost reductions of 50%+ will be required. At current prices, the economic argument for a switch to direct drive technology, for the onshore conditions evaluated, appears to be weak.

V. CONCLUSION

An operational comparison of direct drive and gearbox-driven wind turbines has been presented in this paper. The results suggest that there may be a technical advantage in deploying direct drive machines over more established gearbox-driven designs (see Fig. 9). In all cases, the economic analysis shows that gearbox-driven machines are still preferable, unless manufacturing costs of direct drive technology can be significantly reduced (see Fig. 11).

There are some issues that need to be better understood in order to make more precise comparisons of these technologies. One is that the repair probability of the components needs to be investigated, in a manner similar to the one presented in [13] but for all WT components. The failure rate increase for a synchronous generator relative to an induction generator (reported in [3], [4]) will be made up mainly of electrical-related failures rather than mechanical failures. It would be interesting to see what proportion of direct drive WT generator failures are low downtime (e.g., 1–3 days) as opposed to a mechanical failure of a rotating component, which in some cases could take as long as 60 days to replace [14]. Such an analysis would aid understanding of WT failure modes and make operational comparisons more accurate.

This study was carried out for fairly typical onshore conditions, but the conclusions may be linked to the site conditions. Direct drive machines are perceived by some manufacturers as primarily an offshore technology [18]. By modeling the offshore wind resource, logistics, increased downtimes, and offshore access constraints, it may be possible to determine if direct drive machines would become more economically attractive in offshore conditions than the analysis presented in this paper shows. The conclusions of the results in this paper and any further analysis as described will be of value to both manufacturers and operators of wind turbines.

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Techno-Economic Comparison of Operational Aspects for Direct Drive and Gearbox-Driven Wind Turbines

David McMillan, *Member, IEEE*, and Graham W. Ault, *Member, IEEE*

***Abstract*—The majority of wind turbines currently in operation have the conventional Danish concept design—that is, the three-bladed rotor of such turbines is indirectly coupled with an electrical generator via a gearbox. Recent technological developments have enabled direct drive wind turbines to become economically feasible. Potentially, direct drive wind turbines may enjoy higher levels of availability due to the removal of the gearbox from the design. However, this is only a theory: so far not substantiated by detailed analytic calculation. By providing such a calculation, this paper enables us to quantitatively evaluate technical and economic merits of direct drive and gearbox-driven wind turbines.**

***Index Terms*—Markov chain, operational comparison, reliability, wind turbines.**

I. Introduction

WORLDWIDE installed capacity of wind generation is growing significantly and is likely to continue to increase in the future. The twin policy objectives of energy security and climate change mitigation have resulted in economic incentives, which in turn, have driven investment in wind energy. Taking the U.K. as an example, Fig. 1 shows how the installed capacity has grown since 2005—by the end of 2008, the installed capacity broke through the 3 GW barrier [1]. This 3 GW capacity consists of 2276 individual wind turbines (WTs) [2], the vast majority of which are conventional Danish concept, gearbox-driven machines. However, recent technical strides have enabled direct drive machines to become economically feasible.

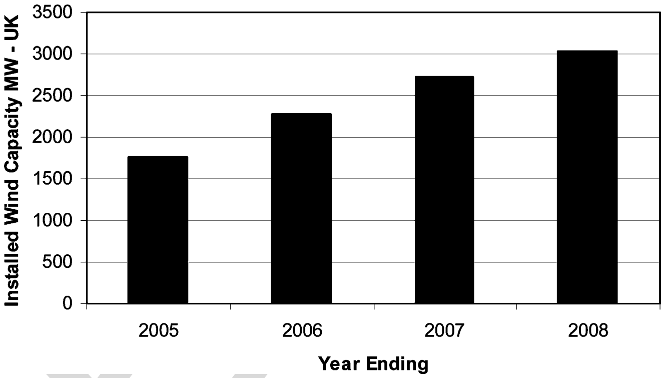

Fig. 1. Recent growth in U.K. wind generation capacity [2].

Since a gearbox is not included in the direct drive concept, it is clear that the reliability and availability of the WT will improve—if it can be assumed that all other factors remain unchanged. On the other hand, it has been reported in the paper that failure rates of electrical components and generators of direct drive wind turbines are significantly higher than those of gearbox-driven equivalents [3], [4]. The purpose of this paper is to establish if there is a technical and/ or economic advantage in deploying direct drive wind turbines instead of gearbox-driven machines. This analysis is based on quantitative modeling of the operation, failure, and maintenance of wind turbine units as proposed in [5]. Such an operational comparison of different wind turbine concepts is not available in the existing literature.

II. Comparison of Concepts

A. *Conventional Danish Concept—Gearbox Driven*

The conventional Danish concept comprises a three-bladed upwind rotor, which revolves on the horizontal axis (sometimes called horizontal axis wind turbine, HAWT). The coupling between rotor and electrical generator is indirect and is achieved via a gearbox in order to increase the rotational speed to a level that can drive a relatively small-diameter, lightweight induction generator. A conceptual view of the energy conversion process for such a typical modern wind turbine is outlined in Fig. 2.

The whole wind turbine assembly rotates into the prevalent wind direction on its vertical axis by means of an electromechanical yaw system. Once facing into the wind, control of the mechanical input power is achieved either by aerodynamic design of the rotor (stall control) or by actively changing the angle of attack of the rotor blades to the wind (pitch control) via electrical motors or hydraulics.

The electrical configuration of Danish concept WTs is influenced by mechanical aspects, as one main objective of the WT mechanical design is to minimize the weight at the top of the tower, where the nacelle (containing the generator) is located in modern HAWTs. This means the generator has to be as light as possible and must have a relatively small physical footprint. For this reason, induction generators are employed: induction generators have the added advantage of being more robust than

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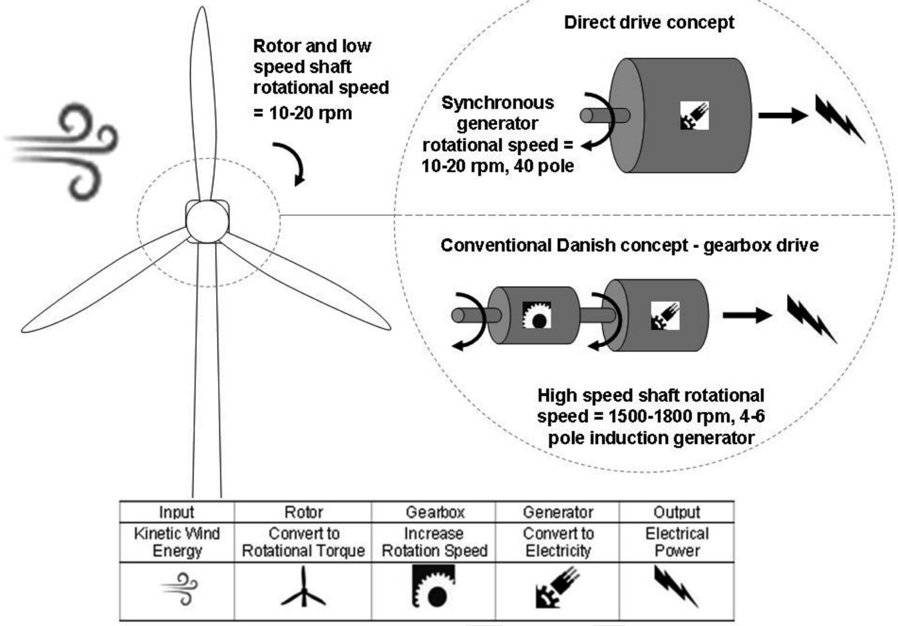

Input	Rotor	Gearbox	Generator	Output
Kinetic Wind Energy	Convert to Rotational Torque	Increase Rotation Speed	Convert to Electricity	Electrical Power

Fig. 2. Process diagram for gearbox-driven and direct drive wind turbines.

synchronous generators and tend to have fewer electrical faults. However, due to the low rotational speed of the wind turbine rotor, a gearbox has to be used to increase the rotation from tens of revolutions per minute at the gearbox input to thousands at the output. The primary reason for this is the low number of induction generator poles.

The older Danish concept WTs that operated at fixed speed employed squirrel cage induction generators; however, newer variable speed technology has resulted in a switch to doubly fed induction generators (DFIG), which are now the dominant wind turbine generator configuration. The reason for the dominance of this configuration is that it represents a good compromise between economy and performance. It is relatively economic because it has only a partial electronic converter rated at ~30% of the generator output [6], not a full converter.

B. *Direct Drive Concept*

In a direct drive WT, the main rotor is coupled to the generator input shaft, eliminating the need for a gearbox in the design. In order to generate power at such a low rotation speed, the generator has to have many pole pairs, and usually a synchronous generator is employed. This implies much greater dimensions and weight as compared with an induction generator. In addition, a fully rated electronic power converter is required, which increases the cost of the system.

C. *Types of Comparison*

There are several examples in the published literature where a comparison is made between the two concepts. For example, Tavner *et al.* [3] focused on how the configuration of the WT generator and converter in different design concepts affected overall WT reliability. The data utilized by the authors had enough detail to enable a direct reliability comparison of three WT concepts: fixed speed with gearbox, variable speed with gearbox, and variable speed direct drive (no gearbox: synchronous generator). The main conclusion was that direct drive systems are less reliable than models with a gearbox because the potential increase in reliability due to elimination of gearbox failures is cancelled out by increased generator, inverter, and electrical system failures.

Interestingly, the authors recognized that overall availability would also be affected by component repair times: In this sense direct drive systems may have an advantage, as mean time to repair (MTTR) for a gearbox is likely to be very much more than MTTR for an electronics subassembly. As yet, no other research has addressed this operational comparison of the two concepts.

Echavarria *et al.* [4] analyzed a similar dataset, which provides some highly relevant information regarding the reliability of the two WT concepts. In particular, the data suggest that generator failures in direct drive WTs are roughly two times the gearbox-driven equivalent (0.22 failures per annum compared with 0.12 suggested by Tavner *et al.* [7]). Similarly, power electronics failures in direct drive synchronous machines are quantified as 1.03 failures per annum compared to 0.661 suggested in [7] for the induction machine equivalent.

Polinder *et al.* [6] examine direct drive and gearbox-driven WT concepts from the viewpoint of design and economic performance. The authors define a typical Danish concept WT with a three-stage gearbox (3GDFIG) and a direct drive machine coupled to a synchronous generator (DDSG). Three other concepts are also defined (DFIG with a single-stage gearbox, permanent magnet direct drive, and permanent magnet single-stage gearbox) but these are not considered in this paper due to the fact that they are not currently deployed in significant numbers.

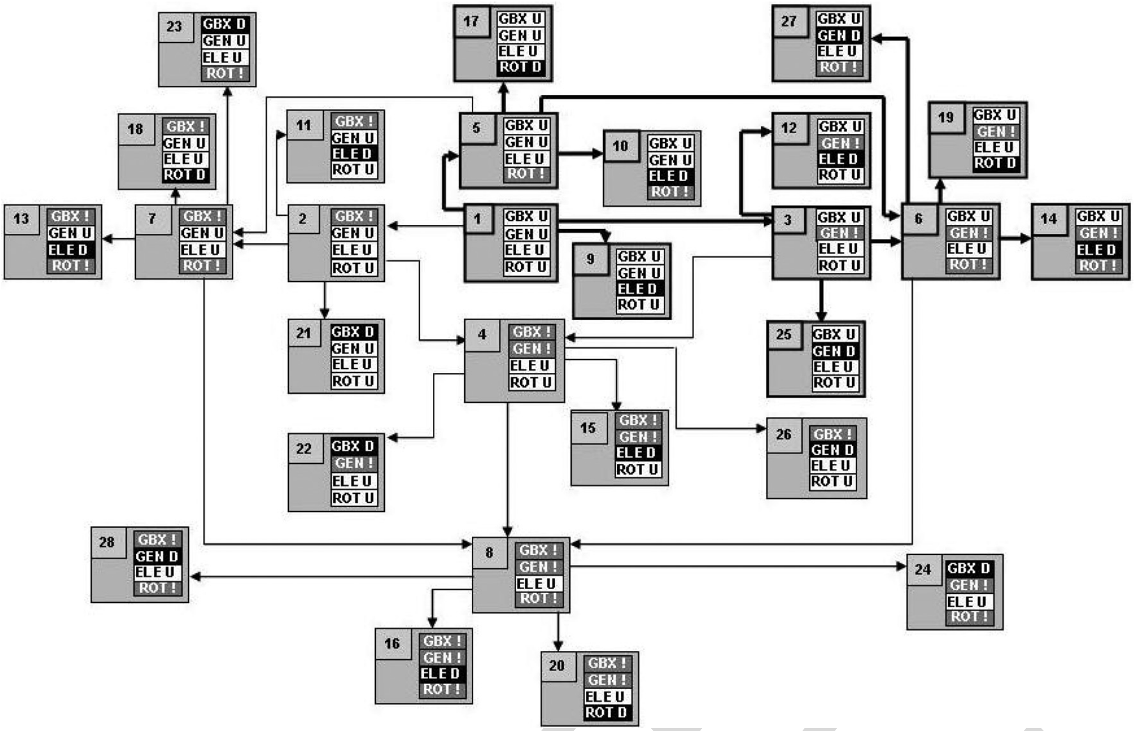

Fig. 3. Markov chain of key wind turbine components. Bold arrows and boxes indicate direct drive system.

The authors again highlight the need for further work to better understand the reliability and availability benefits of adopting different WT design concepts—a requirement which this paper aims to meet.

III. MODELING OF WIND TURBINE CONCEPTS

A. *Physical Modeling of Wind Turbine Components*

In order to build an accurate operational model, the key physical components of the WT must be identified and a suitable mathematical representation decided upon. It was reported in [5] that using a combination of failure rate data, downtime estimates, and expert opinion, the key components of a gearbox-driven WT could be identified as follows:

1) gearbox (GBX);
2) generator (GEN);
3) rotor blades (ROT); and
4) inverter, electronics, and control (ELE).

In terms of the mathematical representation, a Markov chain solved via Monte Carlo simulation (MCS) was identified in previous studies as a suitable model framework [5]. The Markov chain representation has been very successfully applied to power systems infrastructure deterioration and failure modeling, including wind turbines [8], [9]. The main problem with these analytically solved models is that the introduction of constraints, such as weather-constrained maintenance, makes obtaining a solution rather difficult. Although not computationally efficient, MCS methods overcome this difficulty and have been applied to similar problems in the past [10], [11]. Since the problem considered is essentially a planning problem, the time required to get the solution is of little importance.

It has been assumed that three states are sufficient to capture the deterioration and failure processes of the GBX, GEN, and ROT. ELE failures are assumed to be instantaneous and, therefore, require only binary representation. When all four components are modeled in a single Markov state-space, the total number of states is 54. This is cut down to 28 by assuming that degradation and failure events of different WT components cannot happen concurrently. Furthermore, for a GBX, GEN, or ROT failure to occur, the system must transit through the deteriorated (intermediate) state before outright failure.

The possible Markov states and transitions for the overall WT system are visualized in Fig. 3. The three possible deterioration levels are indicated as fully up (U), deteriorated (!), and down (D).

All 28 states and transitions are possible for the case of gearbox-driven WTs. The obvious physical difference when modeling a direct drive WT is that there are no gearbox states. Thus, the bold arrows in Fig. 3 refer to the transitions and states that represent direct drive WTs, as a 12-state subset.

The arrows in Fig. 3 represent transition probabilities (e.g., probability of transition from state *a* to state *b* is $p_{a,b}$), whose magnitude must be estimated. These probabilities depend only on the current state of the system (*s*) at current time t_k. Equation 1 expresses this "memory-less" property of a Markov chain

$$p_{a,b} = p(s_b, t_{k+1} | s_a, t_k) \qquad k = 1, 2, 3, \ldots . \tag{1}$$

Furthermore, the transition probabilities are constant in time: This is the "time-stationary" property. The magnitude of all transition probabilities from one state (*a*) to all others in the

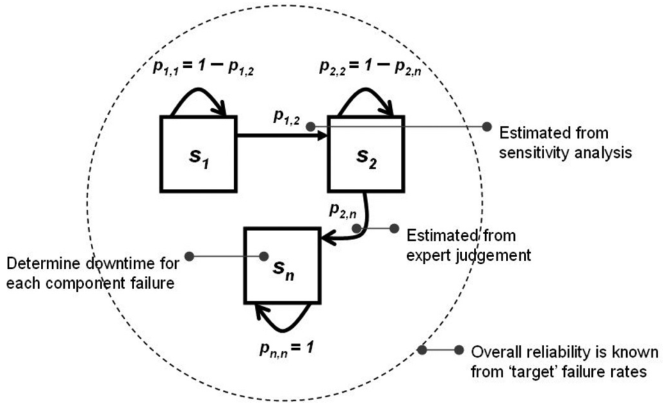

Fig. 4. Parameter estimation for Markov chain.

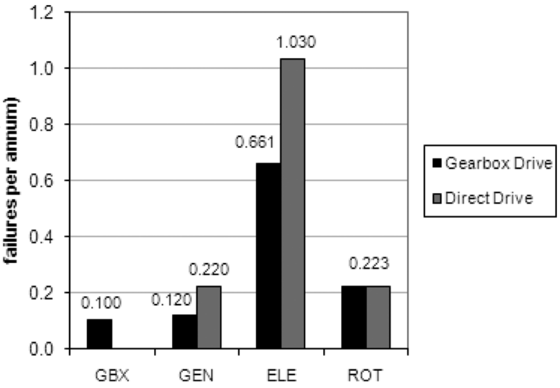

Fig. 5. Reliability for gearbox-driven and direct drive wind turbines.

system must sum to unity. This is shown in (2)

$$\sum\nolimits_b p_{a,b} = 1 \qquad a = 1 \ldots n \tag{2}$$

where *n* is the total number of system states. For convenience, the transition probabilities for the whole system are expressed in a transition probability matrix (TPM). For the case of the system in Fig. 3, the TPM is shown in (3). Note that only the possible transitions (indicated in Fig. 3. with arrows) need to be estimated—all other probabilities are equal to zero

$$\text{TPM} = \begin{bmatrix} p_{1,1} & p_{1,2} & . & p_{1,28} \\ p_{2,1} & p_{2,2} & . & . \\ . & . & . & . \\ p_{28,1} & . & . & p_{28,28} \end{bmatrix}. \tag{3}$$

The TPM values are estimated based on the partial information available, as illustrated in Fig. 4. A good estimate of the overall reliability ("target" failure rate) is known from the work of Tavner *et al.* [7].

Similarly, downtime estimates can be made for the outage of the key components [5]. The probability of an outright failure in a deteriorated condition ($p_{2,n}$) can be estimated based on expert opinion of times to failure. The remaining parameters can then be estimated by conducting sensitivity analyses (previously reported in [5]).

B. Data for Physical Model

The study of Tavner *et al.* [7] provided estimates of component failure rates based on populations of Danish and German WTs. The German population was larger (over 4,000 machines) and the population consisted of more modern WTs. Therefore, the German figures are used to fit the gearbox-drive WT physical model.

On the other hand, Echavarria *et al.* [4] suggest modifications to the GEN and ELE failure rates for direct drive machines. Taking this into account, the target failure rates for both WT concepts can be visualized in Fig. 5.

Downtimes for the failure types are as follows: GBX—30 days, GEN—21 days, ELE—1 day, and ROT—30 days. They are based on domain knowledge elicited in [5]. Using this information, the TPM parameters were estimated based on the iterative procedure devised in [5]. The procedure is based on sensitivity analysis estimation of the unknown parameter $p_{1,2}$ (see Fig. 4).

The Markov chain has been defined for both gearbox-driven and direct drive concepts. In the following sections, other aspects of operational modeling—which are common to both concepts—are discussed.

C. Energy Yield Modeling

There are two main components to the energy yield model. These are the wind speed model and the power curve model. The wind speed (WS) model previously used by the authors [5] was based on a single parameter autoregressive process, or AR(1). This is displayed in (4), where μ is the mean of a wind speed time series, ϕ is the autoregressive parameter and the process is driven by a Gaussian white noise function ε_t.

$$\text{WS}_t - \mu = \phi\,(\text{WS}_{t-1} - \mu) + \varepsilon_t\,. \tag{4}$$

The dataset used to fit the model was sourced from a supervisory control and data acquisition (SCADA) system of a U.K. wind farm. Estimation of ϕ and ε_t was achieved by linear least squares, while classification of the model was based on inspection of the autocorrelation and partial-autocorrelation functions.

The power curve model is based on a manufacturers' datasheet for a 2 MW WT [12], which is sampled and the theoretical equation for the power (*P*) in the wind (5) is matched to the data samples by modeling the coefficient of performance C_p

$$P = \frac{1}{2}\rho\pi r^2 v^3 (\times C_p). \tag{5}$$

In (5), ρ is air density (kg/m^3), *r* is the rotor radius (m), and *v* is air velocity through the WT rotor (m/s). The re-created power curve is shown in Fig. 6 and has cut in, rated, and cut out wind speeds of 4, 14, and 25 m/s, respectively. It is assumed that both WT concepts adhere to the same power curve.

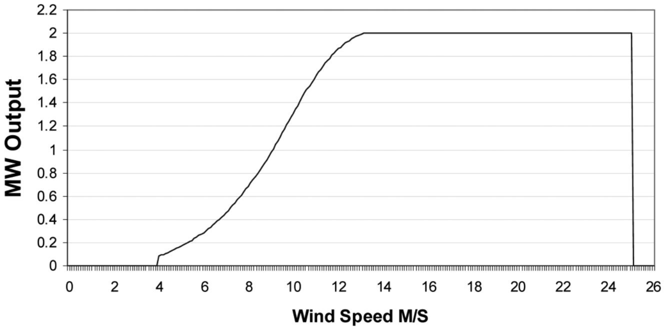

Fig. 6. Power curve for 2 MW wind turbine [12].

D. Maintenance Modeling

It is assumed that a six-monthly periodic maintenance plan is adopted for both WT concepts. The assumptions in the maintenance model are that maintenance actions restore the WT to the fully up state (state 1 in Fig. 3) and that each maintenance visit involves a one-day outage. The model can easily accommodate condition-based maintenance (CBM), but since maintenance paradigms are not the focus of this paper, this possibility is neglected.

If a component failure occurs, a maintenance team is dispatched immediately. There is a probability that a component replacement is necessary (replacement factor $\beta = 0.6$) or that it can be repaired ($1-\beta = 0.4$). This is based on an analysis by Ribrant and Bertling [13] who highlighted that around 60% of gearbox failures require a replacement rather than a repair action. Similar figures have not been published for the other WT components; therefore, due to the lack of data, they are assumed to have the same probabilities of repair and replacement as the gearbox.

If the component can be repaired, it is restored instantaneously to a functional state. If a replacement is required, downtime lasts as follows: GBX–30 days, GEN—21 days, ELE—1 day, and ROT—30 days. This is based on the experience of a wind farm operator. Furthermore, maintenance actions are constrained by wind speed as in [5]. This means that nacelle-related replacements need wind speed conditions of less than 10 m/s, while rotor maintenance cannot be conducted in wind speeds over 7 m/s.

E. Costs and Revenue

It is of interest to compare the economic merits of the two WT configurations. Therefore, a cost model has been built which generates revenue from energy yield and incurs maintenance and replacement costs.

Polinder *et al.* provided costs for gearbox-driven and direct drive wind turbine components rated at 3 MW [6]. Figures can be derived for 2 MW machines of both types assuming that the cost varies linearly with the rating. These costs are provided in Table I. The rotor cost was not provided in [6] and so the value derived previously by the authors of this paper is adopted [5]. In the case of a component replacement, the full cost in Table I is incurred. In the case of a repair, it is assumed that only 10% of this cost is incurred (repair cost factor $\alpha = 0.1$).

TABLE I
COMPONENT COSTS FOR WIND TURBINE CONCEPTS

Component	Gearbox driven Cost £	Direct drive
GBX	121,733	N/A
GEN	177,066	313,740
ROT	210,000	210,000
ELE	22,133	66,400

Besides the costs of the components themselves, the cost of labor and equipment hire has been included. Andrawus [14] showed that skilled labor for WT repairs costs around £50/h. It has been assumed that three crew working an 8 h shift constitute one maintenance action. Therefore, the cost of labor (C_{LAB}) is £1200 per action. Similarly, hire rates for telescopic cranes (C_{EQ}) needed to perform nacelle component lifting operations have been quantified by industry sources [15] as £1500 per week. Lost revenue due to downtime is also taken into account (R_{LOST})—this is wind speed-dependent. These costs are combined with the component costs (see Table I) to calculate replacement (6), repair, (7) and O&M cost (8)

$$C_{\mathrm{replace}} = \beta\lambda \left(C_{\mathrm{CAP}} + C_{\mathrm{LAB}} + C_{\mathrm{EQ}} + R_{\mathrm{LOST}}\right) \tag{6}$$

$$C_{\mathrm{repair}} = (1-\beta)\,\lambda \times \left(\alpha\, C_{\mathrm{CAP}} + C_{\mathrm{LAB}} + C_{\mathrm{EQ}} + R_{\mathrm{LOST}}\right) \tag{7}$$

$$C_{\mathrm{O\&M}} = C_{\mathrm{replace}} + C_{\mathrm{repair}}\,. \tag{8}$$

The revenue model for the WT is based on the energy yield in each one-day simulation interval. Using equations (4) and (5), this energy yield *Y* can be calculated as the power (see Fig. 6) multiplied by a time interval Δt. The energy yielded in a year is then calculated by summing the output over all individual days in the year.

The revenue stream *R* can then be calculated by applying equation (9). MP represents the market price for electricity and renewable obligation certificates (ROCs). For this paper, $\mathrm{MP}_{\mathrm{elec}}$ and $\mathrm{MP}_{\mathrm{ROC}}$ are set to £36 and £40 per MWh, respectively. Although in reality, electricity and ROC prices fluctuate, the annual mean is adequately represented by the figures presented as

$$R = Y\left(\mathrm{MP}_{\mathrm{elec}} + \mathrm{MP}_{\mathrm{ROC}}\right) - C_{\mathrm{O\&M}}\,. \tag{9}$$

It is important to note that any differences in yield between the two WT concepts will be related to the reliability and downtime (see Fig. 5 and Section III-D) of the two WT concepts, rather than to the differences in the electrical design. This is because the same power curve (Fig. 6) has been used for both WT concepts.

Polinder *et al.* showed that the theoretical difference in yield between a 3 MW direct drive machine (DDSG) and a typical 3 MW DFIG (DFIG3G) is +150 MWh [6], if the detail of the electrical machine design is taken into account. Assuming this difference scales linearly with WT rating, it means that for the 2 MW machines considered in this paper, the direct drive machine yields roughly 100 MWh more per annum than the

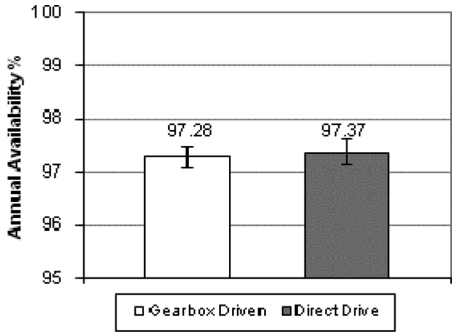

Fig. 7. Availability comparison of wind turbine concepts.

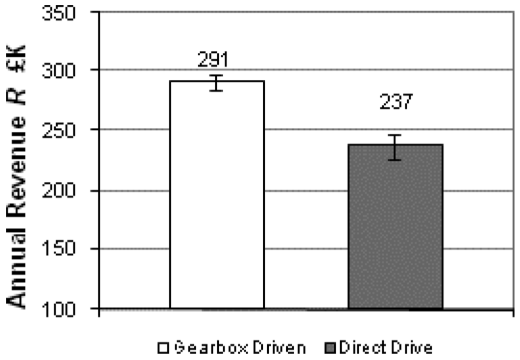

Fig. 8. Economic comparison of wind turbine concepts.

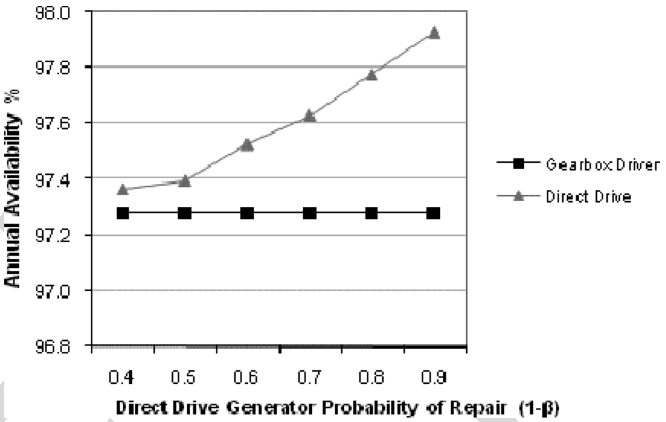

Fig. 9. Availability improvement of direct drive wind turbine as a function of generator reparability.

DFIG. Applying (9) and neglecting the O&M cost, this translates to £7600 more revenue per annum for the direct drive machine. Therefore, the annual revenue for the direct drive machine has been boosted by £7600 per annum in the studies that follow.

F. Program Operation

The models outlined in this section were coded in FORTRAN 95, with the SCADA database interface for the wind speed model written using f90SQL [16]. The statistical programming language R was used to fit the wind speed model defined in (4). The resultant capacity factor of the wind turbine based on the simulated wind speed and power curve is just under 30%.

The confidence limit L of the simulation results can be measured by applying (10). Taking the Student-t distribution, and setting the level of confidence to 95%, it means that L can be specified, provided that the number of samples (N) and standard deviation (σ) of the quantity are known. L is shown in the results as confidence bands that specify the accuracy of the results

$$L = \pm\frac{2.045 \times \sigma}{\sqrt{N}}. \tag{10}$$

IV. RESULTS

A. Operational Comparison of Concepts

Two comparisons are made in order to benchmark the operational merits of the two WT concepts: a technical comparison and an economic comparison. The first result in Fig. 7 compares the overall availability of the two concepts.

It can be seen that despite removing the gearbox from the design, the direct drive concept has similar overall availability to the gearbox-driven machine. Although the availability is marginally better for the case of the direct drive machine, the confidence limits show that this technical benefit is uncertain. It should be noted that grid availability is not included in this paper.

The second result, displayed in Fig. 8, shows the revenue generated (9) for both concepts. This shows that the gearbox-driven design has a much larger economic benefit than the direct drive concept.

The contribution to the revenue of increased energy yield due to avoidance of downtime is negligible in the case of Fig. 8 (direct drive machine avoids loss of ~6.35 MWh more energy than gearbox-driven, economic benefit = £482 per annum). Therefore, the large disparity in revenue (~£44 000 per annum) must be due to incurred repair and replacement costs. The large increase in cost and failure rate for the generator in particular (see Table I and Fig. 5) appears to economically handicap the direct drive concept.

B. Operational Impact of Generator Reparability

One possible explanation of the superior economic performance of the gearbox-drive concept is that a replacement factor (β) of 0.6 per failure (see Section III-D) may represent a pessimistic view of the "reparability" of a WT synchronous generator. Indeed, it has been reported elsewhere [3] that the increase in generator failure rate for the direct drive concept is related to electrical failures rather than mechanical failures. Electrical faults will be less likely to involve a complete component replacement; therefore, the robustness of the conclusion drawn from Fig. 8 is tested by modeling different levels of reparability for the direct drive generator.

The replacement factor β was reduced from the base value of 0.6–0.1, as shown in Fig. 9. This figure shows that the operational availability of the direct drive concept WT can be significantly higher than the gearbox-driven WT, if a high proportion of synchronous generator failures are minor electrical failures rather than severe mechanical failures (e.g., bearing problems).

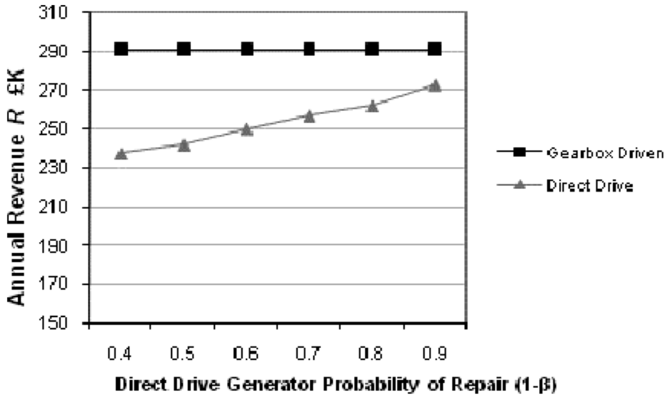

Fig. 10. Revenue increase of direct drive wind turbine as a function of generator reparability.

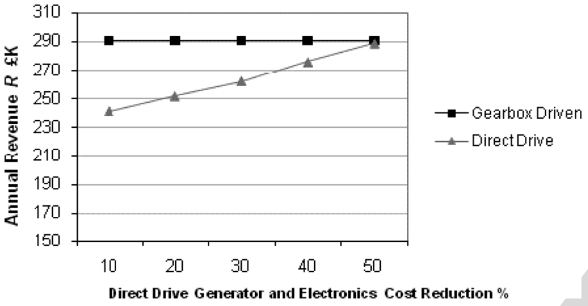

Fig. 11. Revenue increase of direct drive wind turbine as a function of component cost reduction.

The economic impact of this variation is illustrated in Fig. 10. This figure shows that even for an optimistic scenario, the annual revenue of the direct drive WT is still $\sim$£20 000 less than the equivalent gearbox-driven WT. This aspect of WT component reparability has not received much attention in the literature, but Fig. 10 in particular shows that it is a significant factor when conducting operational modeling of WT concepts. More studies of the type conducted by Ribrant and Bertling [13] will be needed in order to better understand the reparability of different WT components and their effect on operational metrics such as availability and revenue. Analysis of WT failures in the context of repairs and replacements along with their probabilities and costs are crucial for a deep understanding of wind farm operational issues.

C. *Operational Impact of Component Cost Reduction*

In the WT marketplace, there is currently one company that builds 2MW direct drive machines on an industrial scale [17]; however, other large WT manufacturers have identified direct drive machines as an avenue for future production [18]. With more players in the market, it may be possible to significantly reduce the direct drive component cost through a refinement of mass production manufacturing processes. Therefore, it is of interest to review the effect on the economic case for direct drive machines if component costs are lowered. Such a review is provided in Fig. 11, where the GEN and ELE component costs are reduced in 10% steps to 50% of the original Table I values.

The final result shows that if substantial cost reductions in direct drive technology are achieved in the future, this measure may be enough to make the technology cost-competitive with DFIGs. However, very large cost reductions of 50%+ will be required. At current prices, the economic argument for a switch to direct drive technology, for the onshore conditions evaluated, appears to be weak.

V. CONCLUSION

An operational comparison of direct drive and gearbox-driven wind turbines has been presented in this paper. The results suggest that there may be a technical advantage in deploying direct drive machines over more established gearbox-driven designs (see Fig. 9). In all cases, the economic analysis shows that gearbox-driven machines are still preferable, unless manufacturing costs of direct drive technology can be significantly reduced (see Fig. 11).

There are some issues that need to be better understood in order to make more precise comparisons of these technologies. One is that the repair probability of the components needs to be investigated, in a manner similar to the one presented in [13] but for all WT components. The failure rate increase for a synchronous generator relative to an induction generator (reported in [3], [4]) will be made up mainly of electrical-related failures rather than mechanical failures. It would be interesting to see what proportion of direct drive WT generator failures are low downtime (e.g., 1–3 days) as opposed to a mechanical failure of a rotating component, which in some cases could take as long as 60 days to replace [14]. Such an analysis would aid understanding of WT failure modes and make operational comparisons more accurate.

This study was carried out for fairly typical onshore conditions, but the conclusions may be linked to the site conditions. Direct drive machines are perceived by some manufacturers as primarily an offshore technology [18]. By modeling the offshore wind resource, logistics, increased downtimes, and offshore access constraints, it may be possible to determine if direct drive machines would become more economically attractive in offshore conditions than the analysis presented in this paper shows. The conclusions of the results in this paper and any further analysis as described will be of value to both manufacturers and operators of wind turbines.

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