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Speed and Torque Control Strategies for Loss Reduction of Vertical Axis Wind Turbines

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Abstract. This paper builds on the work into modelling the generator losses for Vertical Axis Wind Turbines from their intrinsic torque cycling to investigate the effects of aerodynamic inefficiencies caused by the varying rotational speed resulting from different torque control strategies to the cyclic torque. This is achieved by modelling the wake that builds up from the rotation of the VAWT rotor to investigate how the wake responds to a changing rotor speed and how this in turn affects the torque produced by the blades as well as the corresponding change in generator losses and any changes to the energy extracted by the wind turbine rotor.

1. Introduction

With the continued drive to reduce the cost of energy of commercial offshore wind turbines, there is increasing interest in researching the use of Vertical Axis Wind Turbines (VAWTs) for this environment. Two specific VAWT designs in development are the Aerogenerator V-rotor [1] and the VertAx H-rotor [2] which both use directly driven permanent magnet generators.

VAWTs have a number of inherent disadvantages compared to conventional Horizontal Axis Wind Turbines (HAWTs) which need to be quantified to determine whether VAWTs can be viable for commercial offshore generation. One aspect is that the rotational speed of VAWTs tend to be lower than for an equivalent HAWT. This implies that the torque rating of the VAWT will be higher for the same power rating, which results in a drivetrain that is more expensive and/or that experiences higher losses. A further aggravating factor is the cyclic nature of the torque caused by the varying angle of attack during each rotor revolution. This means that even with a constant wind speed the peak rotor torque can be substantially greater than the mean torque for that wind speed.

This paper is concerned with the drivetrain's response to that cyclic torque pattern and how that influences the losses experienced by the generator and turbine. In order to be able to find an optimal generator design one needs to be able to determine the maximum torque rating for the generator. This torque rating depends on whether one chooses a constant speed strategy (with generator torque matching the varying rotor torque), a constant torque strategy (where the rotational speed varies during each revolution) or some strategy in between. The choice of strategy has implications for the generator losses, the cost of the drivetrain and as investigated in this paper it could lead to changes to the energy extracted by the wind turbine rotor.

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2. Methodology

This paper evaluates three types of losses for an assumed VAWT with an assumed direct drive permanent magnet generator. One of these losses can be characterised by turbine rotor energy extraction that is sacrificed by choosing strategies that lie at different points on the spectrum between fixed torque and fixed speed modes of operation (for a given constant wind speed). This choice is characterised by introducing a torque control factor q which is defined (by Equation 1) as the ratio of electrical torque variation to mechanical torque variation (at a constant wind speed). This value can vary between 0 (fixed electrical torque for a given wind speed) and 1 (fixed rotational speed for a given wind speed).

$$q = \frac{T_{\Delta_{\mathrm{elec}}}}{T_{\Delta_{\mathrm{mech}}}} \tag{1}$$

It is of interest to find out whether the energy extraction of the turbine rotor is affected by this choice of q, as the other two generator loss types are sensitive on q. The copper loss depends on the torque variation while the iron loss depends on the speed variation.

The first step in the methodology defines various parameters describing the torque and its variation with azimuth angle. The choice of generator torque is detailed next and the implications for generator losses and costs are then explained. After that the method for assessing the variation in turbine rotor energy extraction is introduced.

2.1. *Torque modelling*

The mechanical torque exerted on the generator varies due to the varying aerodynamic load generated by the rotor blades. In this paper, it is calculated by using a panel method algorithm which calculates the change in the wake caused by a rotor blade as the angle of attack varies (due to changes in azimuth angle, rotational speed and pitch angle) and thus calculating the resultant aerodynamic torque for each blade around the full rotation, which is then summed to give the mechanical torque loading on the generator.

Since this torque cycling is periodic it can be represented by a Fourier series of sine waves (as described in Equation 2) with an offset equal to the mean torque $\bar{T}$. The turbine in this paper has two blades and it is the 2nd harmonic (h = 2) which dominates the variation in torque.

$$T_{\mathrm{mech}} = \bar{T} + \sum_{h=1}^{n} T_h \sin(h\theta) \tag{2}$$

2.2. *Electrical Torque Response: Torque Control Strategies*

Any difference in mechanical and electrical torques will lead to a variation in rotational speed; this angular acceleration α can be calculated using the Swing Equation (Equation 3):

$$T_{\mathrm{mech}} - T_{\mathrm{elec}} = J\alpha \tag{3}$$

As this is a multi-MW turbine, the moment of inertia of the rotor, J is large (~10^8 kg m^2). The larger the moment of inertia, the smaller the variation in rotor speed. For a given wind speed the turbine designer has a choice how much the generator torque varies with azimuth angle.

At one extreme the electrical torque can match the mechanical torque perfectly and so the rotational speed will be constant (i.e. setting q = 1). The downside to this is that the generator torque rating is equal to $\bar{T} + T_{\Delta_{\mathrm{mech}}}$ and not just $\bar{T}$, leading to extra cost and potential for additional generator copper losses. The other extreme generator operational strategy is for q = 0 which means that the generator keeps the electrical torque at a fixed value for each wind speed. A downside would be that this leads to the largest variation in rotational speed and so additional generator iron losses. Further strategies can be envisaged where $0 \leq q \leq 1$ and the value of optimal q may vary with wind speed.

Fig. 1 gives an illustration of the choice of q based on the mechanical torque harmonics that are described by Fig. 2. This shows that the mechanical torque is dominated by the mean torque and the 2nd harmonic (although there are small contributions from other harmonics). The waveform of mechanical torque is the same as the q = 1 curve in Fig. 1; for this turbine, the rated torque is around $2.1\overline{T}$. By contrast when q = 0, the electrical torque does not vary with rotor angle. Fig. 1 also shows an example strategy of q = 0.5 strategy where the peak torque is approximately $1.5\overline{T}$ [3].

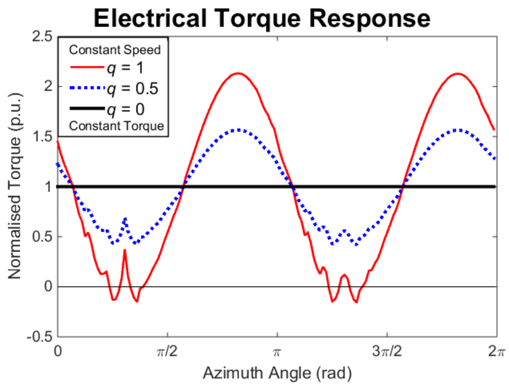

Fig. 1 Cyclic variation of Electrical Torque for different Torque Factors q

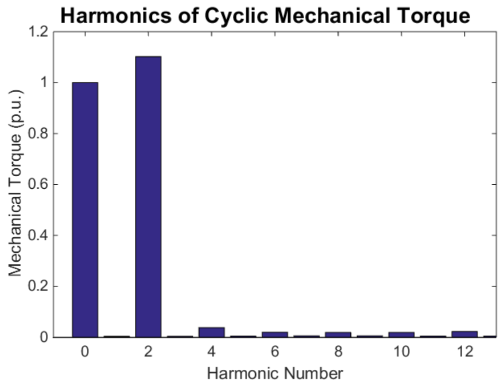

Fig. 2 Harmonic Components of Cyclic Mechanical Torque Loading

2.3. Generator Model

In order to evaluate the losses in the generator and how they are related to the changes in speed and torque, it is first necessary to describe the generator model. The radial-flux permanent magnet generator is simulated by modelling a generator segment using a combination of an equivalent electrical circuit (shown in Fig. 3) modelled in MATLAB and a magnetic circuit modelled in a Finite Element Analysis package FEMM. For the given generator dimensions, FEMM calculates the flux density waveform in the airgap. This is passed to the equivalent circuit model to calculate the no-load voltage. The stator resistance and magnetising inductance is modelled using the approach as outlined by Polinder [4] while the current is set to provide the desired electrical torque response.

The generator cost can be calculated by multiplying the material (magnet, copper, steel) by the specific cost of each material.

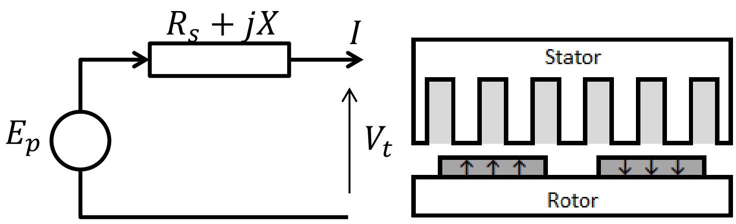

Fig. 3 (a) Per phase electrical equivalent circuit of the generator
(b) Cross section of a pole pair of the generator

2.4. Generator Losses

The two major generator loss mechanisms modelled in this paper are the copper losses in the stator windings and the iron losses in the stator teeth and back iron.

The copper losses depend on the current through the stator coils and are calculated by integrating the varying I^2R losses over an entire rotor revolution. Generally the torque of an electrical machine is proportional to the current, so the current will vary according to strategy defined as outlined in section 2.2. Equation 4 shows how copper losses vary with the square of q and of the square of the current harmonics I_h (which are proportional to the torque harmonics T_h).

$$P_{\mathrm{Cu}} = R\left(\bar{I}^2 + \frac{q^2}{2}\sum_{h=1}^{n} {I_h}^2\right) \tag{4}$$

The copper losses are at largest at fixed speed (q = 1) operation where the rate of increase in these losses is also high.

The iron losses depend on the flux density in the stator iron and the electrical frequency (product of the rotational speed of the rotor and the number of pole pairs of the generator). The variation in electrical frequency is calculated by rearranging the Equation 3 for α and substituting into the angular equations of motion, which is then integrated over the complete revolution to calculate mean values of both the electrical frequency and the square of electrical frequency (Equation 5).

$$\bar{f}_{\mathrm{e}} = \frac{p}{2\pi}\left(\omega_0 + \frac{(1-q)}{J\,\omega_0}\sum_{h=1}^{n}\frac{T_h}{h}\right) \qquad \overline{f_{\mathrm{e}}^2} = \left(\frac{p}{2\pi}\right)^2\left(\omega_0^2 + \frac{2(1-q)}{J}\sum_{h=1}^{n}\frac{T_h}{h}\right) \tag{5}$$

Using the method outlined by Polinder [4] the iron losses are calculated individually for the stator teeth and yoke before being summed up as in Equation 6.

$$P_{\mathrm{Fe}} = \sum_i \left(A_{\mathrm{h}}\bar{f}_{\mathrm{e}} + A_{\mathrm{e}}\overline{f_{\mathrm{e}}^{\,2}}\right)\hat{B}_{\mathrm{Fe}_i}^{\;2} m_i$$
$$A_{\mathrm{h}} = \frac{2P_{\mathrm{Feoh}}}{f_0 \hat{B}_0^{\,2}} \quad A_e = \frac{2P_{\mathrm{Feoe}}}{f_0^{\,2}\hat{B}_0^{\,2}} \tag{6}$$

The iron losses have a component that is proportional to (1-q), therefore the iron losses are largest at fixed torque operation (where q = 0).

As for the relative importance of the torque harmonics on generator losses, the copper losses depend on the magnitude squared meaning that only the largest magnitudes have significant impact (regardless of their harmonic number). On the other hand, the iron losses depend on the ratio of the magnitude divided by the harmonic number meaning that the higher harmonics will have less of an impact. Previous research showed that the mean and 2$^{\mathrm{nd}}$ harmonic could be used for a 2 bladed wind turbine without significant loss of accuracy [3].

2.5. Aerodynamic Inefficiencies

A range of modelling techniques have been used for capturing the aerodynamics of Vertical Axis machines. One of the simplest and most widely used of these is based on BEM theory and is known as the Double-Multiple Streamtube (DMST) algorithm. The DMST algorithm assumes that the wind speed and rotor speed is fixed; thus, it is considered inappropriate for use in this work. Of the more complicated modelling techniques, there are those which employ a free-wake vortex model. These models, unlike DMST models which employ averaging, are time-stepping solutions, which therefore allows the rotor speed to vary around the cycle. In these models, at each time step, the wake is amended through the addition of new vortex segments shed from the trailing edges of the blades. The strength of the vortex segments is found through application of Kelvin's circulation theorem and the Kutta condition. Though the Kutta condition is, strictly speaking, only applicable to steady flow, it has been shown to be acceptable for the range of reduced frequencies experienced by a Vertical Axis machine with a conventional chord-to-radius ratio [5][6]. At each time step, the deformation of the wake is then found by calculating the influence of the blades and all the wake vortex segments on each and every wake vortex segment. In this work, a 2D source-doublet panel method following the formulation of Katz and Plotkin is employed [6]. As a result, at each time step, each trailing edge sheds wake doublet panels. The newly shed wake doublets are converted to vortex systems by noting that a doublet panel is equivalent to a pair of counter rotating vortex blobs located at the panel corners.

Numerical instabilities associated with blade-wake intersections are handled by having the contribution of the far wake vortices (defined as anything from more than 10 time steps prior to the time step of interest) accommodated for in the source term calculation as proposed by Dixon and Ferreira [7].

Previous work by Ferreira and Zanon [8] suggests that such a technique is adequate for determining the apparent wind speed experienced by the blades along with the angle of attack and induction factors at high Reynolds numbers and tip-speed ratios above 3.

In order to model the effect of this varying wake on the generator, the desired electrical torque (defined by the mean torque and the torque control setting q) is input to this algorithm and at each time step the change in rotor speed is calculated from the torque imbalance (Equation 3) which in turn feeds forward in the calculation of the aerodynamic loading at the next time step. The aerodynamic loading forces of all the blades are aggregated together to calculate the resulting mechanical torque loading on the generator. Once the simulation has been completed, the resulting relationship of mechanical torque to azimuth angle is established and the harmonic components extracted using Fourier Analysis, which are then passed on to the previously established equations for copper and iron loss [3] as well as for calculating the mean mechanical power for each q setting to account for any power loss from the varying wake.

The panel code works in fixed time steps, while the loss modelling equations work in fixed azimuth steps. Conversion was made in this regard by calculating the mean rotor speed of each time step and using that to alter the spacing of the angular displacement. This approach could be taken because the variation in rotor speed is smooth and small in magnitude.

As a result of the varying sampling rate in angular displacement it is not possible to run a simple Fast Fourier Transform algorithm. However as previous research shows, the fixed component and the 2^{nd} harmonic of the mechanical torque account for the large majority of iron and copper losses of the generator [3]. This mean mechanical torque and the corresponding 2^{nd} harmonic coefficient were calculated using a curve fitting least squares method.

2.6. Previous Results

This paper builds on work previously published [3] that focused on the generator losses associated with the harmonics of the mechanical torque. That testing used a single torque profile (Fig. 2) which was rescaled to correspond to the appropriate mean torque for that wind speed.

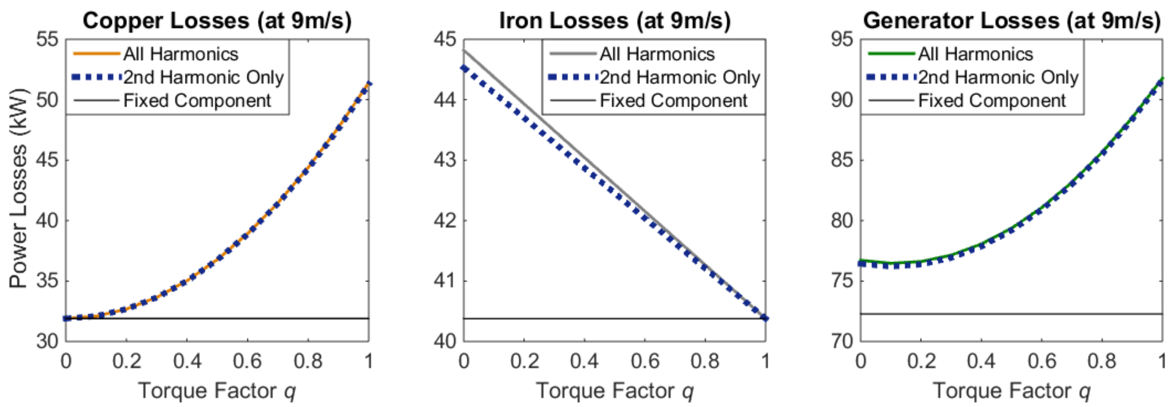

Fig. 4 Generator Losses at Fixed Wind Speed (9m/s)

Fig. 4 shows how the generator losses varied with q (at a fixed wind speed). These plots agree with the equations outlined in Equations 4-6; the copper losses increased with q^2 while the iron losses decreased linearly with q. With the generator design in that case study, the copper losses had a bigger influence on the total losses of the generator than the iron losses; which explains why the total generator losses were minimised at q = 0.1 (as the copper losses are lower at low q). The optimal q setting depends on the specific design of the generator used as well as the particular wind speed.

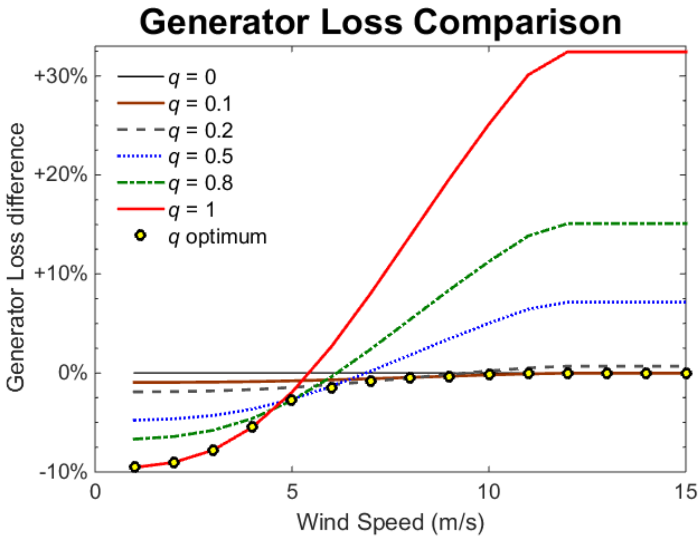

Fig. 5 Generator Loss Difference (relative to q=0 baseline)

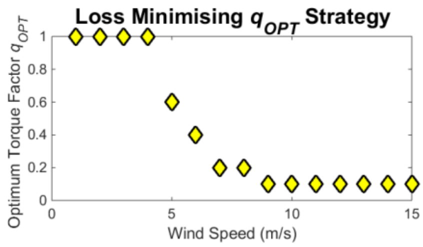

Fig. 6 q_{OPT} Strategy to Minimise Generator Losses

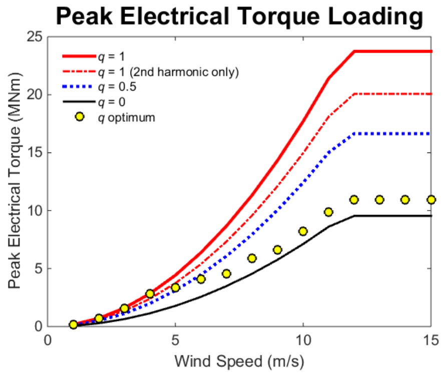

Fig. 7 Peak Electrical Torque for different q strategies

Fig. 5 demonstrates how the relationship between generator losses and torque control factor q evolves over the whole range of wind speeds. At low wind speeds iron losses dominate, while at high wind speeds the copper losses dominate. In Fig. 6 a variable q strategy was defined that minimises the generator losses for each individual wind speed. This strategy involved running a fixed speed regime (q = 1) at low wind speeds, while at rated operation running a low q setting (reducing torque variations). In between there is a cross-over area where running an intermediate q setting is optimal (its location depends on the generator design). One by-product of this loss minimisation strategy is that by running a low q setting at rated operation, the peak electrical torque experienced by the generator is decreased (as shown in Fig. 7). As a result it may be possible to reduce the size and rating of the generator resulting in a potential cost saving.

2.7. Case Study Generator Specifications

The generator used in this case study is a directly-driven permanent magnet generator designed for use in an offshore 10MW H-rotor VAWT. It has evolved from a 3MW HAWT generator as defined by Polinder [4]. The generator is comprised of 160 pole pairs covering a stator radius of 5.8m and a stack length of 2.6m. More specifications are listed in the appendix at the end of this paper. For this case study the electrical torque is set so that the mean electrical torque produces a mean rotor speed equal to a tip speed ratio of 4. This ensures that there is a fair comparison between different q settings by minimizing the difference in rotor speed between them and avoiding dropping the tip speed ratio below the recommended value of 3 (see Ferreira and Zanon [8]).

3. Results

3.1. Mechanical Torque

Using the panel method algorithm to calculate the effects of the varying wake from a varying rotor speed, the mechanical torque against azimuth angle was calculated for the whole range of torque control q settings between 0 (fixed electrical torque) and 1 (fixed rotational speed). Fig. 8 shows the resulting mechanical torque loadings, the corresponding electrical torque settings, the rotational speed and the mechanical power output from the rotor.

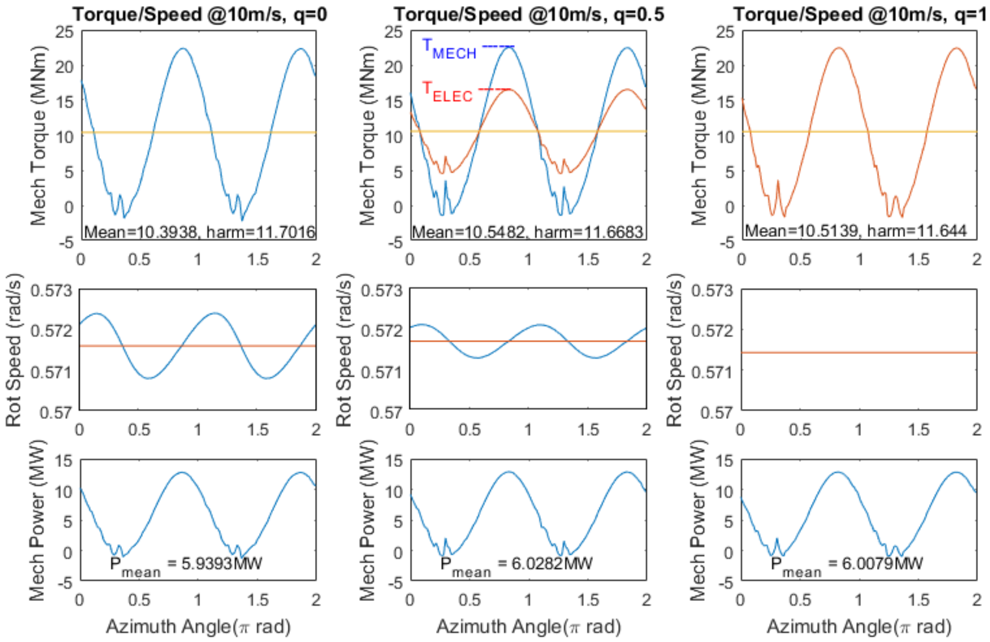

Fig. 8 Mechanical Torque Loading incorporating aerodynamic effects (at 10m/s)

Due to the large inertia of the test turbine, the variation in rotor speed is very small; in particular the maximum variation of rotor speed (achieved in the $q = 0$ case) is only ±0.2% about the mean. In practice, this means that the change in the wake of the rotor is so small that there is no discernible pattern between mean mechanical torque and q setting.

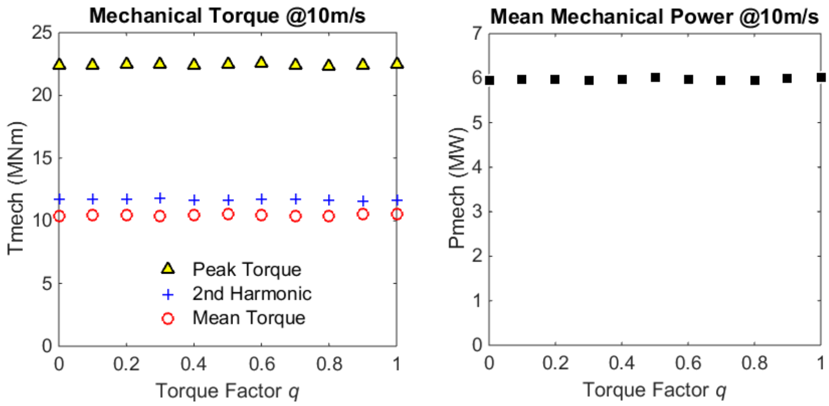

Fig. 9 Comparison of Mean Mechanical Torque and Power at 10m/s

Fig. 9 shows the magnitude of the fixed component, and the 2^{nd} harmonic across the range of q settings, where there is no pattern of increase or decrease in either harmonic torque component against q (any small variations are down to modelling uncertainty).

3.2. Aerodynamic Inefficiencies from q Strategies

When analysing the effect of the changing aerodynamic wake on the generator losses it is best to consider the effect on each harmonic individually upon the copper and iron losses. Fig. 10 shows how copper and iron losses from the different components vary with q when factoring in the mechanical torque as calculated above.

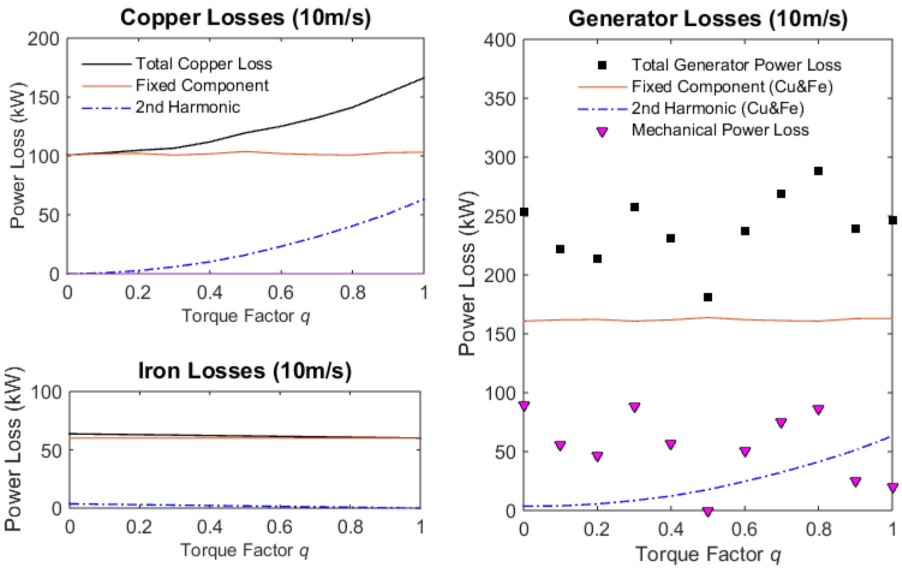

Fig. 10 Generator Losses (Aero Factored) at 10m/s

Since the mechanical torque coefficients only change by a relatively small amount between different q settings, the overall form of the iron and copper losses remain similar to the forms previously established [3]. There is some slight variation in the mean mechanical torque and so there is a corresponding variation in the fixed component of the copper losses between different values of q. However, the overall shape of the copper losses remains close to the quadratic form previously mentioned. It is hard to discern any change in the iron losses as the electrical frequency variation between different q settings is not significant on this scale, therefore the iron losses keep to their previously defined linear form.

There is a third loss type to consider and that is the loss in mechanical power from the wake, which is defined as the difference between the mean mechanical power of any given q setting subtracted from the case that gives the largest mean mechanical power. Due to the aforementioned variation in the mean mechanical torque, and thus the mean mechanical power, it is hard to draw conclusions about relationship of this loss against q. However, it does have the potential to contribute a sizable proportion of the total losses, as the variation in this case is more than the variation in copper losses (which dominate over iron losses). Therefore, this mechanical power loss cannot be ignored.

Fig. 10 shows that in terms of loss magnitudes, the fixed component of generator losses are largest, then come the aerodynamic losses and then the generator losses associated with the 2nd harmonic.

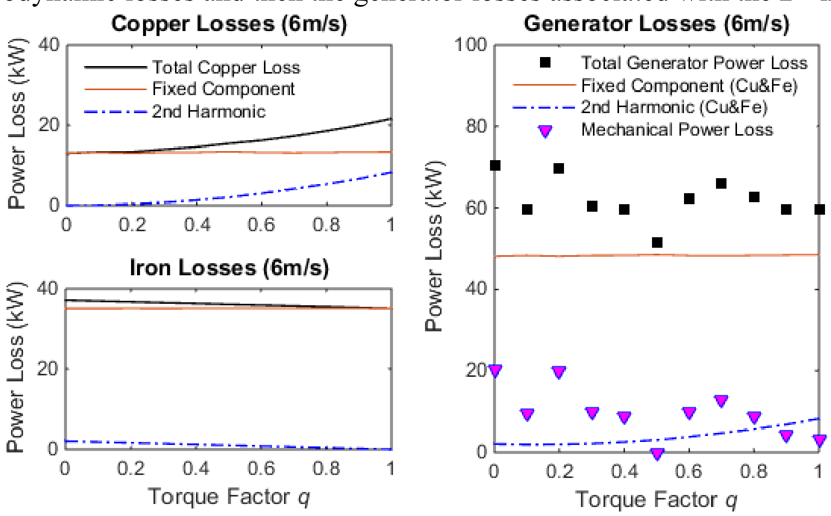

Fig. 11 Generator Losses at 6m/s

Analysis was also carried out at a lower wind speed of 6m/s where the iron losses have a greater effect on the total losses. The results (as shown in Fig. 11) are not significantly different from that at 10m/s with some slight variation in the fixed component of the copper losses, but with the copper and iron losses behaving in line with previous patterns, while the mechanical power loss (though noisy) again contributed to the overall generator losses, particularly at lower q settings.

4. Discussion

4.1. Implications of Varying Aerodynamic Wake on generator inefficiencies

Previous research showed that the generator losses could be minimized by running a variable q strategy that involved running at high q for low speed operation and at a lower q setting as the speed approached rated [3]. This low q operation would result in a larger variation in rotational speed which could cause aerodynamic inefficiencies due to the changing wake. This is the reason for investigating the effect on the varying wake on the turbine losses. This would be comprised of the direct effects on the copper and iron losses from the varying mechanical torque experienced (due to the changing aerodynamic loading of the blades from the varying wake) as well as an additional power loss due to an overall reduction of the mechanical power available.

As it turned out, the large moment of inertia of the test H-rotor VAWT resulted in only a relatively small variation in rotational speed (which was only ±0.2% for the q = 0, fixed torque case). This would likely limit the change in the wake to a point that its effect would be barely noticeable. The variation in the mean torque seems not to follow a clear pattern and it is likely that this 'noise' is a result of some of the modeling assumptions and simplifications.

The noise did lead to a small variation in the mean component of the copper losses (which are directly proportional to the mean mechanical torque) but otherwise did not cause a significant effect on the copper and iron losses. However the variation in power loss from variations in mean mechanical power was of an order to have a noticeable effect on the overall power loss of the generator. While it is likely that this effect has a lower magnitude than that demonstrated here, it requires further investigation as it could still have a measurable effect on the overall turbine loss (particularly at low q) which could potentially alter the shape of the loss minimizing strategy.

4.2. Future Research

Future work will be carried out to reduce the noise of the aerodynamic data by improving the integration of the aerodynamic code with the generator loss code. This will allow for a more definitive analysis of the relationship between mechanical torque and q setting incorporating changing wake effects. This will also be tested for a turbine with a lower moment of inertia – e.g. turbines with smaller swept areas or lighter rotor blades – to allow for a larger variation in rotational speed and to quantify the impact of moment of inertia.

Further research will also go into the effects of rescaling the generator and limiting the electrical torque variation allowed (particularly at rated operation). The strategy to reduce generator losses involves running a low q at rated speed and this reduces the peak electrical torque. In addition, the cost of the generator will also be modelled in order to balance out the potential loss increase against the cost savings from running a smaller generator as opposed to an under-used large generator.

5. Conclusions

This research demonstrates that the aerodynamic inefficiencies caused by the cyclic variation of rotational speed of a Vertical Axis Wind Turbine have the potential to have a noticeable impact on the turbine total losses experienced when running at or near fixed torque operation because of a reduction in the mean mechanical power available. The pattern of this impact is not clear, but appears to be of a significant magnitude. As improvements in the methodology are introduced, it is hoped that the 'noise' can be removed and so optimal q values can be found for different turbine/generator combinations at

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each wind speed. The likely impact is limited by the large moment of inertia of a multi-MW offshore VAWT which reduces the variation in rotor speed.

This aerodynamic loss is combined with the previous work on copper and iron losses which need to be individually calculated for the specific VAWT generator to assess the torque control strategy that minimizes overall generator losses. Furthermore, these loss calculations are part of a larger model to calculate the overall costs and losses of the drivetrain associated with the characteristics of VAWTs which need to be factored in optimizing the drivetrain to minimize the cost of energy contribution of the drivetrain as part of the evaluation as to the viability of VAWTs for use in offshore commercial generation.

Acknowledgements

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Appendix: Generator Data

Rated Power	10MW
Rated Speed	12m/s (@5rpm)
Turbine System Moment of Inertia	1.05×10^8 kg m^2
Stator Radius	5.8m
Stack Length	2.8m
Pole Pairs / Pole Pitch	160 / 114mm
Stator Tooth (Width × Height)	18mm × 80mm
Stator Slot (Width × Height)	20mm × 80mm
Stator Yoke (Height)	40mm
Rotor Yoke (Height)	40mm
Rotor Magnet (Width × Height)	79mm × 15mm
Air Gap	5mm

Table 1 Case Study Generator Data