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VERTICAL AXIS WIND TURBINES: MINIMISING GENERATOR LOSSES BY TORQUE CONTROL

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ABSTRACT

Vertical Axis Wind Turbines (VAWTs) tend to produce mechanical torque which varies significantly with rotor azimuth angle. The cost of the electrical generator is related to the peak generator torque which in turn depends on the choice of torque/speed control strategy. This choice of control strategy also affects the copper and iron losses of the generator; these can be modelled using harmonic analysis. The paper demonstrates how an optimal control strategy (from a generator loss point of view) can be achieved without significant extra cost.

NOMENCLATURE

q	Torque Control Factor (dimensionless ratio)	h	Harmonic Number
T, $\bar{T}$	Torque, Mean Torque (Nm)	n	Largest Harmonic Number Considered
T_h	Harmonic Torque Magnitude (Nm)	α	Angular Acceleration (rad/s^2)
J	Moment of Inertia of the Rotor (kg m/s^2)	ω	Rotational Speed (rad/s)
I	Stator r.m.s. Current (A)	f_e	Electrical Frequency (Hz)
b	Number of blades on the turbine rotor (default = 2)	p	Number of Generator Pole Pairs

INTRODUCTION

In recent years there has been increased research into the use of Vertical Axis Wind Turbines (VAWTs) for use in commercial offshore generation. Two specific designs under research and development are the Aerogenerator V-rotor [1] and the VertAx H-rotor [2] which both use directly driven permanent magnet generators.

One of the inherit disadvantages of VAWTs compared to conventional Horizontal Axis Wind Turbines (HAWTs) is the cyclic torque loading caused by the varying angle of attack during each revolution of the rotor. The resulting losses experienced by the generator, and how they are influenced by the generator's response, is what this paper is concerned with. The cyclic torque can be represented by a Fourier series and the overall generator losses can be calculated by summing up the effects of the individual sinusoidal components. It is assumed that at rated wind speeds the turbine has pitch (or similar) regulation that can be used to limit speed and torque.

METHODOLOGY

This paper looks at the effects of cyclic torque loading on a directly driven permanent magnet generator for a 5MW VAWT. This involves defining a sample mechanical torque loading and the generator's electrical torque response which are then combined with a generator model to calculate the losses associated with various torque control strategies.

The cyclic mechanical torque loading on the generator (caused by the varying angle of attack of the rotor blades) can be represented by a Fourier series of sine waves about a mean torque $\bar{T}$ (as described by Equation 1). This cyclic torque can result in an imbalance between the electrical and mechanical torque. The response of the rotating inertia to this torque imbalance is defined by Newton's 2nd Law for a rotating system (Equation 2), the resulting angular acceleration α of the rotor leads to the variation in rotational speed ω.

Mechanical Torque (Equation 1)

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

Newton's 2nd Law – rotating (Equation 2)

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

Torque Factor q (Equation 3)

$$q = \frac{T_{\Delta\mathrm{elec}}}{T_{\Delta\mathrm{mech}}}$$

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The electric torque response of the generator (controlled by adjusting the current through the stator coils) takes a similar form to Equation 1. However there is a parameter which limits the electrical torque variation and reduces the peak electrical torque experienced by the generator. This torque control parameter q is defined (in Equation 3) as the ratio of the electrical torque variation divided by the mechanical torque variation and is applied uniformly to all torque harmonics. A demonstration of how this is applied to the electrical torque is shown in Figure 1.

The torque control strategy can be set between two basic strategies. Fixed Torque operation (q = 0) keeps the electrical torque fixed but also results in the maximum variation in rotational speed. By contrast, Fixed Speed operation (q = 1) keeps the electrical torque equal to the mechanical torque at all times, but this results in the largest peak torque of any strategy. Any q strategy between 0 and 1 will result in some combination of both electrical torque and rotational speed variation (Figure 1 shows the resulting variation for q = 0.5).

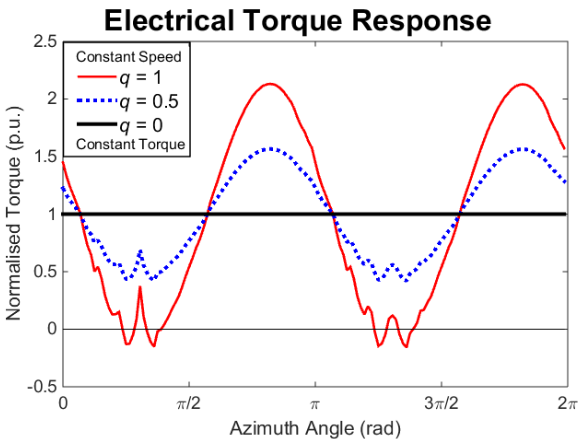

Fig. 1. Cyclic variation of Electrical Torque for different Torque Factors q

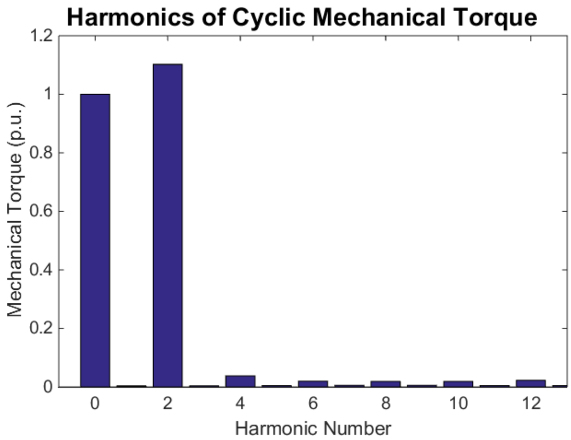

Fig. 2. Harmonic Components of Cyclic Mechanical Torque Loading

Figure 2 shows the harmonic components of the mechanic torque normalised to the magnitude of the mean torque (i.e. $\bar{T}$ is equivalent to a magnitude of 1 p.u.). The predominant harmonic for this 2-bladed turbine is the 2nd harmonic corresponding to a sinusoidal torque at a frequency twice that of the rotor speed. If the rotor had three blades then the 3rd harmonic would dominate. For this test turbine the magnitude of the 2nd torque harmonic is 1.1 p.u. which corresponds to 68% of the sum of all harmonic components (1.63 p.u. excluding $\bar{T}$).

The 5MW directly-driven permanent magnet generator in this case study is designed for use in an offshore H-rotor VAWT. It has evolved from Polinder's 3MW HAWT generator [3] using parameters from Michon [4], e.g. power output and rotational speed. It has a stator radius of 5.8m, a stack length of 2.8m and it is comprised of 160 pole pairs.

The generator is simulated by modelling a generator segment (single pole pair) using a combination of an equivalent electrical circuit (as described by Polinder [3]) modelled in MATLAB and a magnetic circuit modelled in the 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 inductances are modelled using the approach as outlined by Polinder [3] while the current is set to provide the desired electrical torque response.

This research focused on the generator losses from the copper and the iron. The copper losses depend on the current through the stator coils (proportional to the electrical torque response) and are calculated by integrating the varying I^2R losses over an entire rotor revolution. Equation 4 shows how copper losses vary with both the square of q and the square of the current harmonics I_h (which are proportional to the torque harmonics T_h). The copper losses are largest during fixed speed (q = 1) operation where the rate of increase in copper losses is much larger than that of the iron losses.

Copper Losses (Equation 4)

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

Mean Electrical Frequency (Equation 5)

$$\bar{f_e} = \frac{p}{2\pi}\left(\omega_0 + \frac{(1-q)}{b\,J\,\omega_0}\sum_{h=1}^{n}\frac{T_h}{h}\right)$$

$$\overline{f_e^2} = \left(\frac{p}{2\pi}\right)^2\left(\omega_0^2 + \frac{2(1-q)}{bJ}\sum_{h=1}^{n}\frac{T_h}{h}\right)$$

Iron Losses (Equation 6)

$$P_{Fe} = \sum_{i}\left(A_h\bar{f_e} + A_e\overline{{f_e}^2}\right)\hat{B}_{Fe_i}{}^2 m_i$$

Summed up for all steel segments i

$$A_h = \frac{2P_{Fe0h}}{f_0\hat{B}_0{}^2} \quad A_e = \frac{2P_{Fe0e}}{{f_0}^2\hat{B}_0{}^2}$$

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 Equation 2 (for α) and substituting into the angular equations of motion; this is then integrated over the complete revolution to calculate mean values of both the electrical frequency and the square of electrical frequency (Equation 5). Using the method outlined by Polinder [3] the iron losses are calculated individually for the stator teeth and yoke before being summed up (Equation 6). The iron losses have a component that is proportional to (1-q), therefore the iron losses are largest during fixed torque operation (q = 0) and decrease linearly with wind speed.

As for the relative importance of the torque harmonics on losses, the copper losses depend on the torque (and hence current) magnitude squared; therefore 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 torque magnitude divided by the harmonic number meaning that the higher harmonics will have less of an impact. In this case study the copper and iron losses for all harmonics will be compared with that of the 2nd harmonic only.

RESULTS

This first set of results in (Fig. 3) demonstrate how the torque factor q affects the copper and iron losses at a fixed wind speed (9m/s). Considering the second harmonic only, the copper losses increase with the square of q (as in Equation 4) while the iron losses decrease linearly with q (Equations 5-6). Since the other harmonic coefficients of the mechanical torque are small compared to the 2nd harmonic, they do not contribute a great deal to the losses, in particular the copper loss, although they have a greater effect on the iron losses. The relative magnitude of these losses will vary with q. For this generator (at a 9m/s wind speed) the total losses are minimised when the torque factor is set to q = 0.1.

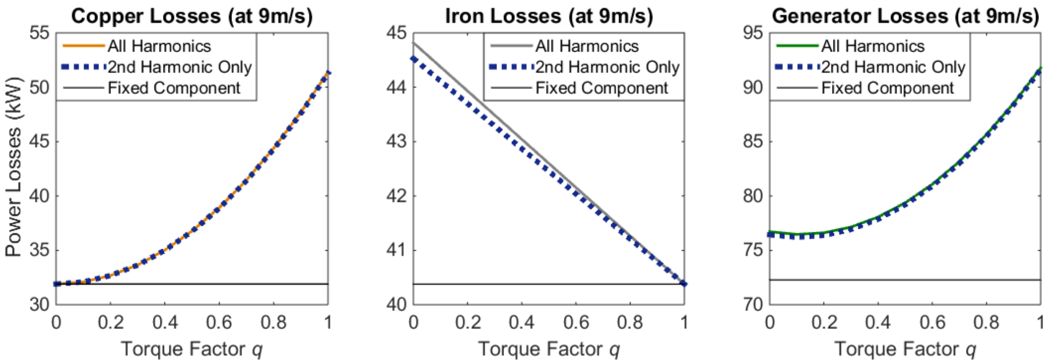

Fig. 3. Generator Losses (at 9m/s) considering (a) 2nd Harmonic only, (b) All Harmonics

The next test involves assessing the combined generator loss for different q strategies across the full spectrum of wind speeds. In the interests of clarity the results (Figure 4) show the difference in the generator loss compared to the baseline q = 0 fixed torque strategy. In addition only the losses for the full set of torque harmonics are shown. Figure 5 describes the strategy where the q setting is adjusted for each wind speed to minimise the total generator losses. This strategy results in fixed speed operation (q = 1) for low wind speeds, with q reducing for medium wind speeds down to a final setting of q = 0.1 at rated wind speed. The exact details of this relationship (including crossover point and q at rated speed) depend on the relationship between iron and copper losses due to the specific generator design. The optimal strategy at high wind speed is explained by the dominance of copper losses (over iron losses) which can be minimized when $q \rightarrow 0$; however at low q the reduction in iron losses w.r.t. q are more significant than the increase in copper losses.

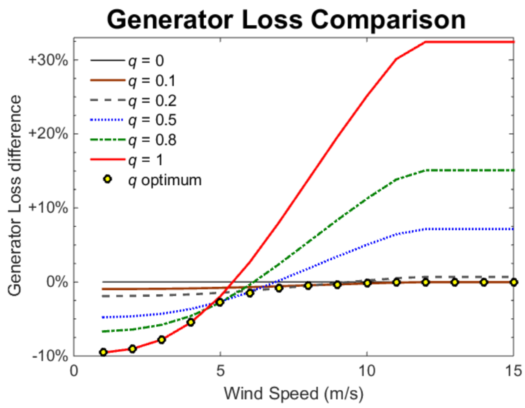

Fig. 4. Generator Loss Difference (relative to q=0 baseline)

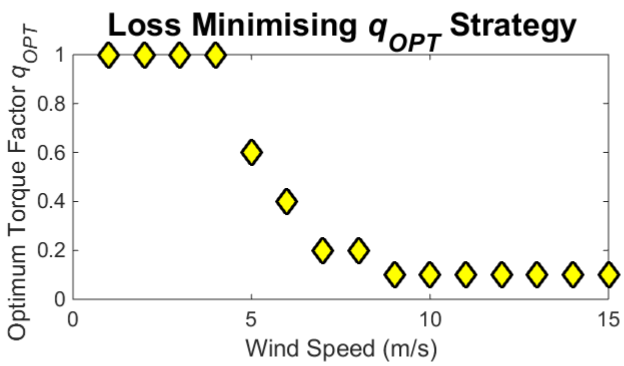

Fig. 5. q_{OPT} Strategy to Minimise Generator Losses

The annual energy losses for each q strategy can be calculated using the energy loss per hour for each wind speed and the prevalence of each wind speed from the Weibull distribution. These results are compared against the baseline q = 0 strategy in Table 1. For this turbine, the best strategy for a fixed value of q is when q = 0.2, although this only results in a 0.1% loss reduction against the baseline. The fixed speed (q = 1) strategy results in a 20% increase in energy losses due to the large increase in copper losses. The variable q loss minimization strategy reduces losses by 0.8% over the best fixed q strategy. It is also worth noting that the losses can be closely approximated by considering only the mean torque and the 2nd torque harmonic.

Torque Factor q	All Harmonics: Annual Losses [MWh]	All Harmonics: % Loss (vs q=0)	2nd harmonic (h=2): Annual Losses [MWh]	2nd harmonic (h=2): % of Loss from h=2
0	504.3	0.0%	502.4	99.63%
0.2	503.7	-0.1%	502.2	99.70%
0.4	513.4	+1.8%	512.1	99.76%
0.6	533.3	+5.8%	532.3	99.80%
0.8	563.6	+11.8%	562.6	99.84%
1	604.1	+19.8%	603.2	99.86%
q_{OPT}	499.7	-0.9%		

Table 1: Annual Energy Losses for different q strategies

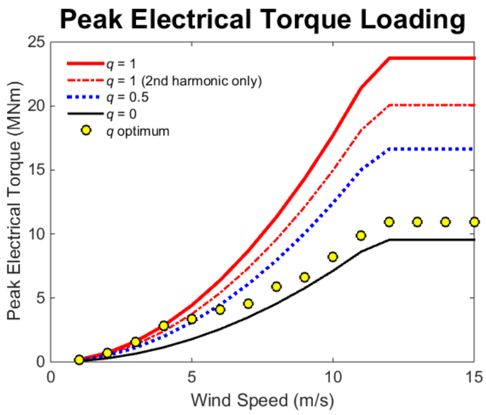

Fig. 6. Peak Electrical Torque at different wind speeds for different q strategies

Figure 6 compares the peak electrical torque rating necessary for different q strategies. A generator has to be rated to the largest torque it expects to develop within normal operation. By controlling the electrical torque of the generator (using a q < 1 strategy, particular at rated speed) the rating of the generator can be reduced which also reduces its cost. As described previously, the loss minimization strategy runs a low q at rated wind speed and as a result the peak torque experienced by the generator approximates to the mean torque. This restriction in q at rated operation has little bearing on the operation at lower wind speeds allowing for high q operation to reduce iron losses at low wind speeds while remaining below the reduced rating of the machine. It is also important to note that handling the full range of torque harmonics results in a higher peak torque than the sinusoidal equivalent.

CONCLUSIONS

This paper shows that for a VAWT generator adjusting the torque/speed control strategy of the generator can lead to potential loss reductions of the generator, while allowing the generator to adapt for changing wind speeds can lead to the biggest reductions. In general it is better to run a fixed speed strategy at low wind speed and reduce the electrical torque variation at higher wind speeds (the exact optimal strategy will depend on the specific generator design). This case study has shown that a sinusoidal approximation of the torque variation based on the 2nd harmonic for a 2 bladed turbine is a good approximation especially when calculating the energy loss of the generator (although the cumulative effect of these harmonics on the peak torque experienced does need to be taken into account).

The loss minimization strategy of varying q with wind speed also reduces the peak electrical torque experienced by the generator which in turn offers the opportunity to specify a smaller, cheaper generator for use in this VAWT. There are still additional factors that need to be accounted for such as the effects of resizing a generator on the losses in order to improve the generator model for use in an optimisation of generator design as part of the process to establish the viability of VAWTs for commercial offshore generation. There is likely to be aerodynamic penalties for some torque/speed control settings that also need to be taken into account.

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