Vertical Axis Wind Turbine Case Study: Costs and Losses associated with Variable Torque and Speed Strategies

Michael Argent[1], Alasdair McDonald[1]

[1] CDT Wind Energy Systems, Rm 3.36, Royal College Building
University of Strathclyde, 204 George Street, Glasgow, G1 1XW

michael.argent@strath.ac.uk

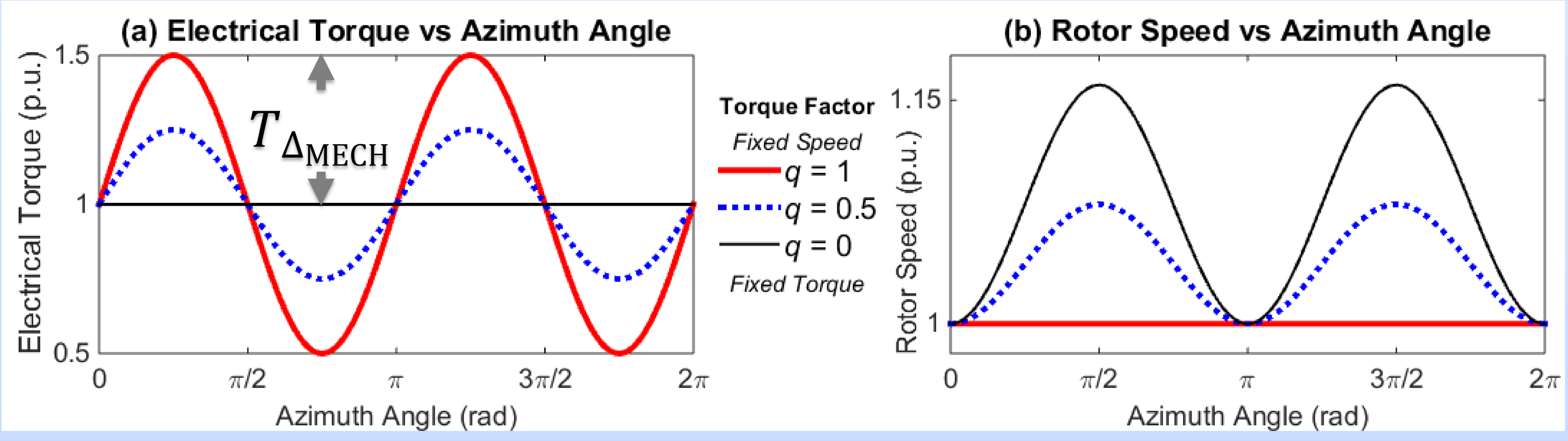
University of Strathclyde Engineering

1) OVERVIEW

- Generator Case Study for Large Offshore VAWT
- Directly Driven Permanent Magnet Generator (DD PMG)
- Modelling effect on costs & losses of inherent cyclic torque loading caused by periodic variation in aerodynamic load from rotor blades
- Strategies to control magnitude of electrical torque variation *q* ratio
- Equations for Copper and Iron Losses based on these strategies
- Relationship between cost and electrical torque variation allowed
- ***Work presented is part of 3 year PhD into VAWT Drivetrains***

2) CYCLIC TORQUE

- Mechanical torque is modelled using a sinusoidal variation
  $T_{\mathrm{MECH}} = \bar{T} + T_{\Delta}\sin(2\theta)$ [2 bladed rotor]
- Electrical torque control is parameterised by $q = \frac{T_{\Delta\mathrm{ELEC}}}{T_{\Delta\mathrm{MECH}}}$
- Torque control strategies can vary between two extremes: $q = 0$ (fixed T_{ELEC}) and $q = 1$ (fixed rotor speed)



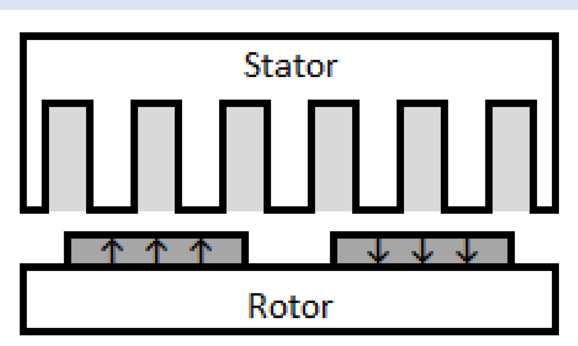
- Depending on the strategy, there can be a torque imbalance between T_{MECH} and T_{ELEC} resulting in a changing rotor speed:
  $T_{\mathrm{MECH}} - T_{\mathrm{ELEC}} = J\alpha$
- The variance in electrical torque and/or rotor speed will effect the copper and iron losses experienced by the generator

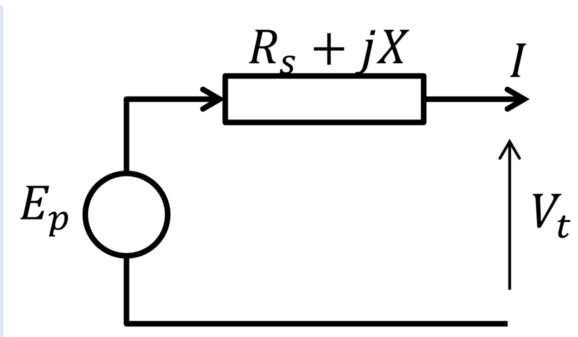
Varying T_{ELEC} (q>0)	**Varying Rotor Speed (q<1)**
Varying Current I	=> Varying Electrical Frequency
Copper Losses : $\int I^2R$	Iron Losses depend on f_e
$P_{Cu} = R\left(\bar{I}^2 + \frac{1}{2}(qI_{\Delta})^2\right)$	$P_{Fe} = \sum\left(A_h\bar{f_e} + A_e\overline{f_e^2}\right)\hat{B}_{Fe_i}^{\,2} m_i$ Both $\bar{f_e}$ & $\overline{f_e^{\,2}}$ proportional to $(1-q)$
Copper Losses ∝ q^2	**Iron Losses ∝ $(1-q)$**

- Generator cost depends on peak electrical torque loading

3) GENERATOR MODELLING

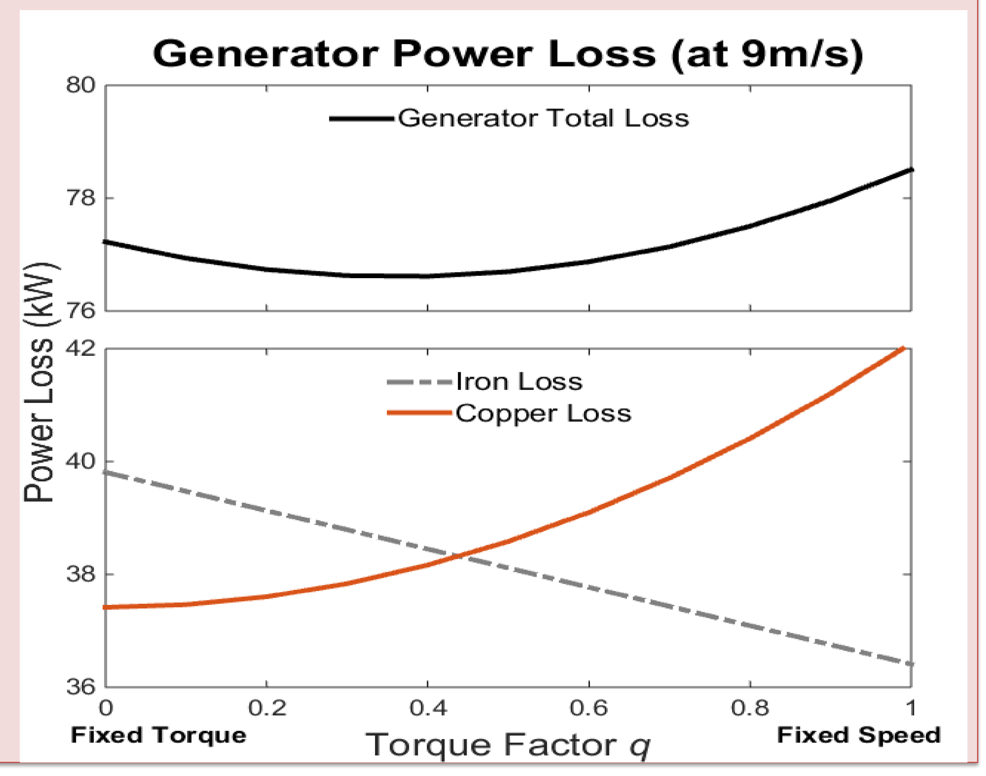
- Single pole pair of generator modelled
  - Electrical equivalent circuit in MATLAB
  - Magnetic Circuit Model in Finite Element Analysis package FEMM
- Programming Procedure:
  - MATLAB calculates generator sizings
  - FEMM calculates airgap flux density
  - MATLAB calculates equivalent circuit and resulting power output & losses
- Generator is 5MW DD PMG for use in offshore H-rotor VAWT, *see paper for specs*





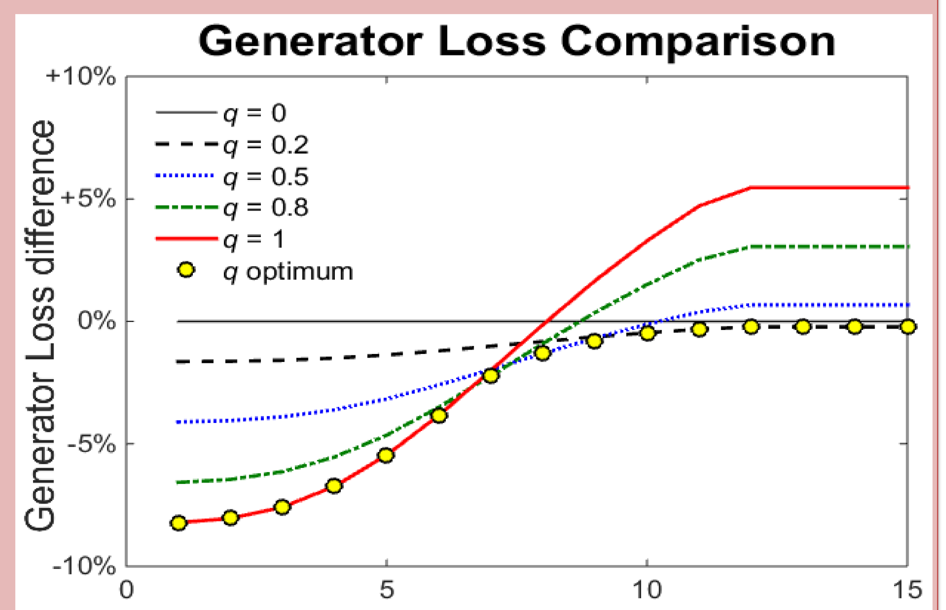
4) LOSSES FOR A FIXED WIND SPEED

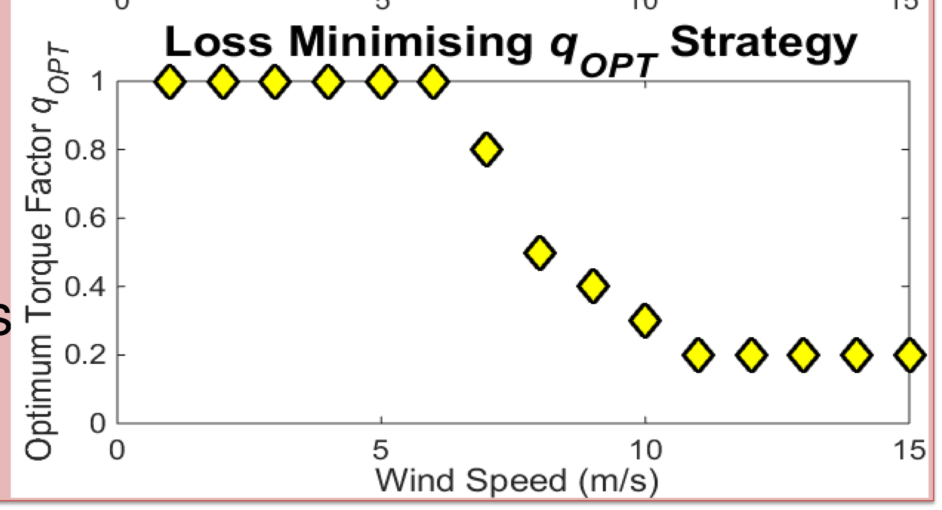
- Comparing how losses vary for different torque factor *q* settings.
- Copper losses increase with q^2
- Iron losses decrease linearly with *q*
- At this speed losses are of similar magnitude
  - For 9m/s Losses minimised at *q*=0.4



5) LOSS MINIMISATION STRATEGIES

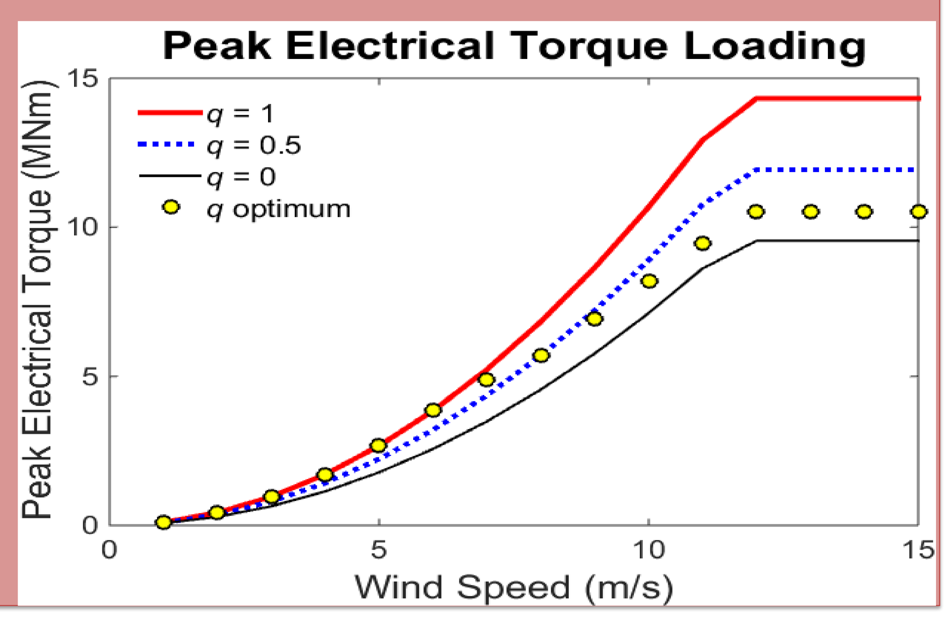
- Calculate losses for each *q* strategy for whole range of wind speeds (% change vs fixed torque setting *q*=0)
- **Losses minimised when:**
  - ***q* = 1 at low wind speeds**
  - ***q* near 0 at high speeds**
  - **0<*q*<1 medium speeds**
- A loss minimisation strategy q_{OPT} can be setup which varies *q* with wind speed to minimise generator losses
- q_{OPT} **0.8% loss reduction** vs best single *q* strategy (*q*=0.4) (1.5% vs *q*=0 fixed torque)





6) PEAK TORQUE AND COSTS

- Peak $T_{\mathrm{ELEC}} \propto q$ (larger peak torque for fixed speed than fixed torque requires larger generator)
- q_{OPT} strategy: lower torque at rated => lower cost
- Restricting *q* at rated can lead to cost saving



7) CONCLUSIONS

- Adjusting torque control strategy can lead to loss reductions
- Biggest reductions allowing generator to adapt to wind speed
- Loss reduction: fixed speed at low wind speeds
  low torque variation at higher speeds
- Future research: aerodynamic efficiency from speed variation (potential loss at low *q*, limited effect due to large rotor inertia); rescaling the generator (smaller generator with limit on *q* at rated)
- ***PhD Overall Aim: optimise the VAWT powertrain design to minimise Cost of Energy & compare with commercial HAWTs***

EPSRC Engineering and Physical Sciences Research Council

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