Drivetrain Optimization in Multi-megawatt Offshore Wind Turbines

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Outline of the Presentation

1 Introduction

2 Proposed drivetrain optimization approach

3 Generator optimization

4 Gearbox optimization

5 Numerical results

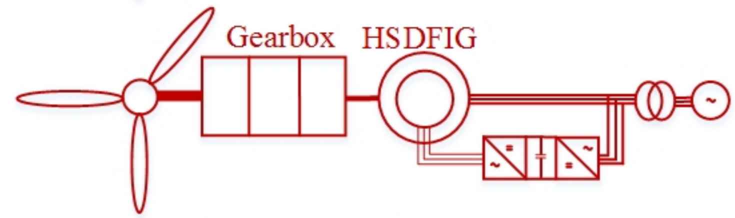
5 Conclusion

Introduction

Drivetrain Most Conventional Technologies

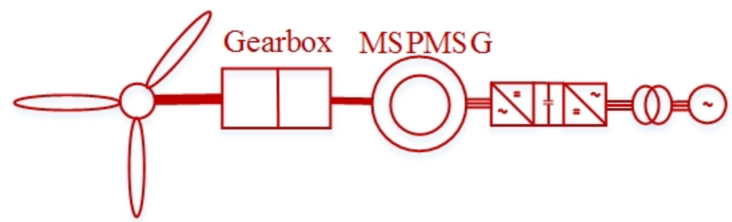
- High-speed induction generator
  - ➢ Advantages: cheap
  - ➢ Disadvantages: sensitive to transients & dynamics, low efficiency

- High speed doubly fed induction generator
  - ➢ Advantages: cheap, fractional converter
  - ➢ Disadvantages: brushes, sensitive to transients, low efficiency



- Direct drive self-excited synchronous generator
  - ➢ Advantages: cheap
  - ➢ Disadvantages: brushes, low efficiency, higher weight

- Medium speed permanent magnet synchronous generator
  - ➢ Advantages: high efficiency, less weight
  - ➢ Disadvantages: expensive



- Direct drive permanent magnet synchronous generator
  - ➢ Advantages: high efficiency
  - ➢ Disadvantages: expensive

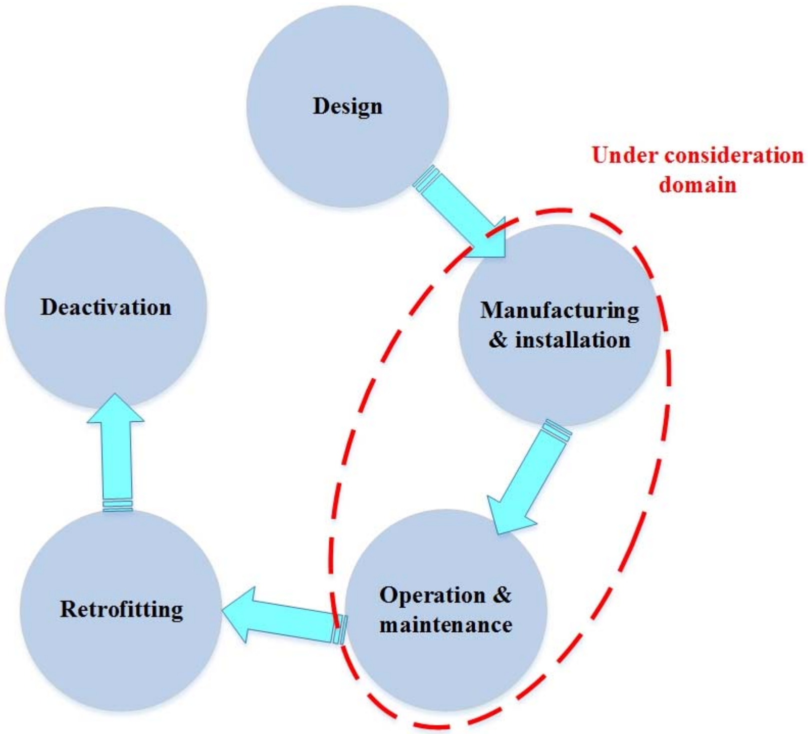
A Glance at Wind Turbine Industry

Most popular in offshore

IG	DFIG	DDSESG	DDPMSG	MSPMSG
SWT-4.0-130	GE 5.3-158	EN136-4.2	SG 8.0-167 DD	V164-10.0MW
Siemens	General Electric	Envision	Siemens	Vestas
4MW	5.3MW	4.2MW	8MW	10MW
Off-/onshore	onshore	Off-/onshore	offshore	offshore
1 : 119	geared	direct drive	direct drive	>41
V136-4.2 MW	SG 4.5-145	E-126 7.580	YZ150/10.0	SCD 8.0/168
Vestas	Siemens	Enercon	Swiss Electric	Aerodyn
4MW	4.5MW	7.6MW	10MW	8MW
onshore	onshore	onshore	offshore	offshore
geared (3 stages)	geared (3 stages)	direct drive	direct drive	1:27

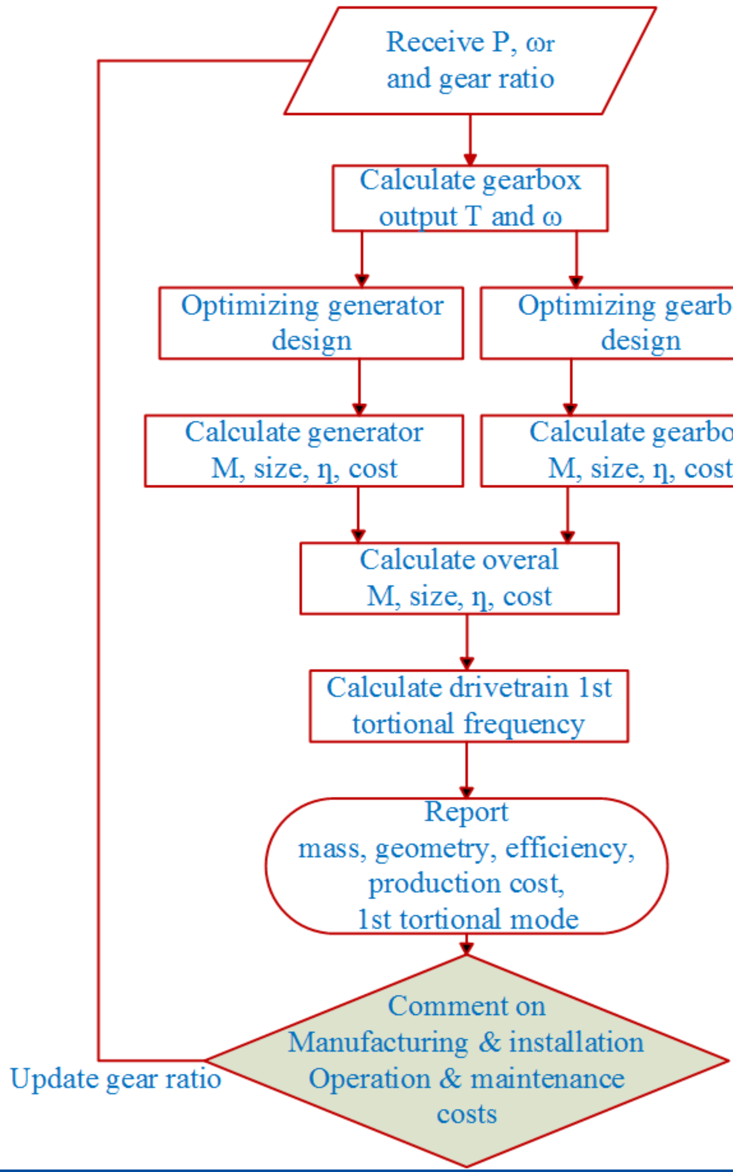
Permanent Magnet Synchronous Generator

- Most popular technology for offshore wind turbines
  - High efficiency
  - Low maintenance
- Direct drive
  - Gearbox removal
- Medium speed
  - Smaller generator
  - Less manufacturing efforts
  - Easier installation and maintenance
- Research problem:
  - Which topology gives the highest benefits?
- To answer, we need to see the performance over the life cycle
- We will focus more on
  - Production cost
  - Efficiency
  - Operation



Proposed Drivetrain Optimization

Proposed Drivetrain Optimization Approach



NTNU

Generator Optimized Design

Generator Optimized Design

- Cost function

$$C_{Gen}^{Act} = c_{Fe}m_{Fe} + c_{cu}m_{cu} + c_{PM}m_{PM},$$

where $c_{Fe}, c_{cu} and\ c_{PM}$ are the unit costs, and $m_{Fe}, m_{cu} and\ m_{PM}$ are the weight of active materials.

- Optimization variables
  - Air gap diameter (Ds), Stack length (Ls), Slot width (bs), Slot height (hs), Magnet height (hm)
  - The other design variables are either a function of optimization variables or constant
- Constant design variables
  - The values will change using an external loop, but will take a constant value in each optimization: Slot per pole per phase, Magnet width to pole pitch ratio, Air gap
- Dependent design variables
  - Air gap/teeth/stator yoke/ rotor yoke flux densities, stator/rotor yoke lengths, teeth width/height
- Subject to
  - A wide range of electrical loading, magnetic loading, insulation requirements, and mechanical forces mitigation, and efficiency based constraints to ensure a secure operation.
- Outputs:
  - Geometry, Weight, Cost, Efficiency
- Constrained nonlinear multi-variable nonconvex problem.
- Using Matlab Fmincon solver to find local optimizars.

Generator Optimization Results

- DTU 10MW PMSG realisation
  - Direct drive
  - Medium speed (G/R= 50)
  - High speed (G/R= 156)
- The following has been modelled
  - Carter impact
  - Iron fill factor
  - Insulation
  - 2-layers, full pitch
- Structure weight
  - Cooling
  - Beams
  - Cylinder
  - Shaft
  - Modeled as a function of design variables

Generator parameters	DDPMSG	MSPMSG	HSPMSG

Results will be reported in the paper.

Gearbox Optimized Design

Gearbox Optimized Design

- Cost function for a three-stages gearbox

$$C_{Gearbox}^{Gears} = c_{Fe}(m_{Gear}^{1} + m_{Gear}^{2} + m_{Gear}^{3}) \,,$$

where c_{Fe} is the unit cost of gears, and $m_{Gear}^{1}, m_{Gear}^{2} and\ m_{Gear}^{3}$ are the weight of 1st , 2nd and 3rd stages .

- Parallel stage: $m_{Gear}^{Parallel} = K_{AG}\frac{2Q_p}{k}(1 + \frac{1}{U_s} + U_s + U_s^2)$

- Planetary stage: $m_{Gear}^{Planetary} = K_{AG}\frac{2Q_s}{K}(\frac{1}{B} + \frac{1}{BU_{SN}} + U_{SN} + U_{SN}^2 + K_r\frac{(U_s-1)^2}{B} + K_r\frac{(U_s-1)^2}{BU_{SN}})$

- The overal cost function for a sample three-stages gearbox with two planetary and one parallel will be:

$$\begin{aligned} V = & \frac{2Q_0}{K}\frac{1}{U_1}\left[\frac{1}{B_1} + \frac{1}{B_1(\frac{U_1}{2}-1)} + (\frac{U_1}{2} - 1) + (\frac{U_1}{2} - 1)^2 + K_{r1}\frac{(U_1-1)^2}{B_1} + K_{r1}\frac{(U_1-1)^2}{B_1(\frac{U_1}{2}-1)}\right] \\ & + \frac{2Q_0}{K}\frac{1}{U_1U_2}\left[\frac{1}{B_2} + \frac{1}{B_2(\frac{U_2}{2}-1)} + (\frac{U_2}{2} - 1) + (\frac{U_2}{2} - 1)^2 + K_{r2}\frac{(U_2-1)^2}{B_2} + K_{r2}\frac{(U_2-1)^2}{B_2(\frac{U_2}{2}-1)}\right] \\ & + \frac{2Q_0}{K}\frac{1}{U_1U_2U_3}\left[1 + \frac{1}{U_3} + U_3 + U_3^2\right] \end{aligned}$$

where *U* is gear ratio, *B* is number of planets, *Kr* is ring scaling factor, *Q* is input torque.

- Subject to
  - Constraints related to gear ratio of each stage, and the overall gear ratio, concerning with the mechanical design limitations.
- Outputs: Optimized gear ratios, Weight, Cost, Efficiency
- Constrained nonlinear multi-variable nonconvex problem. Matlab Fmincon solver is used.

Gearbox Optimization Results

- DTU 10MW gearbox realisation
  - Direct drive
  - Medium speed (G/R= 50)
  - High speed (G/R= 156)

- Structure weight
  - Bearings
  - Housing
  - Carriers
  - Modeled as a fraction of gears weight

Gearbox parameters	MSPMSG	HSPMSG

Results will be reported in the paper.

Concluding Remarks

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- Results show that medium speed drivetrain seems to be a better option for offshore wind turbines.
- It would help to have a safe distance from the external excitations frequencies, and is recommended for offshore floating applications.
- Redection of drivetrain weight, and consequently reduction of nacelle weight potentially reduces the required nacelle, tower and platform costs.
- Impacts on reliability, operation and maintenance costs will be investigated in future works.