Comparative Advantage of Flux Switching PM Machines for Medium-speed Wind Drives

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Outline

- Introduction
- Study objective and methods
- FSPM machine
  - *basic topology/operation*
  - *overview*
- Comparison and results
- Conclusion and future work

Drivetrain Concepts

Parameter	High speed	Medium speed	Low speed
Speed	1500 rpm	200 rpm	30 rpm (depending on power level)
Mass	Lowest	Intermediate	Highest
Size	Smallest	Intermediate	Largest
Gearbox	Present (3G)	Present (2G/1G)	Absent
Generator	Asynchronous/ Synchronous	Synchronous	Synchronous
Losses	High gearbox losses during less wind	Intermediate	High thermal losses with stronger winds
Costs	Lowest for generators but high for gears and converters	Intermediate	High due to large amount of raw materials
Overall efficiency	Not as good	Best	Not as good

Introduction

- **It is on record that there is growing interest by wind turbine manufacturers in the medium-speed drivetrains [1].**
- **The three major drivetrains are high-speed (HS), medium-speed (MS) and low-speed (LS) (gearless) systems.**
- **The main concerns for low-speed systems, especially at MW ratings, have been on their increasing head mass, size as well as cost; whereas high downtime for gear transmission in high-speed has been observed.**

[1] **E. de Vries**. ABB shifts focus to medium speed drive systems. *WINDPOWER Monthly*, 4 September 2012.
Available at: http://www.windpowermonthly.com

Introduction (Contd.)

- **To this end, medium-speed drivetrains provide a good compromise for wind generator drives.**
- **Comparison in wind generator drives have been based on conventional generator topologies such as squirrel cage induction generators (SCIG), wound rotor induction generator (WRIG), double-fed induction generators (DFIG), electrically excited synchronous generators (EESG) and PM synchronous generators (PMSG) [4]-[6].**

Introduction (Contd.)

- **By comparing conventional PM generator in the three wind generator drivetrains, it was reported that MS drivetrains provide the lowest cost of energy and highest efficiency at full load [2].**
- **So far, the literature does not provide further details for such comparison among relatively newer wind generator designs vis-à-vis FSPM machines.**

[2] **S. Schmidt and A. Vath**. Comparison of existing medium-speed drive train concepts with a differential gearbox approach. *European Wind Energy Association*, Copenhagen, April 2012.

Objective and Method

- **Objective:**
  – To compare and evaluate different drivetrains of the flux-switching permanent magnet machine for wind generator drives.
- **Method:**
  – Two-dimensional finite-element analysis (2D-FEA) is employed to design and predict the operating point of a {semi-optimised [9], [10]} FSPM generator in the low-, medium-, and high-speed drivetrains for the same power level and design constraints.

[10] **L. E. Somesan; I. A. Viorel.** "Permanent magnet flux-switching machine, optimal design and performance analysis," *Advances in Electrical Engineering*, Vol. 11, no. 2, pp.46-53, 2013.

[11] **Z. Q. Zhu; Y. Pang; J. T. Chen; Z. P. Xia; D. Howe**. "Influence of design parameters on output torque of flux-switching permanent magnet machines," *Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE*, vol., no., pp.1, 6, 3-5 Sept. 2008.

FSPM Machine: Basic Topology/Operation

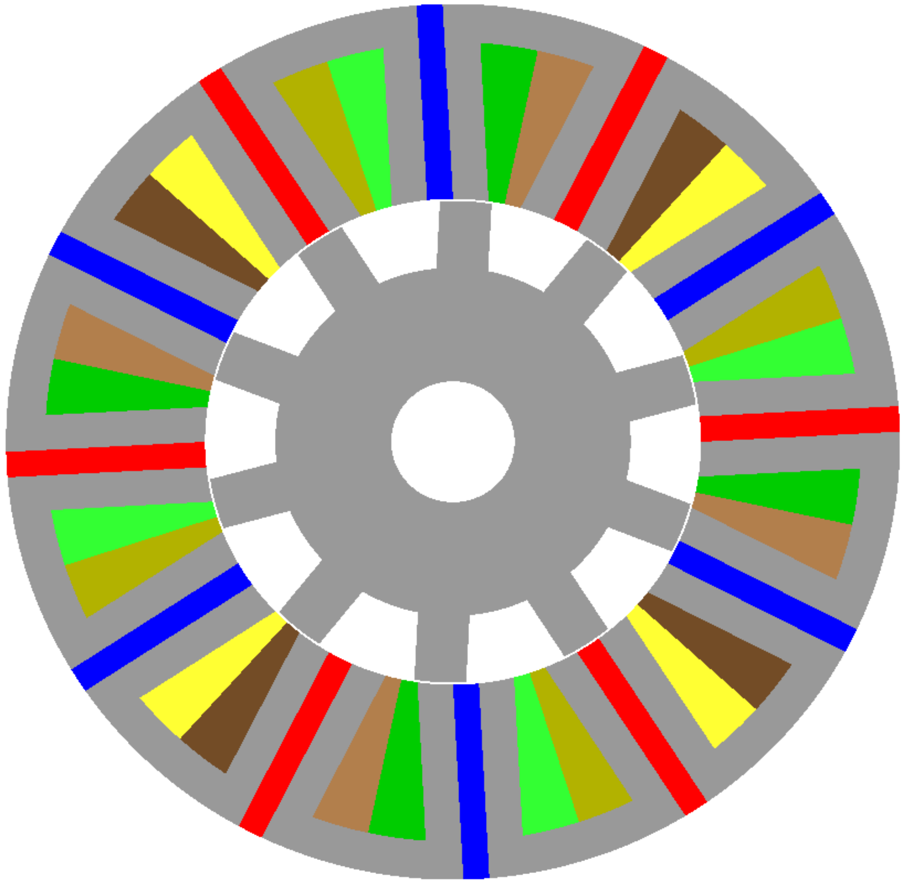

Fig. 1. Basic topology: 3-phase
12/10 FSPM model in static 2D-FEA.

FSPM Machine: Basic Topology/Operation (Contd.)

Operation: The alignment of a particular rotor pole with one part of a stator teeth over which a coil is wound, results in the movement of the flux from the stator to the rotor and vice versa.

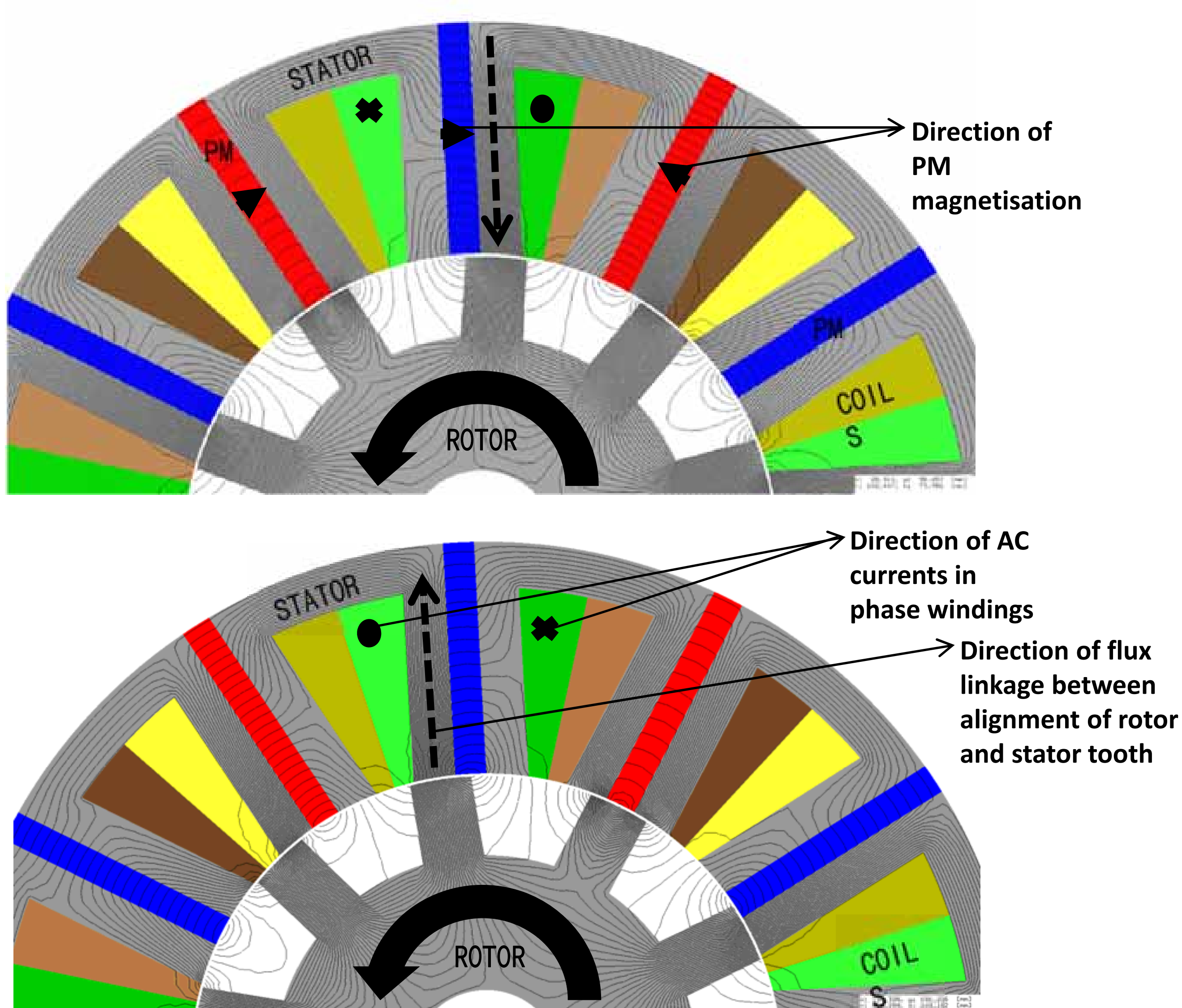

Fig. 2. Flux-linkage action in FSPM based on rotor movement.

FSPM Machine: Overview

- **FSPM is a non-conventional PM machine which has recently been on the spotlight :**
  - **high torque density due to robust rotor.**
  - **good thermal dissipation due to 'mainly-active' stator.**
  - **High efficiency due short end-windings due to concentrated winding arrangement.**
  - **high cogging torque due to high air-gap flux density and double saliency with backlash on wind power systems.**

FSPM Machine: Overview (Contd.)

- **The electrical period per mechanical revolution is given as:**

$$f_e = \frac{N_r n_m}{60}, \qquad (1)$$

  - where N_r is the number of rotor teeth and n_m is the mechanical speed of the machine in r/min.

- **The generated phase induced EMF is according to:**

$$E_g = N_t \frac{\pi n_m}{30} N_r k_E l_{st} \frac{\pi D_g}{N_s} \overline{B}_{g(\max)}, \qquad (2)$$

  - where l_{st} is the stack length, D_g is the machine air-gap diameter and N_s is the number of stator slots.

- **The electromagnetic torque of a three-phase FSPM machine in dq reference can be calculated using:**

$$T_e = \frac{3N_r}{2}\left[\psi_{max} i_q + i_d i_q \left(L_d - L_q\right)\right], \qquad (3)$$

  - where L_d, L_q, i_d and i_q are the dq-axis inductances and currents respectively, and ψ_{max} is the maximum air-gap flux.

Comparison and Results

The per unit **cogging torque** for the three FSPM machines is observed to be lowest in the MS drivetrain as shown in Fig. 6.

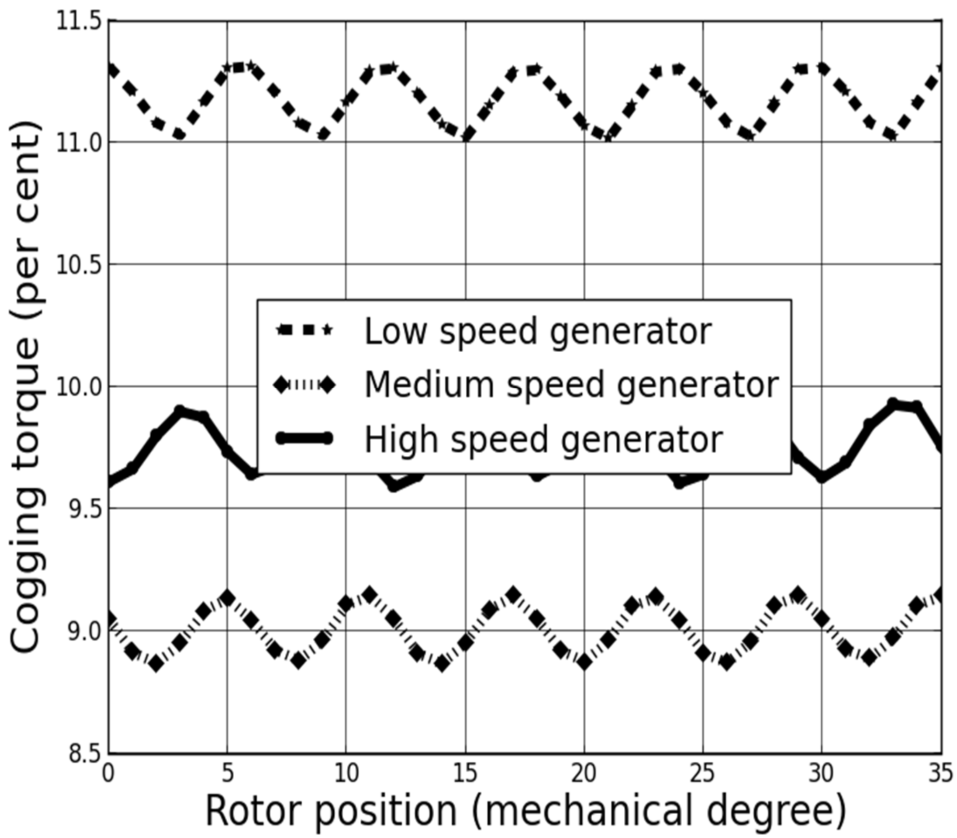

Fig. 6. Per unit cogging torque comparison for different FSPM drivetrains.

Comparison and Results (Contd.)

Also, $\boldsymbol{k_{PM}} = \frac{\boldsymbol{Torque}}{\textbf{PM}\ \boldsymbol{mass}}$, and is $\mathrm{k}_{\in}$, defined as: $\boldsymbol{k_{\in}} = \frac{\boldsymbol{Torque}}{\textbf{Total component}\ \boldsymbol{mass}}$ gives a good compromise for the MS drivetrain as shown in Fig. 7, though the best results is in the LS drivetrain because of its highest output torque potential amongst the three drivetrains.

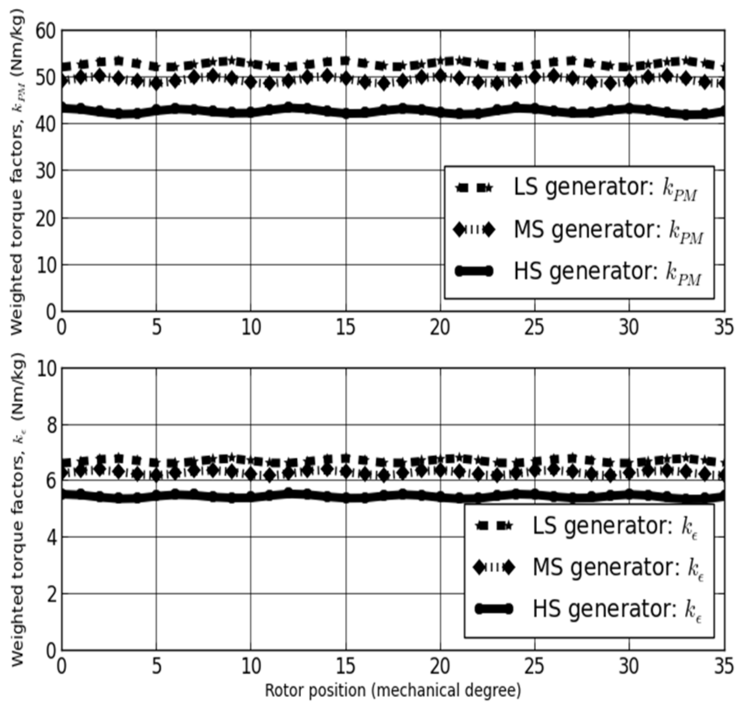

Fig. 7. Torque per mass comparison for different FSPM drivetrains.

Comparison and Results (Contd.)

- For the same power rating, the head **mass** of the LS FSPM generator may not only be bulky, but also costly as shown in Fig. 8, and especially if rare earth PM is utilised.

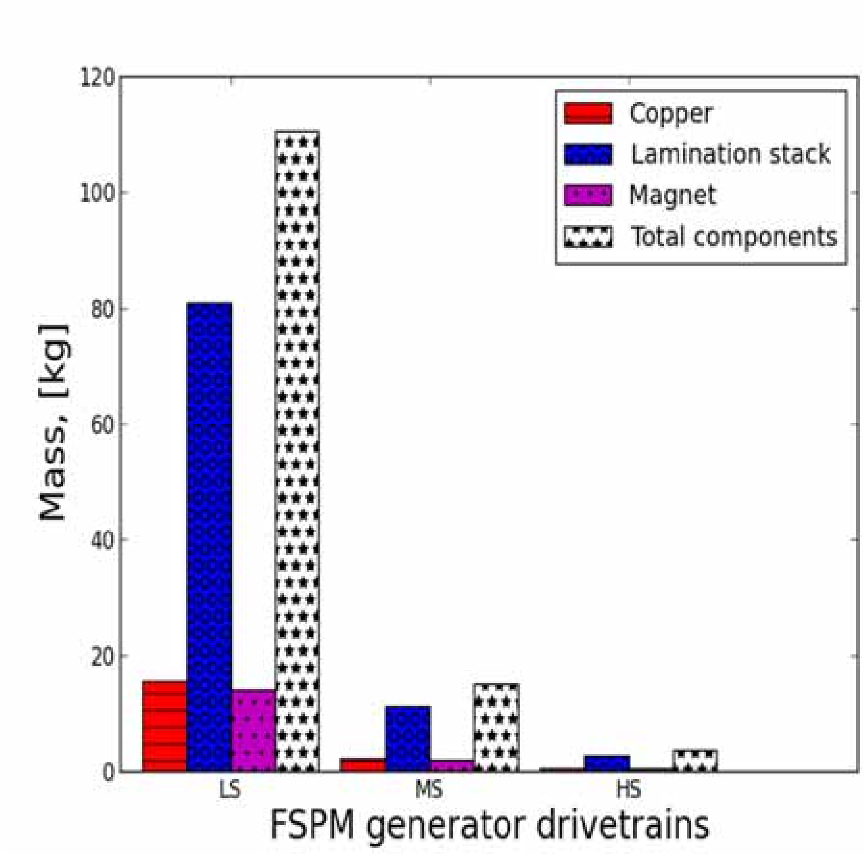

Fig. 8. Generator mass for different FSPM drivetrains.

Comparison and Results (Contd.)

- The MS and LS drivetrains achieved commensurate higher **machine efficiency** at above 91% compared to the HS drivetrain as shown in Fig. 9.

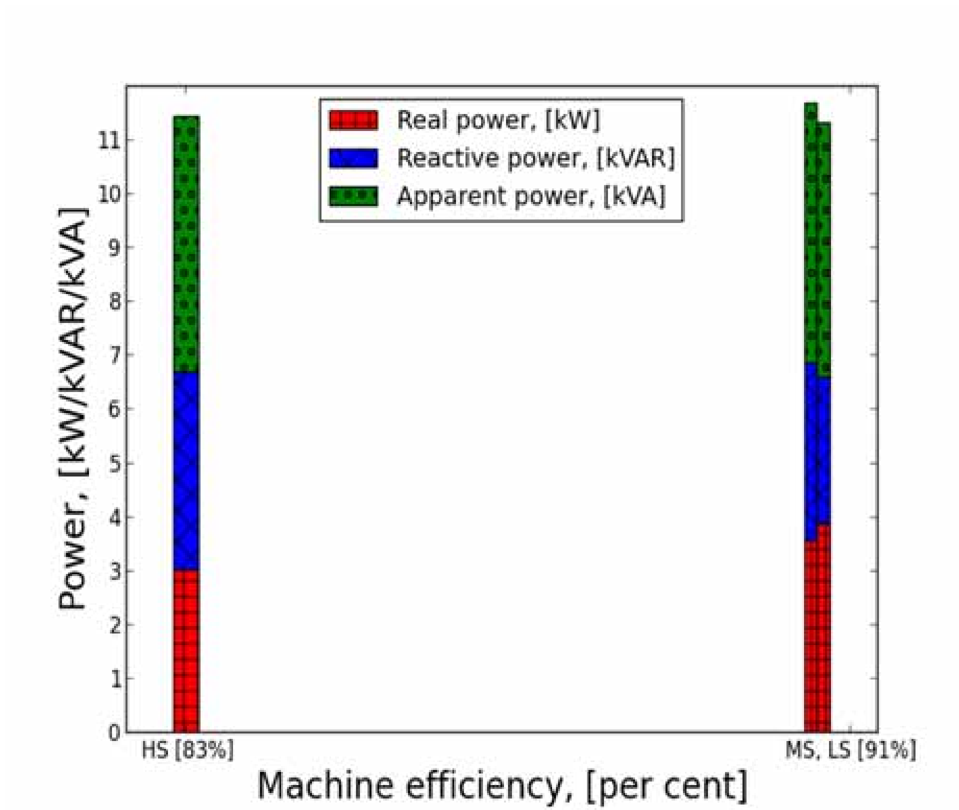

Fig. 9. Comparison of machine efficiency for different FSPM drivetrains.

Comparison and Results (Contd.)

- The HS drivetrain experiences high **machine losses** due to its highest frequency core losses which limits the generator total power output, as shown in Fig. 10.

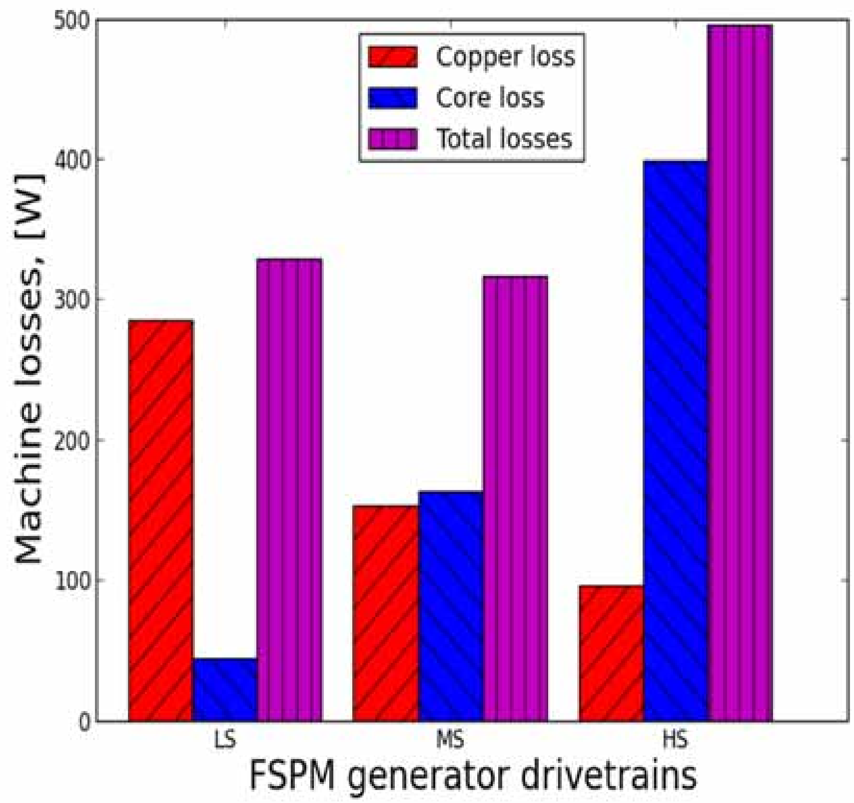

Fig. 10. Comparison of machine losses for different FSPM drivetrains.

Comparison and Results (Contd.)

Overall, the MS drivetrain appears to give the highest machine output performance index defined by a parameter $\boldsymbol{k_{\varphi}} = \frac{\textbf{Power } \boldsymbol{factor}}{\textbf{Cogging } \boldsymbol{torque}}$. A higher value of the parameter k_{φ} indicates that the power factor and cogging toque for a given drivetrain is optimised as shown in Fig. 11.

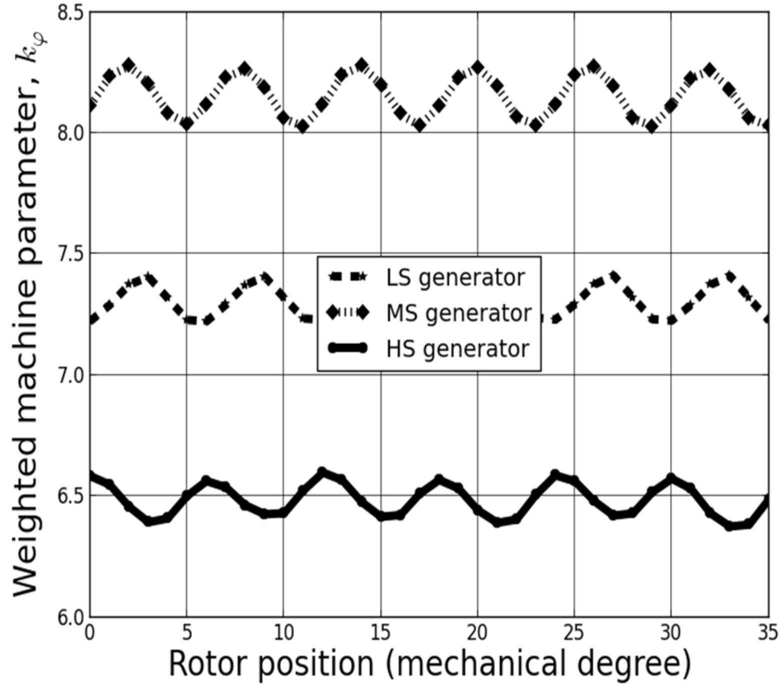

Fig. 11. Machine output performance index for different FSPM drivetrains.

Comparison and Results (Contd.)

Table 2 gives a summary of the main results of the FEA-based comparison of the three FSPM machine drivetrains.

Table II. 2-D FEA simulation results for 4.2 kW FSPM drivetrains.

Parameters	Unit	Values		
Drivetrain	-	LS	MS	HS
Machine speed, n_m	r/min	50	360	1500
Cogging Torque	Nm	82.93	8.52	1.87
Rated Torque	Nm	741.81	94.67	19.18
Per unit cogging torque	%	11.17	9.00	9.76
Active component mass	kg	110.41	15.03	3.51
Average torque per total component mass, $k_{\in}$	Nm/kg	6.72	6.30	5.46
Average torque per PM mass, k_{PM}	Nm/kg	52.79	49.42	42.74
Power output	kW	3.86	3.55	3.00
Power factor	%	81.71	73.43	63.28
Average power factor per cogging torque (%), k_{φ}	**-**	**7.30**	**8.15**	**6.48**
Total machine losses	kW	328.948	316.43	495.18
Efficiency	**%**	**91.53**	**91.13**	**83.57**
Rated phase voltage, $V_{ph\ (rms)}$	V	159.07	168.81	189.53
Phase voltage, $V_{ph\ (rms)}$ (no load)	V	204.89	204.94	211.14
Phase current, $I_{ph\ (rms)}$	A	7.309	8.151	6.484

Conclusion and Future Work

- **Conclusion**
  - Another evidence that MS drivetrains holds the future for wind generator drives among the other available drivetrains have been demonstrated using semi-optimised FSPM generator modelled in 2D-FEA package.
  - At the same power rating among other constraints, the FSPM MS drivetrain in comparison with LS and HS drivetrains exhibit the following potentials critical to the superior performance of wind generator drives:
    - **low cogging torque ratio.**
    - **high machine performance index.**
    - **low cost per active component mass.**

Conclusion and Future Work (Contd.)

- **Future Work**
  - On-going comparison of the fully-optimised models in 2D-FEA package (and measurements)…
  - In-depth cost analysis…

Thank you slide

- **Thank you for your attention.**