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Power Electronics, Machines and Drives (PEMD 2016), 8th IET International Conference on

Conference contribution :

Bhuiyan, N. & McDonald, A. (2016). *Optimisation and comparison of generators with different magnet materials for a 6MW offshore direct drive wind turbine.* Power Electronics, Machines and Drives (PEMD 2016), 8th IET International Conference on, Glasgow, UK: 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016).

http://dx.doi.org/10.1049/cp.2016.0300

Optimisation and comparison of generators with different magnet materials for a 6MW offshore direct drive wind turbine

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Keywords: Cost of energy, permanent magnet (PM), ferrite magnet, optimisation, objective functions, direct-drive, wind turbine.

Abstract

In the past few years interest in the use of low speed permanent magnet generators for direct-drive wind turbine generator applications has increased significantly. The significant fluctuations in NdFeB magnet prices has encouraged designers to optimise magnet utilisation and to look at alternative magnet materials for wind turbine electrical generators. In this paper an analytical design model is developed for 6 MW offshore direct-drive wind turbine generators using different magnet materials (one with surface mounted NdFeB and another with flux concentrating ferrite magnet). Finite element method models are used to check key dependent variables calculated by the analytical models. The generator designs are optimised using a hybrid optimisation method incorporating a Genetic Algorithm and Pattern Search approaches. This is applied for four different objective functions, the first two which concentrate on maximising rated torque per unit magnet mass or unit of generator active material cost. They are simple and quick to execute but prioritise cost reduction and ignore lower efficiencies leading to lower turbine energy yields and hence poor cost of energy. A third objective function which seeks to minimise the sum of the generator active material cost and the costs of lost revenue over a finite number of operational years. This gives similar results to a fourth objective function which is an explicit turbine cost of energy calculation. The cost of NdFeB magnets affect the cost of energy of the surface mounted generator which tested with different cost €40/kg, €60/kg and €80/kg. The ferrite magnet generator being better when the NdFeB magnet price rises to €80/kg.

1 Introduction

The use of permanent magnet (PM) synchronous generators with rare earth materials in direct-drive wind turbines has grown significantly in the past few years. PM generators are suited to the application due to their high efficiency, high torque-to-size ratio, and low maintenance requirements. The most common material used in permanent magnet electrical machines is Neodymium - Iron - Boron (NdFeB). During last few years, the price of NdFeB has increased and fluctuated significantly. The price of rare earth metals such as neodymium increased more than 350% from August 2009 to August 2011. This means that wind turbine manufacturers (who use permanent magnet generators) are faced with a significant cost uncertainty. In terms of availability and price stability, ferrite magnets could be a suitable alternative to NdFeB when mass (and inertia) of a generator rotor is of less importance [1]. Some sample comparative material data is given in Table 1.

Magnetic Materials		
Magnet material	NdFeB	Ferrite
Grade	N40H	Y30
Remanent flux density (T)	1.25	0.4
Normal Coercivity (kA/m)	923	240
Intrinsic Coercivity (kA/m)	1355	245
Density (kg/m^3)	7600	5000

Table 1: Example magnet properties for rare earth and ferrite magnet materials.

A further approach to reducing magnet content is to optimise the magnet utilisation. Optimisation allows the designer to find the best value of an objective function from some set of available alternatives. Genetic Algorithms (GA) are a popular and reliable algorithm for finding global optimum solutions. They are suitable for both constrained and unconstrained optimisation problems. A GA can solve a variety of optimisation problems including those that are discontinuous, non-differentiable, stochastic and include highly nonlinear models. A GA can work for mixed integer programming, where some variables are restricted to be integer-valued [2]. As a result they are often used in electrical machine optimisations.

Others have looked extensively at ferrite magnet use for wind turbine generators. This paper builds on the work of Eriksson and Bernhoff [1] with an emphasis on a typical 6 MW offshore wind turbine. A number of generators for a 6 MW wind turbine are designed parametrically using lumped parameter models and equivalent circuits: one with a surface mounted NdFeB (rare earth magnet) rotor and one with a flux concentrating ferrite magnet rotor. So as to check the output of the machine design model, the designs are verified using finite element software. The turbine in [8] is used as the basis for this. In order to optimise both machines, a hybrid optimisation method using Genetic Algorithm (GA) [7] and Pattern Search (PS) is used in MATLAB to optimise four different objective functions: (a) magnet mass per unit torque, (b) generator active material cost per unit torque, (c) the difference between generator active material costs and the wind turbine revenue for 5, 10 and 15 years period of operation and (d) the wind turbine cost of energy. A sensitivity analysis is also done for different specific magnet costs. Finally a comparison of different objective functions for both wind turbine generators is carried out.

2 Methodology

In this section the case study wind turbine is defined, before generator analytical models are outlined – these lead to loss calculations, generator costs and annual energy production. Finite element modelling is introduced to check some of the key dependent variables. After that the optimisation process and objective functions are presented.

2.1 Case study wind turbine

This case study uses an offshore, 3 bladed, pitch regulated, variable speed wind turbine. The major ratings and assumptions are given in Table 2. When calculating steady power curves, it is assumed that the turbine rotor operates at its maximum coefficient of performance below the rated wind speed. As a simplification for the analysis, it is assumed that for wind speeds above rated, the blades are pitched and power output is limited to 6MW and the rotor speed is limited. The assumed wind turbine mechanical power curve is shown in Figure 1.

Each generator has the same rated torque but there are differences in efficiency as described in Section 2.2. This leads to different losses at each wind speed. The turbine is placed at an offshore site with a mean wind speed of 9.6m/s, as defined using a Weibull distribution defined by the data in Table 2.

Wind Turbine and Site Characteristics	
Rated grid power (MW)	6
Rotor diameter (m)	145
Rated wind speed (m/s)	11
Rated rotational speed (rpm)	11.6
Cut in wind speed (m/s)	3
Cut out wind speed (m/s)	25
Optimal tip speed ratio	8.3
Turbine coefficient of performance at optimal tip speed ratio	0.48
Wind turbine availability (%) [3]	94
Rest of wind turbine capital cost ($\times 10^3$ €)	6100
Site wind speed shape parameter	2.32
Site wind speed scale parameter (m/s)	10.8

Table 2: Assumed characteristics for a case study 6MW wind turbine and site wind resource characteristics.

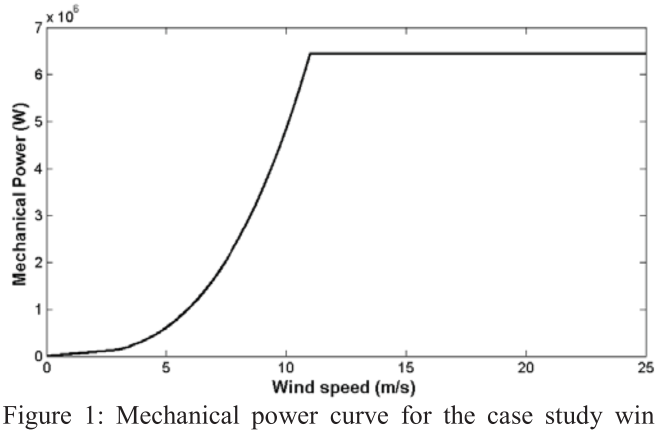

Figure 1: Mechanical power curve for the case study wind turbine

2.2 Analytical generator models

For quick execution of the optimisation process, the generators are modelled analytically. In order to calculate flux per pole, lumped parameter magnetic circuit models are used. The simplified magnetic circuits for one pole pair are shown in Figure 2. The results from this are used to calculate induced emf and flux densities in the various parts of the system. The induced emf E increases up until the rotation speed becomes constant (when the turbine blades are pitched).

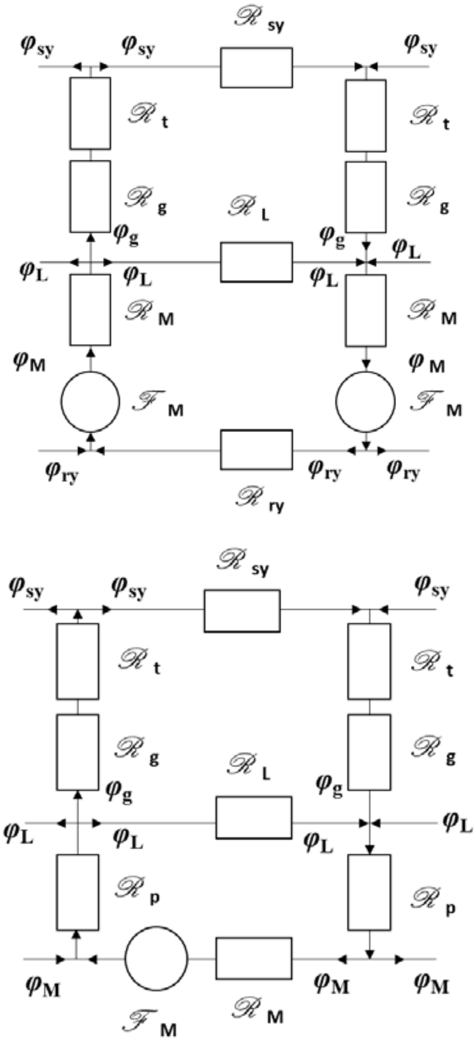

Figure 2: Magnetic circuits for modelling airgap flux per pole: (*a*, top) surface mounted magnet and (*b*, bottom) flux concentrating configuration.

At all wind speed, it is assumed that the machines are running at unity power factor. Although this is sub-optimal operation, it simplifies the optimization process. A generator with surface mounted permanent magnets has equal inductance in direct axis and quadrature axis ($L_d = L_q$ and hence $X_d = X_q$). The phasor diagram for surface mounted machine is shown in Figure 3. To produce correct power at each wind speed, the current I is varied and hence the load angle, δ, also varies.

Generator Material Characteristics	
Slot filling factor k_{sfil}	0.6
Resistivity of copper at 120°C ρ_{Cu} (μΩm)	0.024
Eddy-current losses in laminations at 1.5 T, 50 Hz P_{Fe0e} (W/kg)	0.5
Hysteresis losses in laminations at 1.5 T, 50 Hz P_{Fe0h} (W/kg)	2
Cost Modelling	
Power electronics cost (€/kW)	40
Lamination cost (€/kg)	3
Copper cost (€/kg)	15
Permanent magnet cost (€/kg)	60
Ferrite magnet cost (€/kg)	3
Cost of kWh energy (€/kWh)	0.19
Rotor iron cost (€/kg)	2

Table 3: Generator material and loss characteristics

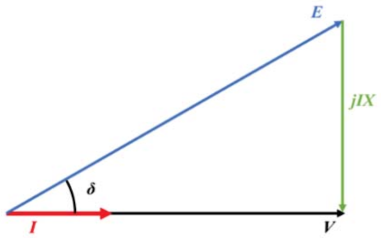

Figure 3: Phasor diagram for surface mounted NdFeB generator

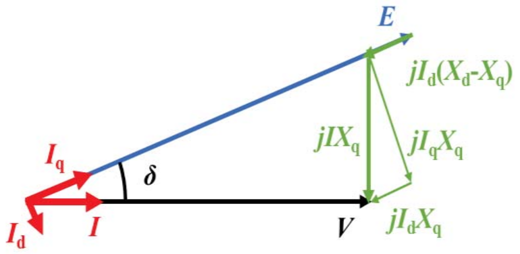

Figure 4: Phasor diagram of machine with buried magnet.

Neglecting resistance, the terminal voltage can be found with equation (1),

$$V = \sqrt{E^2 - (IX)^2} = E \cos \delta \qquad (1)$$

where X is the reactance.

In a flux concentrating buried magnet generator, the inductance in direct axis and quadrature axis are not equal (i.e. $L_{\mathrm{d}} \neq L_{\mathrm{q}}$) because of significant saliency [5]. The phasor diagram for buried magnet machine is shown in Figure 4. The terminal voltage can be calculated according to equation (2).

$$V = \sqrt{(E - I_{\mathrm{d}}(X_{\mathrm{d}} - X_{\mathrm{q}}))^2 - (IX_{\mathrm{q}})^2} = E \cos \delta - I_{\mathrm{d}}(X_{\mathrm{d}} - X_{\mathrm{q}}) \cos \delta \qquad (2)$$

The copper losses, iron losses, magnetizing inductance and leakage inductances and hence reactances are calculated as shown in [6,8]. These are evaluated at each wind speed (which maps onto a combination of rotational speed and current) and the losses are multiplied by the number of hours a year that the turbine operates at that wind speed, as found from the Weibull distribution. This is then used to find annual losses and energy yield.

2.3 Finite element modelling

The results from the analytical model are checked using a 2D finite element code, FEMM [4] in conjunction with Lua scripting language. Figure 5 shows the FE results for two poles of the surface mounted NdFeB rotor and the flux concentrating ferrite magnet rotor. Agreement between analytical and FE models was generally found to be 1% for airgap flux density.

2.4 Optimisation

Design optimisation methods generally use an algorithm to vary independent variables (subject to predetermined constraints) that are inputs to models that are used to evaluate dependent variables and hence optimise an objective function. In this paper, the independent variables describe the main generator design parameters and the analytical models in section 2.3 are used to evaluate a range of different dependent variables, some of which contribute to the objective functions as laid out in section 2.4.3. The process is driven by an optimisation algorithm as described in section 2.4.1.

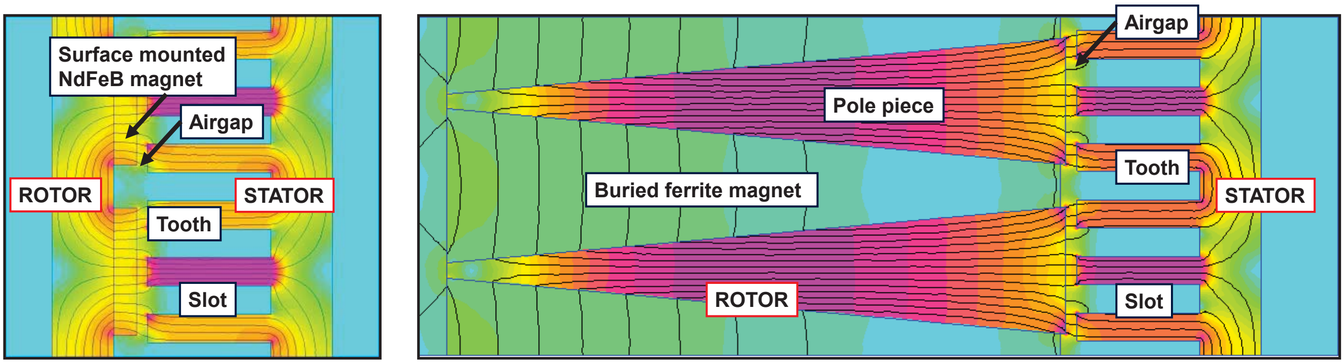

Figure 5: Magnetostatic finite element analysis of surface mounted NdFeB generator (left) and flux concentrating ferrite generator (right). 🟦 0T → 🟪 1.5T . Software is FEMM [4]

2.4.1 Optimisation Method

A hybrid Genetic and Pattern Search algorithm which has been developed in MATLAB is used here as an optimisation procedure [2]. A GA can reach the region near an optimum point relatively quickly but it takes longer to achieve convergence. A commonly used technique is to run the GA for a small number of generations to get near to an optimum point. Then the solution from the GA is used as an initial point for another optimisation solver that is faster and more efficient for a local search. In this case, the GA developed by [7] was used. The hybrid optimisation algorithm [2] runs in a way that takes the results of Genetic Algorithm as an initial guess for the Pattern Search to get the global minimum for each of the objective functions.

2.4.2 Independent Variables and Constraints

A limited number of independent variables are used in this study: machine diameter, axial length, magnet height, the ratio of magnet width to pole pitch, number of pole pairs and tooth height. The lower and upper boundary of independent variables are given in Table 4.

Independent Variables	NdFeB gen.		Ferrite gen.	
	LB	UB	LB	UB
Air gap diameter, D (m)	5	10	6	10
Axial length, L (m)	0.7	1.8	0.7	1.8
Magnet width/pole pitch, w_m/τ_p	0.6	0.9	0.6	0.9
Magnet height, h_m (m)	0.01	0.04	0.1	0.45
Pole pairs, p (-)	60	110	60	100
Height of tooth, h_t (m)	0.04	0.1	0.04	0.09

Table 4: Upper boundary (UB) and lower boundary (LB) for independent variables

A number of simplifying assumptions and constraints are used, such as setting the airgap clearance to a fixed ratio of the machine diameter, maximum flux density to avoid saturation in stator and rotor yoke and greater than or equal to 6 MW electrical power as constraint.

2.4.3 Objective Functions

Four different objective functions are used in this paper. Bearing in mind the comments about minimising the usage of NdFeB magnets, the first objective function tries to minimise the amount of magnet material, m_{PM} per rated generator torque, T. In this case the objective function F_1 is given as,

$$F_1 = \frac{m_{PM}}{T}. \qquad (3)$$

Instead of the magnet mass, the second objective function, F_2 seeks to minimise the cost of the electromagnetically active materials, i.e. magnets and copper as well as the iron in the magnetic circuit,

$$F_2 = \frac{C_{PM}+C_{Cu}+C_{Fe}}{T}, \qquad (4)$$

where C_{PM}, C_{Cu} and C_{Fe} is the cost of the permanent magnets, copper and active iron.

One issue shared by the first two objective functions is that they effectively ignore the performance for wind speeds below rated and so may produce result which have lower efficiency. To address this, a variant of the objective function presented in [9] is used. This third objective function, F_3, seeks to minimise the cost of active material while maximising the revenue produced from the wind turbine over a number of years, P_y. In this paper this objective function is assessed with P_y = 5, 10 and 15 years. In equation (5) this time period is multiplied by C_E, the revenue from a kWh of electrical energy and E_y, the annual energy yield of the turbine,

$$F_3 = C_{PM} + C_{Cu} + C_{Fe} - P_y C_E E_y. \qquad (5)$$

The ultimate customer of the wind turbine manufacturer wants the lowest cost of energy and so the final objective function calculates this,

$$F_4 = CoE = \frac{(FCR \times ICC)+AOM}{E_y} \qquad (6)$$

where FCR is the fixed charge rate, ICC is the initial capital cost of the turbine (including the generator), AOM is the annual operation and maintenance (assumed to be unaffected by the generator design) and AEP annual energy production. Here ICC and AOM are calculated according to [8].

2.4.4 Post processing

After the optimisation process is complete the equations (3-6) for the objective functions are applied to all the designs to help compare the value of the objective functions.

3 Results

3.1 NdFeB magnet generator

Table 5 shows the results from the optimisation for the generators with the surface mounted NdFeB magnets. Figure 6 shows the efficiency curves for the various generator designs.

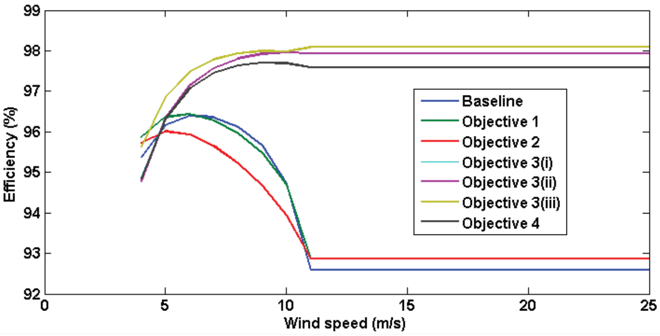

Figure 6: Baseline and optimised efficiency curves for surface mounted NdFeB generators.

3.2 Ferrite magnet generator

Table 6 shows the results from the optimisation for the generators with flux concentrating ferrite magnets. Figure 7 shows the efficiency curves for the various generator designs.

	Baseline	**Objective Function 1**	**Objective Function 2**	**Objective Function 3, P_y = 5 years**	**Objective Function 3, P_y = 10 years**	**Objective Function 3, P_y = 15 years**	**Objective Function 4**
Air gap diameter, D (m)	7	9.93	9.78	9.99	9.99	9.95	9.99
Axial length, L (m)	1.5	1.16	1.23	0.93	1.16	1.16	0.95
Magnet width/pole pitch, w_m/τ_p	0.75	0.63	0.75	0.84	0.84	0.84	0.83
Magnet height, h_m (m)	0.015	0.014	0.013	0.025	0.024	0.027	0.024
Pole pairs, p (-)	100	110	100	109	87	60	110
Height of tooth, h_t (m)	0.08	0.06	0.04	0.1	0.1	0.1	0.1
Mass of magnet, m_{PM} (kg)	2820	2469	2688	4614	5635	6268	4524
Mass of copper, m_{Cu} (kg)	8133	7126	5141	10255	12796	14065	10455
Mass of active iron, m_{Fe} (kg)	21535	19597	18948	26684	37532	47942	27071
Copper Losses (MWh)	1922	1892	1991	522	422	431	523
Iron Losses (MWh)	191	152	135	271	277	222	272
AEP (GWh)	28.7	28.8	28.7	30.0	30.1	30.1	30.0
Cost of generator, C_{gen} (k€)	334	294	276	484	605	683	482
F_1^{-1} (Nm/kg)	1684	**1930**	1773	1085	909	769	1106
F_2^{-1} (Nm/€)	14.2	16.2	**17.2**	10.3	8.3	7.0	10.4
F_3 with P_y = 5 years (k€)	-26969	-27071	-27015	**-27998**	-27961	-27924	**-27998**
F_3 with P_y = 10 years (k€)	-54273	-54436	-54307	-56480	-56527	**-56531**	-56478
F_3 with P_y = 15 years (k€)	-81576	-81801	-81599	-84962	-85093	**-85138**	-84958
F_4 (€/MWh)	108.1	107.7	107.9	**104.2**	104.4	104.5	**104.2**

Table 5: Optimisation results for surface mounted NdFeB generator. Independent variables are shown in lightest grey, major dependent variables are shown in medium grey and the objective function are evaluated in darker grey.

	Baseline	**Objective Function 1**	**Objective Function 2**	**Objective Function 3, P_y = 5 years**	**Objective Function 3, P_y = 10 years**	**Objective Function 3, P_y = 15 years**	**Objective Function 4**
Air gap diameter, D (m)	7	9.73	7.91	9.92	9.95	9.99	9.56
Axial length, L (m)	1.5	1.49	1.42	1.08	1.26	1.26	1.18
Magnet width/pole pitch, w_m/τ_p	0.75	0.84	0.6	0.67	0.73	0.74	0.69
Magnet height, h_m (m)	0.4	0.18	0.26	0.44	0.44	0.45	0.43
Pole pairs, p (-)	100	100	99	70	60	60	66
Height of tooth, h_t (m)	0.08	0.06	0.06	0.09	0.09	0.09	0.09
Mass of magnet, m_{PM} (kg)	37612	21126	30193	45224	50834	51039	46387
Mass of copper, m_{Cu} (kg)	8133	9149	6305	11453	13496	13535	11792
Mass of active iron, m_{Fe} (kg)	61756	49844	38488	68340	87641	89526	72851
Copper Losses (MWh)	1098	1932	1947	594	506	502	585
Iron Losses (MWh)	227	171	202	263	269	269	263
AEP (GWh)	29.4	28.8	28.7	29.9	30.0	30.0	29.9
Cost of generator, C_{gen} (k€)	358	300	262	444	530	535	462
F_1^{-1} (Nm/kg)	129.9	**227**	159	105	94	94	103
F_2^{-1} (Nm/€)	13.7	15.9	**18.2**	10.7	8.9	8.9	10.3
F_3 with P_y = 5 years (k€)	-27649	-27012	-27009	**-27981**	-27968	-27966	-27971
F_3 with P_y = 10 years (k€)	-55656	-54324	-54281	-56405	-56466	**-56468**	-56403
F_3 with P_y = 15 years (k€)	-83663	-81636	-81552	-84830	-84964	**-84969**	-84836
F_4 (€/MWh)	105.5	107.9	107.9	**104.3**	**104.3**	**104.3**	**104.3**

Table 6: Optimisation results for flux concentrating ferrite generator. Independent variables are shown in lightest grey, major dependent variables are shown in medium grey and the objective function are evaluated in darker grey.

4 Discussions

4.1 On the choice of objective function

A number of different objective functions have been used in this study. For both generators, the objective functions F_1 and F_2 tend to produce lower efficiency machines than when energy yield in taken into account (as for F_3 and F_4). This is unsurprising as the formulations for F_3 and F_4 implicitly take losses into account.

Optimisation results in 1st objective function show the lowest magnet mass which makes highest torque per magnet mass and the 2nd objective function gives the lowest cost of generator active materials. The major difference is that F_1 achieves its goal at the expense of additional copper and iron mass. When the cost of energy is evaluated for the results of these optimisations, they give a high cost of energy. Even though the generator capital costs are the lowest, they sacrifices annual energy yield. This can be explained by the fact that the generator capital costs are a minority of the turbine capital costs, yet all of the turbine's energy in converted by the generator. This implies that generator efficiency is a higher priority than generator cost. The first and second objective functions are a poor choice when optimising wind turbine generators.

The major difference in losses between F_1/F_2 and F_3/F_4 is due to copper losses, with higher current density being used to reduce copper mass. More magnet is used in the 3rd and 4th objective functions which generally produces better air-gap flux density and helps to increase energy production. The balance of copper and iron losses are slightly different, with F_3/F_4 having slightly higher iron losses. It is because of lower mass and active iron that used in first two objective functions.

The resulting designs and cost of energy is very similar for F_3 and F_4. The third objective function does not include detailed turbine information and so is more general. The change in the number of years – for F_3 – does not make significant difference to the results. It may be that different turbine costs and designs may lead to a larger difference between F_3 and F_4.

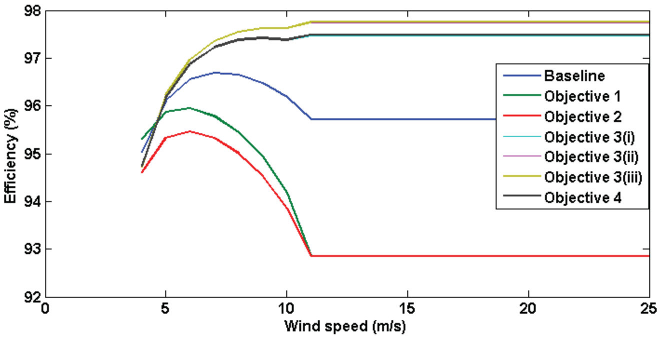

Figure 7: Baseline and optimised efficiency curves for flux concentrating ferrite generators.

4.2 On the choice of generator topology

In comparison to the flux concentrating ferrite magnet generator, the surface mounted NdFeB has a marginally better cost of energy due to higher efficiency and hence higher energy yield. The capital costs of the generators are lower (for most objective functions) in flux concentrating ferrite magnet generator. The generator mass is lower for the surface mounted NdFeB generator because of the large difference in magnet mass and rotor iron mass. The surface mounted NdFeB machines – unsurprisingly – give better torque density, although the costs are similar to the ferrite magnet machines when the rare earth magnet specific cost becomes very high.

In terms of sensitivity to NdFeB specific costs, if the cost were to change to €80/kg, the cost of energy would rise marginally to €104.5/MWh, making the flux concentrating ferrite machine more appealing. However, if the cost were to fall to €40/kg, the cost of energy will fall back to €103.8/MWh. The effect of the magnet cost will be more significant for onshore turbines, as the rest of the system has lower capital costs.

4.3 Limitations and future work

This study is limited to two machine topologies, with a small number of independent variables. The impact of generator structural material on costs has been ignored, even though it may contribute to a significant cost element, especially when the airgap diameter increases. Increasing the generator mass (by using ferrite magnets, or having more structural material) is likely to add to turbine costs; however this has been ignored. These aspects should be included in future work.

5 Conclusions

A number of optimisations have been shown and it has been demonstrated that it is important to include losses in the objective function when attempting to produce a good design for wind turbine generators. A ferrite magnet alternative design (to a NdFeB surface mounted configuration) has been shown to be competitive on a cost of energy basis.

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