Comparison of Air-Cored and Iron-Cored Non-Overlap Winding Radial Flux Permanent Magnet Direct Drive Wind Generators

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Abstract—**In this paper a comparative study of the air-cored and iron-cored direct-drive permanent magnet wind generators is done. The comparative study is based on optimum designed air- and iron-cored wind generators on a 15 kW power level. With the generators designed to have the same power and efficiency performances, mainly mass difference is compared, but other aspects such as performance quality, per unit impedance and magnet demagnetisation, amongst other things, are also compared. Although a high amount of permanent magnet material is used in the air-cored generator, this generator is shown to have very attractive features for converter-fed direct-drive wind generator applications.**

I. Introduction

In the search for better wind generator systems direct-drive (gearless) permanent magnet generators (PMGs) with full-scale grid-connected power electronic converters nowadays receive much attention in research and from industry [1 – 3]. The advantages of a gearless variable speed system, excellent reactive power control and ride through capability are clear. The basic drive system at the generator side is shown in Fig. 1. This consists of the turbine, PMG, LC-filter and an active rectifier [4]. An LC-filter is necessary to prevent high frequency voltages at the terminals of the PMG or high frequency voltages and currents in the transmission cable if the PMG is on top of the tower and the converter at ground level. For maximum torque per copper loss performance of the PMG, the active rectifier controls the generator current to be in-phase with the back EMF voltage as shown in Fig. 1.

Hitherto, slotted or slot-less iron-cored-stator wind generators have been almost the only type of generator considered for direct-drive wind generators. Air-cored-stator direct-drive PMGs have received relatively little attention in literature and are not yet used in medium-scale (100 – 1000 kW) or large-scale (above 1 MW) direct-drive wind turbine generator systems. Axial-flux air-cored PMGs with double-sided PM rotors for small-scale wind applications are considered amongst others by [5, 6]. In [7] large-scale direct-drive axial-flux air-cored PMGs are compared with axial-flux iron-cored PMGs. The main findings are that the air-cored machines have larger diameters, are more expensive and have to some extent less overall (active and structural) mass.

In [8] an innovative very-large-diameter direct-drive PMG with a radial-flux, single-sided PM-rotor and an air-cored-stator is proposed and investigated. In this proposal the rotor and stator are carried by a pair of spoked wheels, with the result a very light direct-drive generator. A radial-flux, double-sided PM-rotor machine with an air-cored stator was first proposed and analysed by [9]. This type of machine is applied in direct-drive wind generator applications at a 15-20 kW power level by [10, 11] using a proposed modular C-core PM-rotor. This design is claimed to result in lightweight direct-drive generators, particularly for large-scale generators. This type of radial flux generator with an air-cored non-overlap stator winding has recently been analysed in detail in terms of its optimum design for converter-fed wind generator applications [12].

Although some analytical comparisons have been done between air- and iron-cored, direct-drive wind PMGs, no detailed comparison has been done specifically of *radial* flux air- and iron-cored PMGs, considering *double-sided* PM-rotors for the air-cored machine. Furthermore, many aspects have to be considered in a true comparison, such as perfor-

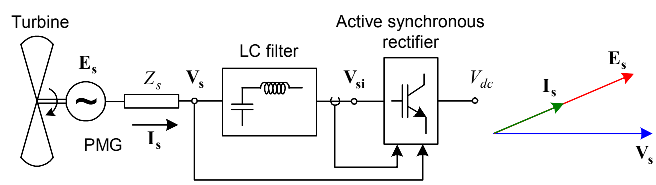


Figure 1. Direct-drive wind energy system and phasor diagram.

The research presented in this paper was funded by the National Research Foundation (NRF) and the Department of Science and Technology (DST) in South Africa.

mance quality, magnet mass and magnet losses, demagnetisation of magnets under short-circuit conditions, cooling and the kVA rating of the converter. These aspects also have to be compared in the right way, namely of generators that have the same (or very close to the same) efficiency, the same rated torque and rated speed, and the same rated voltage and frequency.

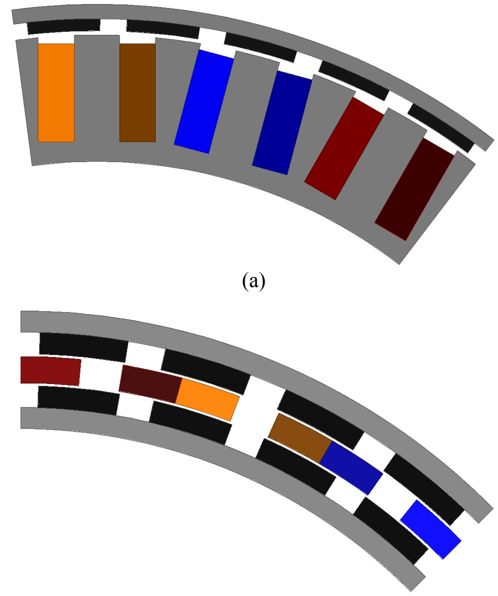
In this paper optimum designed air- and iron-cored radial flux direct-drive wind PMGs are compared. Both types of wind PMGs have been built and tested. As the generators have a power rating of 15 kW, the conclusions reached in this paper are reckoned to be valid for generators in the small-scale (sub 100 kW) wind power region.

II. AIR-CORED AND IRON-CORED PM GENERATORS

Iron-cored direct-drive PMGs are normally radial flux, single-sided generators with outer PM rotors and inner stators or vice versa. The PMs can be surface mounted or embedded for better protection. In the comparative study in this paper only surface mounted PM rotors are considered. The air-cored PMG considered in this paper has a radial flux double-sided PM rotor, i.e. with permanent magnets on both sides of the stator winding. In this case the PMs must be surface mounted to ensure radial flux through the large air gap and to avoid leakage flux back to the rotor yoke.

The cross-sections of the iron- and air-cored wind PMGs investigated in the paper are shown in Figs. 2a and b respectively. With the emphasis on low cogging torque a non-overlap concentrated winding is selected for the iron-cored PMG. To reduce labour cost a single layer winding is chosen that has half the number of coils of the double layer winding. Furthermore, a pre-wound coil winding is made possible by using paralleled slots as shown in Fig. 2a; this will reduce the cost even further. Note that the pitch of these coils and slots can be adjusted. A disadvantage of the single layer winding is the large sub MMF harmonic that severely increases the eddy current losses in the magnets and rotor yoke if they are solid. Non-overlap winding PM machines, however, require in general that the magnets be segmented and the rotor yokes be laminated. It can be argued that this will increase the cost of the machine. Finally, a high winding-factor pole/slot combination of 10/12 is chosen for the iron-cored PMG. The 10/12 combination is shown in Fig. 2a with negative (half-periodic) boundary conditions applied in the finite element (FE) analysis, i.e. modelling five poles and six slots.

Regarding the air-cored PMG, only a non-overlap concentrated coil winding is considered, as an overlap winding with its large end winding overhang is very difficult to fit in-between the double-sided PM rotor – unless the gap between the rotors is largely increased, which will deteriorate the performance of the machine and severely increase the magnet costs. The optimum coil-to-pole number for the air-cored type winding has been shown by [6, 13] to be 3:4. This can also be seen in Fig. 2b where three phase-coils and four poles are used in the FE modelling, in this case with positive (periodic) boundary conditions.



(a)

(b)

Figure 2. FE-modelled cross sections of (a) iron-cored and (b) air-cored direct-drive wind PMGs.

III. INVESTIGATED WIND TURBINE GENERATOR

The power versus speed curves of the wind turbine considered in the investigation are shown in Fig. 3. To keep the tip-speed ratio low the maximum (rated) turbine speed was specified at 150 r/min. The rated turbine power is specified as 16 kW at a wind speed of just above 11 m/s. A photo of the turbine and the generator (in this case the iron-cored PMG of Fig. 2a) is shown in Fig. 4.

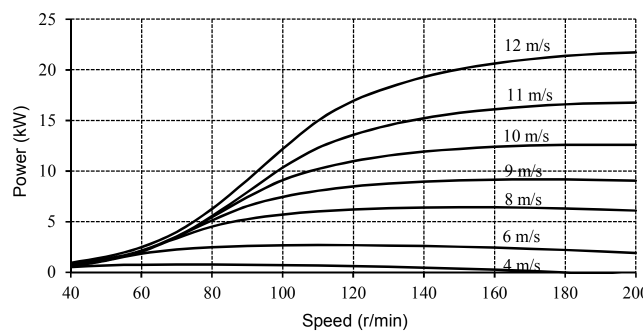


Figure 3. Turbine power versus speed with wind speed a parameter.

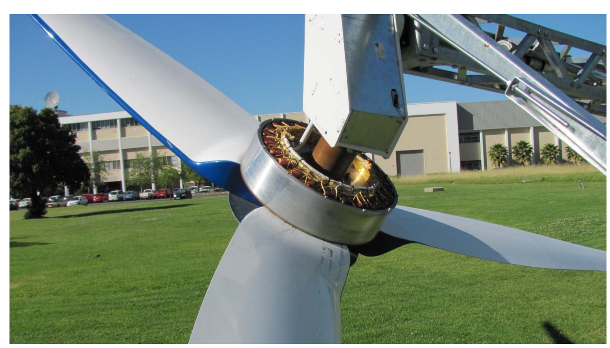


Figure 4. Investigated 15 kW wind turbine and iron-cored generator.

IV. GENERATOR SPECIFICATIONS AND DIMENSIONS

For both the iron- and air-cored wind PMGs the required performance in terms of generated electrical power, P_o, speed, ω_r, and efficiency, η, at 50 Hz is given by **U** in (1). This results in a required rated torque of 1000 Nm, and at 50 Hz a pole number of $p = 40$ for both machines. Some of the important machine dimensions to be optimised are given by $\mathbf{X_1}$ in (2), i.e. the outer diameter, d_o, the inner diameter, d_i, (the air gap diameter, d, is also considered) and the axial length, ℓ, of the machine. The other important dimensions are given by $\mathbf{X_2}$ in (2), namely the stator winding (or slot) height, h, the magnet height, h_m, and the rotor yoke height, h_y. For iron-cored PM machines the dimensions of $\mathbf{X_3}$ in (2) are important, specifically regarding cogging torque. These are the ratio of the magnet pitch to pole pitch, σ_m, the ratio of the parallel slot pitch to the average slot pitch, σ_t, and the ratio of the slot opening width to the average slot pitch, σ_g.

$$\mathbf{U} = \begin{bmatrix} P_o \\ \omega_r \\ \eta \end{bmatrix} = \begin{bmatrix} 14.8 \text{ kW} \\ 15.7 \text{ rad/s} \\ 94 \text{ \%} \end{bmatrix} \tag{1}$$

$$\mathbf{X}_1 = \begin{bmatrix} d_o \\ d_i \\ \ell \end{bmatrix} ; \quad \mathbf{X}_2 = \begin{bmatrix} h \\ h_m \\ h_y \end{bmatrix} ; \quad \mathbf{X}_3 = \begin{bmatrix} \sigma_m \\ \sigma_t \\ \sigma_g \end{bmatrix} \tag{2}$$

V. DESIGN OPTIMISATION

With an active synchronous rectifier used as shown in Fig. 1, sinusoidal phase currents are considered in the design optimisation of the wind PMGs. To maximise the torque per copper loss performance of the generator the phase current is taken in the design optimisation as in-phase with the induced voltage **E** as shown in Fig.1; this implies only q-axis current in the generators.

A. Iron-Cored Generator

The design optimisation of the iron-cored PMG is done by minimising the generator's active mass of the machine subject to the performance requirement of (1). The optimisation is done by means of Powell's algorithm [14] and integrated with magneto static FE analysis as described in [15]. In this way $\mathbf{X_1}$, $\mathbf{X_2}$ and $\mathbf{X_3}$ of (2) are optimised by maximising the torque per copper losses of the generator and keeping the active mass to a minimum subject to the torque constraint. The optimisation is done in an iterative way by setting the outer diameter at each next iteration as a constant. Also the copper loss is set constant at 600 W according to the cooling capacity of the generator. Note that the calculation of the stator iron losses of the machine are included in the design optimisation to calculate the efficiency.

The above-described design optimisation of the iron-cored PMG is based on average performance values and, thus, cogging torque is not considered. Cogging torque, however, is very important as it can lead to a complete failure of start-up due to the very low generated turbine torque at low turbine speeds. Hence, it is very important to minimise the cogging torque of the iron-cored PMG as much as possible. Thus after the above design optimisation is completed, the cogging torque of the PMG is minimised. This is done by optimising mainly the dimensions of $\mathbf{X_3}$ of (2). The method used is described in [16], whereby regions of low cogging torque are quickly identified by means of a set of magneto static FE solutions. These regions are then investigated more comprehensively to find the optimum dimensions of $\mathbf{X_3}$ that minimise the cogging torque. Note that the average torque of the PMG shows a low sensitivity to variations in the dimensional parameters of $\mathbf{X_3}$ of (2), as shown by [16].

B. Air-Cored Generator

The design optimisation of the air-cored PMG is done through an analytical method that takes the saturation of the iron yokes and the eddy current losses in the stator windings into account. This analytical method is proposed and explained in detail in [12]. In this method the stator copper loss is given as a constant and as a ratio of the total losses that consists of the copper and eddy current losses. Also the current and peak air gap flux densities are given as constants. In [12] a functional relationship between the axial length, ℓ, in $\mathbf{X_1}$ of (1) and the air gap diameter, d, is derived for the air-cored PMG. Thus by choosing d, ℓ can be determined. With ℓ and d known, h in $\mathbf{X_2}$ of (2) can be determined from a machine equation derived in [12]. In this way, three important dimensions of the air-cored PMG are determined, which satisfy the required performance **U** in (1). The parameters h_m and h_y in $\mathbf{X_2}$ of (2) are then determined as a result of the obtained values for ℓ and d. With these parameters known the active masses of the air-cored PMG are determined. The dimensional parameters of $\mathbf{X_3}$ are not considered, as $\sigma_m = 0.7$ [12] and σ_t and σ_g are not applicable for air-cored PMGs.

The optimisation method is a graphical method whereby the minimum active mass is found subject to the performance constraints of (1). For the 15 kW air-cored PMG the variation of the active mass and axial length versus air gap diameter of the machine are shown in Fig. 5. This shows that the total active mass comes near a minimum for air gap diameters, say larger than 750 mm, but the magnet mass becomes lower at a much larger air gap diameter. The optimum air gap diameter for minimum active mass is 830 mm in this case. However, the diameters of direct-drive wind generators are in general limited due to, amongst other things, the turbine blades. For the 15 kW case shown in Fig. 4, the largest allowed air gap diameter is 660 mm. According to Fig. 5a this increases the total active mass and magnet mass of the PMG substantially.

VI. OPTIMISATION RESULTS

The design optimisation results of the 15 kW non-overlap air- and iron-cored direct-drive wind PMGs are given in Table I. Note that these machines comply with the required performance of (1). The design data of the un-optimised air-cored PMG built for testing purposes is also given in Table I.

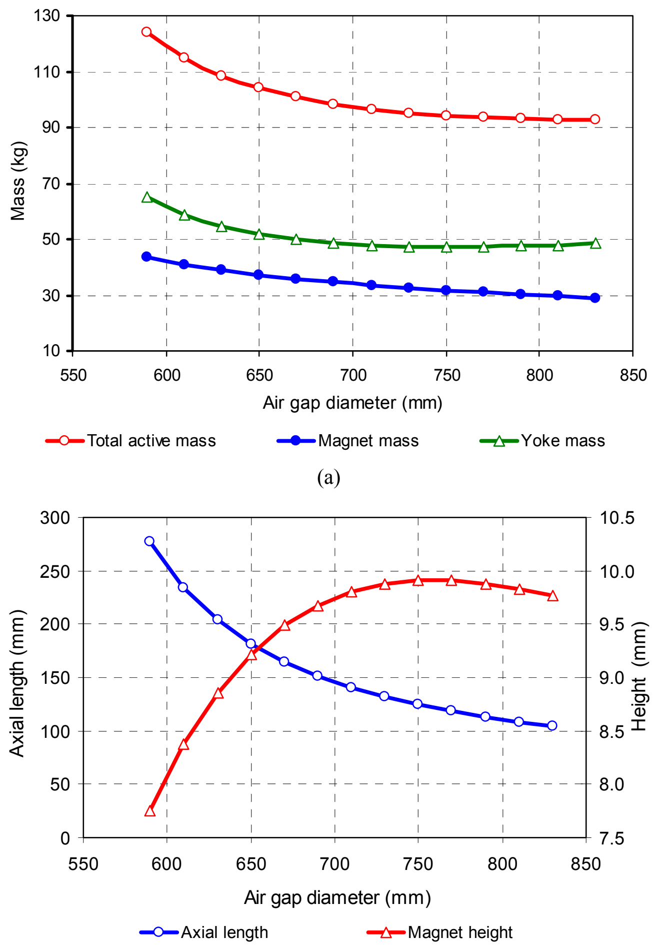


Figure 5. (a) Mass and (b) axial length and magnet height versus air gap diameter of the air-cored PMG {every calculation point satisfies (1)}.

What is prominent from the results in Table I with regard to the optimum designed air-cored machine is the relative large outer diameter, the excessive amount of magnet material, but the much less copper material than the iron-cored machine. It is interesting that the active mass of both machines are almost the same. Note that the total mass of the built air-cored PMG is also very much the same as that of the iron-cored PMG. Further prominent is the very low per unit internal impedance of the built air-cored PMG. From the per unit internal impedance results the steady-state per unit short-circuit current of the air-cored PMG is 10.5 p.u., while that of the iron-cored PMG is 2.13 p.u.

VII. FE-Simulation and Test Results

Prototypes of both the air- and iron-cored wind PMGs have been build and tested in the laboratory. However, the air-cored PMG could not be built according to the optimum dimensions in Table I, as the air gap diameter is limited to 660 mm. Photos of the two PMGs build are shown in Fig. 6. Note from Table I that the efficiency-performance of the build, un-optimised air-cored PMG at rated load (1000 Nm) does not comply with the specifications of (1).

TABLE I. Design Results of Air- and Iron-Cored Direct-Drive Wind PMGs.

Parameters ↓	Air-cored (build)	Air-cored (optimum)	Iron-cored
Outer diameter, d_o (mm)	678	886.8	653.5
Inner diameter, d_i (mm)	576	773.2	494
Active axial length, ℓ (mm)	149	104.3	100
Magnet height, h_m (mm)	9.7	9.77	6.0
Stator (slot) height, h (mm)	11.42	11.41	53
Copper mass (kg)	15.5	15.2	23.9
Active iron mass (kg)	43.9	48.4	58.9
Magnet mass (kg)	30.1	29.0	6.5
Total active mass (kg)	89.5	92.6	89.3
Total mass {structural + active} (kg)	164.4	-	165.6
Synchronous reactance X_s (p.u.)	0.063	-	0.471
Phase resistance R_s (p.u.)	0.072	-	0.034
Current density (A/mm^2)	6.0	4.89	3.39
Power factor {$I_d = 0$ A}	0.998	-	0.934
Efficiency (%) {$I_d = 0$ A}	92.6	94	93.5
Copper losses (W)	1124	857	749
Stator eddy current loss (W)	34.4	85.7	-
Stator core losses (W)	-	-	246
Stator loss / stator volume (kW/m^3)	345	304	90

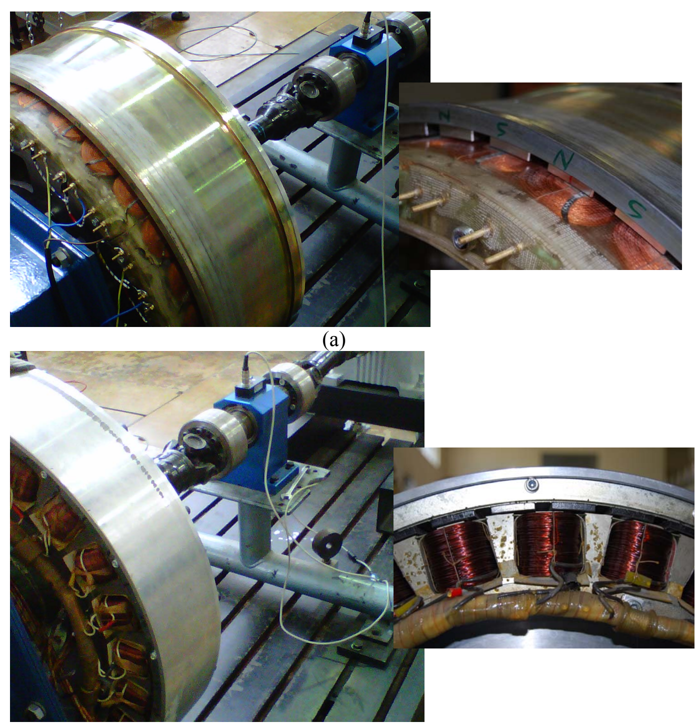

(a)
(b)

Figure 6. 15 kW direct-drive wind PMGs under test and stator windings of (a) air-cored PMG and (b) iron-cored PMG.

A. Induced Voltage Quality

The measured induced open circuit voltage waveforms of the two generators are shown in Fig. 7. Also shown are the transient FE calculated open circuit phase voltages of the PMGs. From these results the agreement between calculated and measured results are clear. Also clear is the high quality of the induced voltage waveform of the air-cored PMG. Certainly the voltage quality of the iron-cored PMG can be improved, but this must be measured against possible loss in torque quality. The induced voltage quality is important for the sinusoidal current control of the PMG drive by means off the active synchronous rectifier (Fig. 1).

B. Torque Quality

The measured and FE-calculated cogging torque waveforms of the iron-cored PMG are compared in Fig. 8. From the measured results a cogging torque of 3.5 % is calculated for this machine. The cogging torque of the air-cored PMG is obviously zero. The FE-calculated full-load (1000 Nm) torque waveforms of the air- and iron-cored PMGs are shown in Fig. 9. The full load torque ripple of the iron-cored PMG is 5.2 %, while that of the air-cored PMG is 1.2 %.

C. Magnet Flux Density

The instantaneous FE-calculated flux density waveforms at the surface of the magnets of the two machines under full-load are shown in Fig. 10. Hence, the large flux pulsations in the magnets of the iron-cored PMG are clear, while the armature reaction effect on the magnet flux density of the air-cored PMG is very small.

D. Magnet Demagnetisation

It is important to investigate the possible demagnetisation of the magnets under short circuit conditions. Due to the close-to-unity R_s/X_s-ratio of the air-cored PM machine (114 % from Table I) the damping of the well-known DC component in the phase currents during a short circuit is high, so that this component is almost non-existing. This can be seen from the transient 2D FE-simulated short-circuit phase current waveforms of the air-cored PMG shown in Fig. 11. For the iron-cored PM machine, however, this is not the case as the R_s/X_s-ratio is very low (7.2 % from Table I). Here the DC component is evident from the simulated short-circuit phase current waveform shown in Fig. 12. The transient demagnetising d-axis current of the iron-cored PMG is also shown to be much more severe. Note that both simulations of Figs. 11 and 12 were done at the worst condition of the short-circuit, i.e. with full PM flux-linkage in one phase at the time of the short circuit. Also in these simulations the end winding impedances of the machines have been taken into account.

From the above, thus, in calculating the worst peak counter MMF per magnet pole for the iron-cored PMG, the instantaneous peak current must be taken as $2\sqrt{2}I_{sc}$ ($I_{sc} = E_s/Z_s$), while in the case of the air-cored machine as $\sqrt{2}I_{sc}$. This is a huge difference in favour of the air-cored machine. Finally, from Figs. 11 and 12, the much larger per unit short-circuit current of the air-cored PMG compared to that of

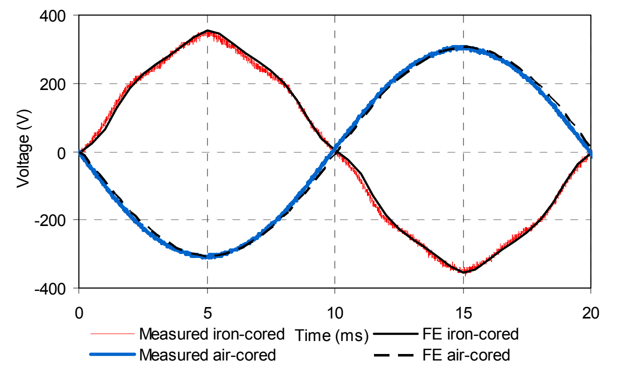


Figure 7. FE-calculated and measured open circuit induced voltages of the air- and iron-cored wind PMGs at 50 Hz and 150 r/min.

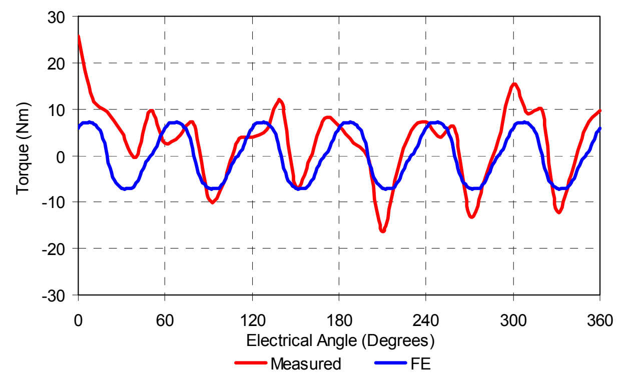


Figure 8. FE-calculated and measured cogging torque of the iron-cored PMG [16].

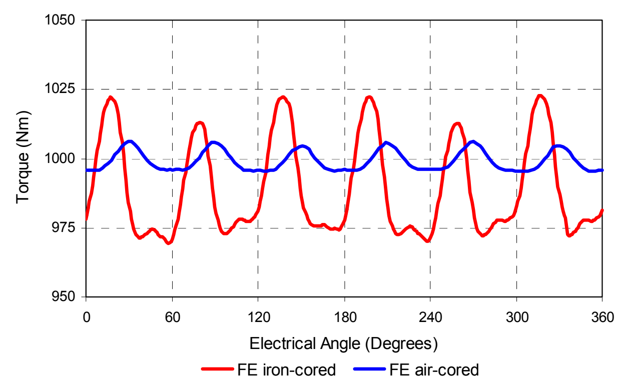


Figure 9. FE-calculated full-load torque waveforms of the air- and iron-cored PMGs.

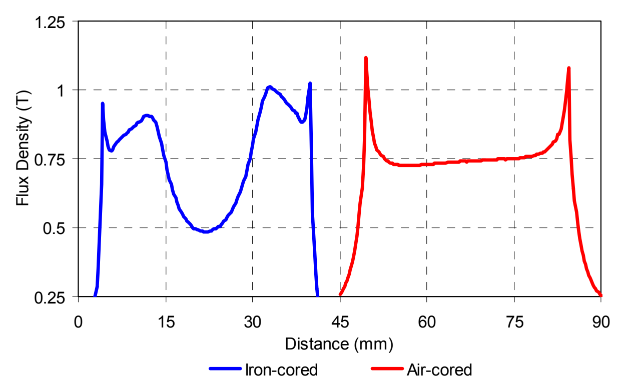


Figure 10. FE-calculated magnitude of the flux density at the surfaces of the magnets of the air- and iron-cored PMGs at full-load.

the iron-cored PMG is evident. In terms of demagnetisation, however, the effective magnet thickness of the air-cored PMG is also much larger (more than three-times from Table I) than that of the iron-cored PMG, hence it can withstand a much higher counter MMF.

To conclude, there is no indication in the above that the air-cored PMG has a higher risk of magnet demagnetisation than the iron-cored PMG. On the contrary, it is shown that the magnets of the iron-cored PMG have to withstand a relatively high counter MMF per magnet pole. The possible demagnetisation of the magnets of the two machines under short circuit conditions is further investigated by using transient 2D FE analysis. Using a straight demagnetisation line and B_{min} = 0 T in the FE analysis, the results in Fig. 13 show that the magnets of both PM machines considered do not demagnetise under short circuit conditions. However, at higher values of B_{min}, parts of the magnets start to demagnetise in both PM machines as shown in Fig. 13.

A final note on magnet demagnetisation in the air-cored machine is that demagnetised magnets can easily be magnetised again within the machine. This can be done by using a quite different modular air-cored winding that can be inserted in-between the magnets. In principle, thus, the air-cored PM machine can be assembled with unmagnetised magnets, to be magnetised then in the machine, which is a huge advantage.

E. Temparature Rise and Cooling

Both the PMG prototypes have been tested at rated current to investigate the hourly temperature rise of the windings and magnets. These measurements were done in the laboratory with no external cooling, thus with much less cooling than outside on a tower in a wind with a speed of 11 m/s. The terminal voltage and load current waveforms of the PMGs with *RC*- and *R*-loads are shown in Figs. 14 and 15 respectively.

For the iron-cored PMG the measured temperature rises were $\Delta T_{\text{windings}}$ = 75 °C and $\Delta T_{\text{magnets}}$ = 45 °C. For the air-cored PMG these measurements could not be completed due to the damage of one of the stator coils during testing. An important cooling parameter to look at, however, is the stator losses per stator volume of the two PMGs at rated current. From Table I this is much higher for the air-cored PMG (304 kW/m^3) than for the iron-cored PMG (90 kW/m^3). Although the stator winding of the air-cored PMG is cooled on both sides of the winding, careful attention should be given to the cooling of this machine.

VIII. Comparison of Characteristics

From the results in the previous sections the characteristics of the air- and iron-cored wind PMGs are compared in Table II. Other aspects not considered in the previous sections are also compared and further discussed below. It is clear that both machines have advantages and disadvantages as summarised in the conclusions.

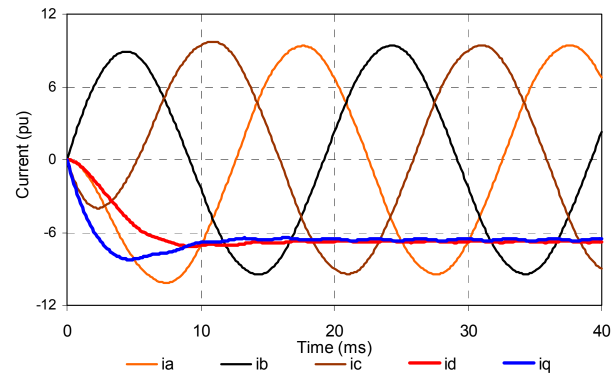


Figure 11. Transient FE-simulation of short-circuit phase currents of the air-cored PMG at rated speed (per unit is based on peak values).

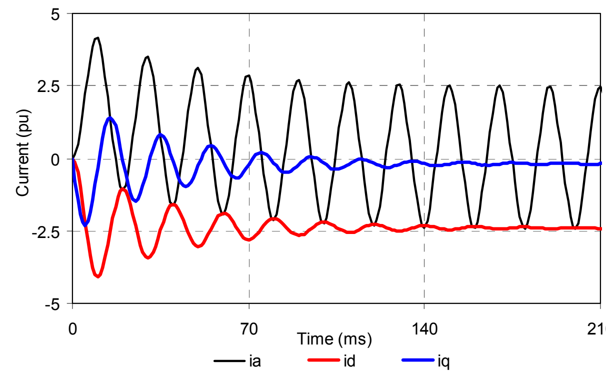


Figure 12. Transient FE-simulation of short-circuit phase current of the iron-cored PMG at rated speed (per unit is based on peak values).

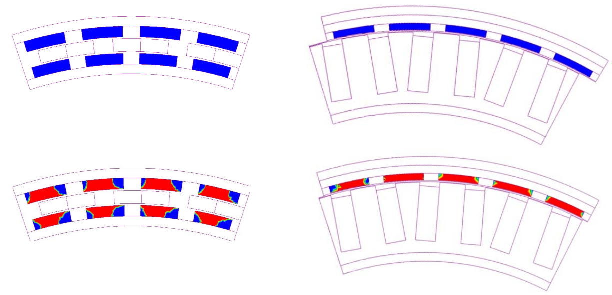


Figure 13. Transient FE-simulations showing no demagnetisation of magnets (blue color, B_{min} = 0 T) and demagnetisation (red color, B_{min} = 0.54 T) during short circuit of air-cored (left) and iron-cored (right) PMGs.

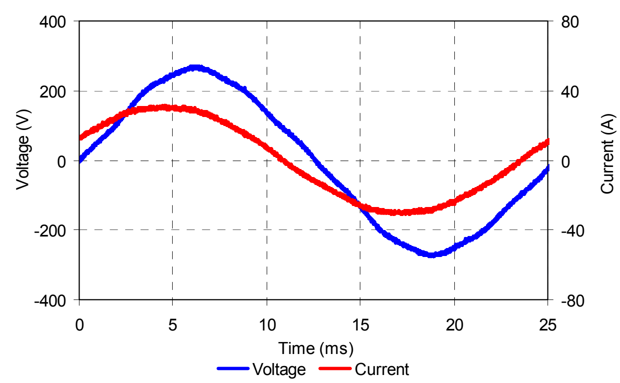


Figure 14. Measured terminal phase voltage and line current of the iron-cored PMG with a resistive + capacitive load at rated current and 150 r/min.

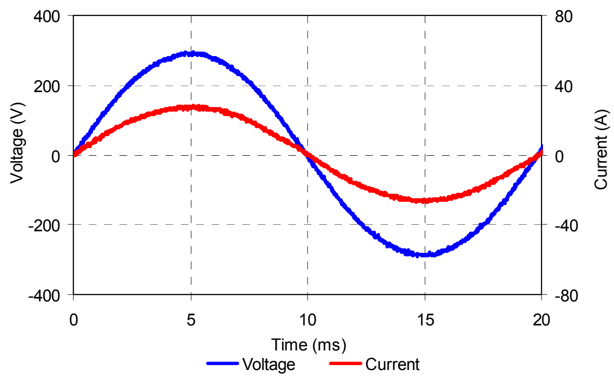


Figure 15. Measured terminal phase voltage and line current of the air-cored PMG with a resistive load at rated current and 150 r/min.

A. Stator Winding

Parallel connected coils cannot be used in air-cored PMGs as stated in Table II. This is due to the very low internal impedances of the coils, which if connected in parallel, result in circulating currents within the stator as a result of even the slightest difference in induced coil voltages.

It can further be seen in Table II that modular stator windings can be used very easily for non-overlap air-cored windings, and is the preferred way of manufacturing. This makes in situ and fast replacement of faulty stators possible, which is a big advantage compared to the iron-cored-winding machine.

Another aspect is the use of high voltage stator windings, say higher than 1 kV. In general for high voltage windings the cost of iron-cored windings rapidly increases and the copper filling decreases. This is not the case for the air-cored winding, which is encapsulated in epoxy resin and thus well insulated. One aspect, however, of the high voltage air-cored winding that has to be considered carefully is the high voltage across the stator-surface and magnet-surface layers.

B. Cost

In Table II it is given that although the cost of the active material of the air-cored PMG is high, the total cost of the complete wind turbine system (tower, nacelle, generator and blades) can be 5 – 8 % higher if an air-cored direct-drive wind PMG is used. This percentage increase is calculated for the prototype 15 kW PMGs considered in this paper by

(i) taking the specific cost (at the time of the writing of this paper) for magnets as USD100/kg and the market price for uninstalled iron-cored direct-drive PMG wind energy systems as between USD2.0 – 3.0 million/MW, and

(ii) assuming that the cost differences in steel, copper and structure of both machines are negligible.

This comparative calculation is obviously very rough, as, for example, the structural cost of the two machines for large scale wind generators may differ substantially [7]. Magnet prices are also currently high and volatile. Note lastly that the above calculated cost-difference will become much lower if the installed cost is also brought into calculation.

TABLE II. CHARACTERISTIC COMPARISON OF NON-OVERLAP WINDING AIR- AND IRON-CORED DIRECT-DRIVE WIND PMGS.

Characteristics	**Air-cored wind PMG**	**Iron-cored wind PMG**
Torque induced voltage quality:		
- cogging torque ripple	- superior (zero)	- moderate*
- load torque ripple	- superior	- moderate*
- induced voltage quality	- superior	- moderate
Stator copper, winding and core:		
- amount of copper material	- low	- normal
- use of parallel connected coils	- not allowed	- no problem
- stator modular manufacturing	- very easy	- difficult
- stator to rotor attraction forces	- zero	- high
- stator assembling / replacement	- very easy, in situ	- difficult
- stator per unit impedance	- very low	- average
- stator eddy current losses	- take care	- no problem
- stator core losses	- zero	- standard
- stator losses per stator volume	- high	- standard
- stator cooling	- special attention	- standard
- short circuit current	- high	- not high
- stator punched laminations?	- no	- yes
- high voltage winding	- easy (low cost)	- expensive
Permanent magnets:		
- amount of material	- excessive	- normal
- magnet losses	- ≈ zero	- high
- demagnetisation concern?	- take care	- take care
- segmented PM required?	- no	- yes
Back yoke:		
- losses	- ≈ zero	- take care
- laminated yoke required	- no	- yes
Mass and size:		
- active material	- same	- same
- total (active + structural)	- same	- same
- overall volumetric size	- large	- standard
Cost:		
- active material	- high	- normal
- per unit total wind system cost	- 1.05 – 1.08	- 1.0
SSC and Control:		
- kVA rating	- lower	- standard
- fit with SSC + LC filter	- as for grid	- as Syn.Mach.
- power factor control	- always unity	- load dependent

* not easy to get ripple low in terms of design and manufacturing.

C. Solid State Converter and LC Filter

Due to the close-to-unity and better power factor of the air-cored PMG the kVA rating of the active rectifier (Fig. 1) is lower than that for the iron-cored PMG. Practically this will make almost no difference in the cost of the converter as wind energy converters are in general rated much higher than the power rating of the wind generator. However, from a control point of view the current of the air-cored PMG can be controlled under all load conditions in-phase with the terminal voltage or else in-phase with the filter capacitor voltage (Fig. 1). For the iron-cored PMG, however, the current must lead the terminal voltage for best operation as shown in Fig. 1, and so the active rectifier must supply reactive power to the generator. In this case the leading angle and reactive power varies with load.

As the air-cored PMG has a very low internal impedance and acts as a very good voltage source such as the grid, the design of the LC filter between the active rectifier and the generator (Fig. 1) can be done in very much the same way as for connecting to the grid. A method for how such an filter can be designed can be found from [17]. In general it is important to consider the resonance frequency, which is given by

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_s + L_f}{L_s L_f C_f}}\ , \tag{3}$$

where L_s is the generator's internal inductance and L_f and C_f are the filter inductor and capacitor respectively. Hence, with the same resonance frequency and the same filter capacitor, the filter inductor is typically larger for the air-cored PMG than for the iron-cored PMG.

IX. Conclusions

In this paper a comparison is done of air- and iron-cored converter-fed PMGs for direct-drive variable speed wind generator applications. Although in the study the focus was on small-scale (sub 100 kW) systems, many of the results and conclusions reached are also applicable to medium and large scale systems.

It is shown that the air-cored PMG is in many respects the ideal generator. It has a superior torque quality, which is important for start-up and low noise. Furthermore, its low internal impedance, high power factor and high induced voltage quality are all aspects that are beneficial to the active rectifier plus LC filter and its current control. The practically zero losses in the magnets and back iron yokes of the air-cored PMG are an important advantage compared to the non-overlap iron-cored PMG, so that solid magnets and solid yokes can be used. The demagnetisation of the magnets of the air-cored PMG under short-circuit conditions is shown to be not more of a problem than in the iron-corded PMG.

A very important construction advantage is the zero attraction force between the PM rotors and the stator, which makes in situ replacement of modular stator windings possible. A disadvantage of the air-cored PMG is the volumetric-size of the generator; this is found to be 1.7 times that of the iron-cored PMG; the optimum outer diameter is about 1.4 times that of the iron-cored PMG. Despite the difference in volumetric size, the active mass and overall mass of both PMGs are found surprisingly to be almost the same. The amount of copper used in the air-cored PMG is found to bea-bout 40 % less than that of the iron-cored PMG, but the amount of magnet material an excessive 4 – 5 times that of the iron-cored PMG. The latter can be considered as the only, but very serious, disadvantage of the air-cored wind PMG.

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