Evaluation and Application of a Slip-Synchronous Permanent Magnet Wind Generator

Johannes H.J. Potgieter
Stellenbosch University

Centre for Renewable and Sustainable Energy Studies

Abstract

This study deals with the evaluation and application of a low maintenance slip-synchronous permanent magnet wind generator, which is based on the concept of a permanent magnet induction generator. This generator is a gearless, directly grid connected wind turbine generator, which means that no gearbox or power electronic converter is needed in the drive train. The least reliable components in the drive train are, thus, omitted which increases the reliability and decreases the maintenance and operation costs of the wind turbine system significantly. The slip-synchronous generator consists of two integrated generating units, a conventional permanent synchronous generator and a second slip-permanent magnet generator. The direct grid connection without a power electronic converter is made possible due to the damping provided by the slip characteristics of the second generator. The main aim of this study is to characterise this system in order to more thoroughly understand its working principles in a wind generating setup and also to obtain an optimum final design which makes this system comparable to other wind turbine drive trains. The best suited applications for this generator also needs to be investigated. Simulation and practical results of a 15 kW test system are also presented in this study.

1 Introduction

Although wind power is ever increasingly being utilised for the supply of clean electrical energy, there are still some factors which hampers the full scale utilisation of this energy source. These factors include, initial capital cost, reliability, maintenance and operation costs. The aim of the technology presented in this study is to improve the reliability and reduce the maintenance and operation costs of wind turbine systems.

1.1 Current Wind Turbine Systems in Use

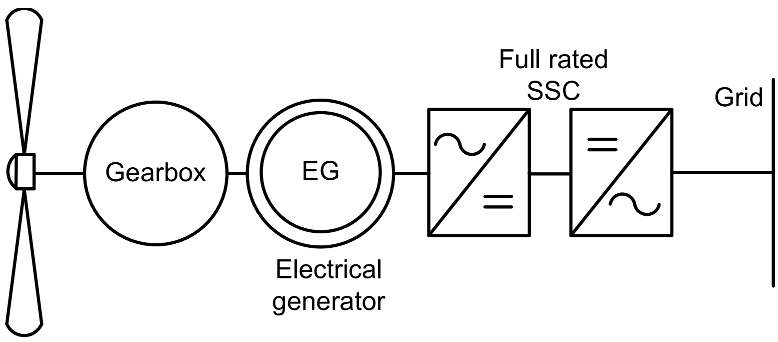

Figure 1: Conventional wind turbine drive-train.

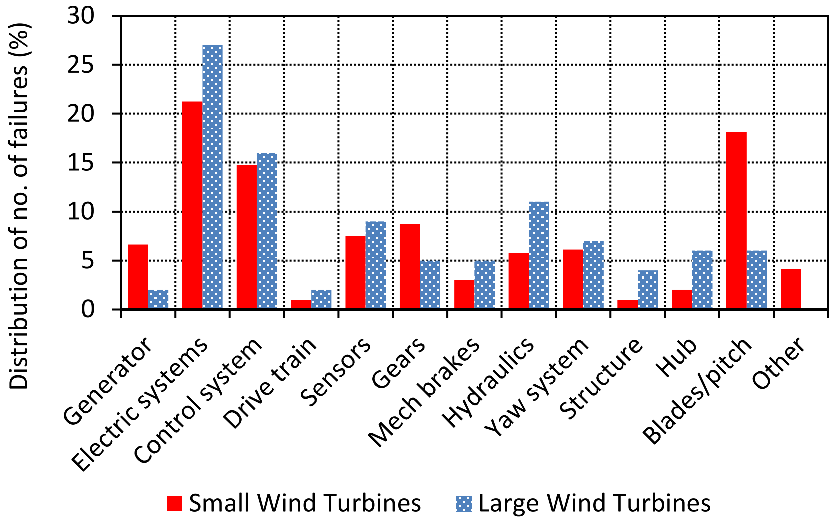

Figure 2: Distribution of failures for small and utility scale wind turbines.

In the past most wind turbine systems made use of a conventional induction machine, connected directly to the grid, and to the turbine through a multi-stage gearbox. Many of these types of systems are however still in use today. At current most utility scale wind turbine systems installed makes use of a double-fed induction generator (DFIG) topology. The drive train of the DFIG topology consists of a gearbox, DFIG and a partially rated power electronic converter connected to the wound rotor of the DFIG. The stator terminals of the DFIG are connected directly to the grid. The newest trend in wind turbine technology is the gearless, permanent magnet synchronous generator (PMSG) connected to the grid via a power electronic converter or solid-state converter (SSC). Synchronous machines can only be connected directly to the grid if a smooth and constant power flow is available, which is not the case in a wind energy conversion system. Due to the souring cost of permanent magnet (PM) material and the sheer size of these machines, many new systems employ so-called hybrid systems, where a medium speed much smaller electrical generator is used with a gearbox consisting of fewer gearing stages. There are also other variations of these drive trains used, for instance conventional induction machines connected to the grid via power electronic converters to comply with grid codes. In some cases the PMSG is replaced by a synchronous generator with a wound rotor to reduce the effects of the volatility of PM prices. Fig. 1 shows a typical drive-train layout with a gearbox, electrical generator and power electronic converter.

Geared drive trains are used to some extent for small scale wind generator systems, but in most cases a PMSG and power electronic converter topology is utilised. These are mostly off-grid battery charging systems. For grid-connected small scale users so-called grid-tie systems are used, where the excess power not being utilised by the residential or commercial customer is fed into the utility grid.

From the above discussion it is clear that all wind turbine drive trains consists of an electrical generator operated in conjunction with either a gearbox or power electronic converter or both. Available failure rate data of wind turbine systems as shown in Fig. 2 for utility scale and small wind turbine systems shows that the components failing the most is the electronic systems. However, the component failure owing to the largest financial implications is gearbox failures. Although electronic failures feature the most often these components are much easier to replace than a gearbox. With small scale systems mostly consisting of an electrical generator and a power electronic converter, power electronic failures will be the dominating consideration regarding maintenance and failures.

Not only do failures induce significant cost for the replacement of the components, it also incurs extra maintenance costs and loss of income due to system downtime. Also the more components in a drive train, the more preventative maintenance is required to keep the system functioning optimally all the time. It is, thus, evident, that by removing the gearbox and power electronics from the drive train, the maintenance requirements and the probability of failures occurring as well as the operating cost of a wind turbine system can be reduced significantly.

1.2 Direct-Grid Wind Systems

Direct-grid wind generators includes all wind turbine systems that connects directly to the grid without a power electronic converter. The only exception is conventional geared induction machines which also connects directly to the grid without a converter.

1.2.1 PMIG type of systems

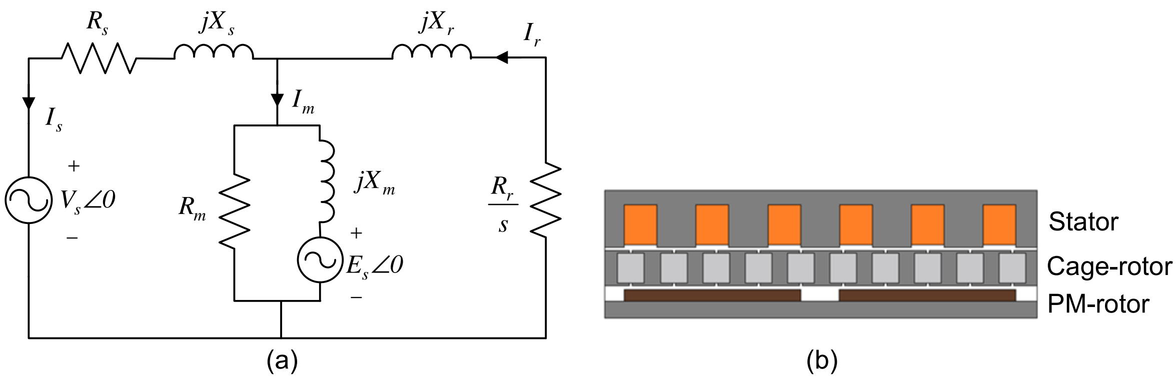

Figure 3: (a) Equivalent circuit and (b) section diagram of a conventional PMIG.

The permanent magnet induction generator (PMIG) concept on which the slip-synchronous permanent magnet generator (SS-PMG) is based upon was first introduced by Punga & Schon (1926). This generator consists of a conventional stator winding and induction machine cage-rotor, with a second free-rotating PM-rotor added to the design as shown in the diagram of Fig. 3(b). This second PM-rotor runs at synchronous speed, with the cage-rotor operating at a relative slip speed with regard to the PM rotor and rotating synchronous stator field. The PMs on the PM-rotor induces a voltage in the stator winding, indicated as E_s in parallel with the magnetizing inductance, X_m, as shown in the equivalent circuit diagram of the PMIG in Fig. 3(b). More early PMIG research includes the work done in Douglas (1959) and Sedivy (1967). However, during those times high energy density PMs were not available yet and the concept was not deemed feasible. The use of rare earth PM materials for this concept was first proposed by Low & Schofield (1992). PMIG research was also conducted in Japan at the Toyota Technological Institute by Shibata et al. (1996) and Shibata et al. (1999) and also at the Kanazawa Institute of Technology by Fukami et al. (2003, 2004), Tsuda et al. (2007). More PMIG research was also conducted in Germany by Hagenkort et al. (2000), Gail et al. (2004), Tröster et al. (2006), where the PMIG was for the first time proposed as a high pole, large diameter, direct drive, directly grid connected wind generator. The first local research on the PMIG concept was launched in 2009 by Potgieter et al. (2009). A variation of the PMIG concept is also proposed in Thomas (2004), where the slip-rotor of the PMIG is wound and a partially rated converter is connected to the rotor winding in a similar manner as for a DFIG. A typical application for PMIGs is mentioned in Vermaak et al. (2009) where several PMIG type systems are connected to a common grid in a wind farm of which the frequency and voltage is controlled by a single power electronic converter. The output power of the power electronic converter is then transmitted to the main utility grid by a central DC link. In this case the fixed speed disadvantage of the PMIG is no longer a drawback.

Although the PMIG is proposed for use as a large diameter, direct drive wind generator, only conceptual research and basic simulation results are reported. From all available literature on the PMIG concept it is found that only small scale prototypes have been manufactured and tested in the laboratory. In most cases a conventional induction machine was modified to include the second PM-rotor. It is, thus, not clear if this concept is feasible for use as a wind generator. The main reasons seems to be the mechanical complexity associated with this type of generator which makes manufacturing difficult and expensive. Mention is also made of thermal issues due to the heat dissipated from both the stator and the cage rotor windings in a very confined space. This could lead to demagnetization of the PMs on the PM-rotor.

1.2.2 Other direct-grid topologies

Although not well known there are also other types of directly-grid connected wind generator topologies reported in literature. These non-conventional methods includes the spring and damper system used to damp power angle oscillations as proposed in Westlake et al. (1996). Another concept investigated in literature is to connect the PMSG to the grid via a hydro-dynamically coupled gearbox. This variable speed gearbox delivers a fixed speed output to a synchronous generator with the input the variable turbine speed as mentioned in Muller et al. (2006). The newest known direct-grid wind generator encountered in literature is the concept reported in Grabic et al. (2008) where a partially rated converter is connected in the star point of a PMSG to damp oscillations. However, also regarding these direct-grid synchronous wind generators there is no clear indication on whether these concepts are feasible in an actual wind generator system.

1.2.3 SS-PMG

The SS-PMG differs from the original PMIG concept due to the fact that the stator winding and cage rotor windings are electromagnetically separated. In Section 2 the main working principles of this generator will be more elaborately discussed. The design and analysis of the SS-PMG system presented in Potgieter & Kamper (2012*a*) is the first known instance where a high pole large diameter directly grid-connected system was successfully manufactured and practically tested. This wind generator was also successfully interfaced with a wind turbine system and integrated to the local municipal grid and was shown to operate stable under several different operating conditions.

1.3 Research Objectives

From the reviewed literature and the research work already done it is clear that the most feasible directly grid connected, direct-drive wind generator solution is the SS-PMG. Although the concept has been successfully introduced and shown to work properly several aspects still needs to be addressed, before this type of generator can be proposed as a solution comparable to other wind generator topologies. The main objectives of this study can be broken down in four main aspects as below:

1.3.1 Correct Parameter Estimation

A very important aspect in the design of the SS-PMG system is the correct prediction of the machine parameters. Incorrect parameter calculations can have a significant effect on the performance of the final product as shown in previous studies. This is especially true for this type of system due to the importance of the maximum torque value, which is difficult to calculate accurately. For stable and safe operation of the system this value needs to be adequately specified. The most important parameter here is the calculation of the per phase inductance. It was found that especially the end-winding inductance and the end-effects of the permanent magnets influences this parameter significantly.

1.3.2 Dynamic Evaluation

Definite more work is needed to better understand the dynamic behaviour of the SS-PMG connected to the grid. Here it is important to know which parameters can influence the stability of the system the most. There is also more work needed to determine whether the torque ripple of especially the slip-PMG unit is a problem. A detailed frequency analysis is, thus, needed. Furthermore preliminary studies show that the SS-PMG system has the potential to filter out certain unwanted turbine effects, for instance tower shadowing, yawing error and turbine shear effects. More work is also needed to determine whether the SS-PMG can successfully handle grid faults and the behaviour of the system during low voltage ride-through (LVRT).

1.3.3 PMSG Design

Although the PMSG is already extensively used as a wind generator, the design requirements of the directly grid-connected PMSG differs from conventional systems. Here it is important that this machine complies to all the grid specifications as there is no power electronic converter to handle the grid requirements. It is also important that this generator can still operate stable during grid faults. An important aspect also generally ignored in the design of PM wind generators is the electromagnetic braking capabilities of the generator.

1.3.4 slip-PMG Design

The slip-PMG is basically a short circuited permanent magnet machine operated at a very low electrical frequency. This makes the design of this generating unit significantly different from the design of conventional PM machines. Several different machine topologies can, thus, be evaluated. The end-goal is to obtain the optimum slip-PMG configuration regarding mass, PM content and ease of manufacturing.

2 Proposed Model or Conceptual Method

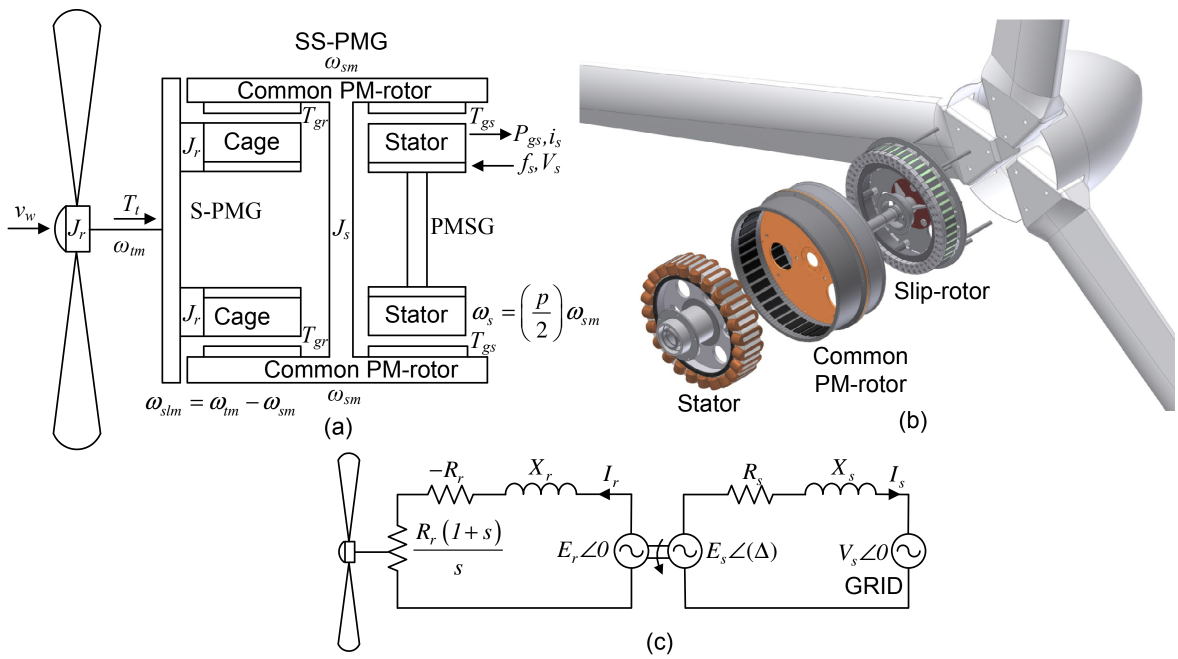

Figure 4: (a) Section diagram, (b) prototype example and (c) equivalent circuit of the SS-PMG.

As mentioned the SS-PMG consists of two integrated generating units, a directly grid connected PMSG and a short circuited slip-PMG connected mechanically directly to the wind turbine as shown in the section diagram and example SS-PMG in Fig. 4(a) and (b). These two generator units are linked by a free rotating common PM-rotor having separate sets of magnets for each of the generators. The main difference of this generator compared to the conventional PMIG is that the slip-rotor cage windings and the stator windings are electromagnetically separated. This electromagnetic separation allows for much more freedom in the design of the SS-PMG which makes the manufacturing of this type of generator much easier.

The two machine units can, thus, be modelled as two separate decoupled machines. The equivalent circuit of the SS-PMG consists of the conventional equivalent circuit of the PMSG with a mechanical link through to the second machine which has its end-connections short circuited. A voltage is induced in the PMSG at synchronous frequency and in the slip-PMG at slip frequency as shown in the equivalent circuit of Fig. 4(c).

The advantages and differences of the SS-PMG versus the PMIG can be summarised as follows:

- The amount of PM material will be the same for the PMIG and SS-PMG.
- The yoke mass of the SS-PMG will be higher, but this will be little compared to the overall active mass for high pole number machines.
- The size of the two machines and the amount of poles can differ. The airgap diameter of both machines can, thus, be put at the optimum value. If more poles are selected for the slip-PMG the yoke mass will be much less, which means that the addition of this extra yoke poses much less of a problem. These design aspects are not possible in the conventional PMIG.
- For the SS-PMG there is no constraint for the type of winding configuration to use, where for the PMIG only overlap windings can be used, with a limited pole slot combination choice.
- With the two units in this example mounted in tandem, the modularity of the system is greatly enhanced. The PMSG unit can be manufactured separately and operated as a conventional PMSG wind generator system. To obtain an SS-PMG system the second slip generator is fixed to the front of this machine and the turbine can then be fixed to the mounting plate of the slip-PMG.

The SS-PMG might sound like an extremely complex generator, however, as explained above it is extremely simple to mount the slip-PMG to the PMSG due to the modular nature of the generator system. Furthermore the second generator uses a very simple construction. Due to this generator only operating at slip speed it has a very low electrical frequency. This means that solid bar-windings, solid unsegmented PMs and solid yokes can be used without any additional losses occurring.

3 Research Methodology

3.1 Correct Parameter Calculation

The issue of correct parameter calculation came to light when especially for the slip-PMG it was found that the short-circuit torque-slip profiles does not match the FE simulated torque-slip profiles. This is especially evident in the above rated region. Further analysis on the PMSG unit highlighted the same problem. With access available to the output terminals of the PMSG, current and voltage can be measured as well as the per phase inductance. With the short-circuit current also much less than predicted, it was, thus, found that the measured inductance is far more than that predicted by FE. From basic machine equations it can be deducted that the short-circuit torque is inversely proportional to the per phase inductance which explains this phenomenon.

The first component of the per phase inductance investigated is the end-winding inductance which is a parameter mostly ignored for non-overlap winding PM machines as is used in this case. Other aspects which can influence the per phase inductance also includes inconsistencies in the lamination steel which causes the saturation levels to be different than

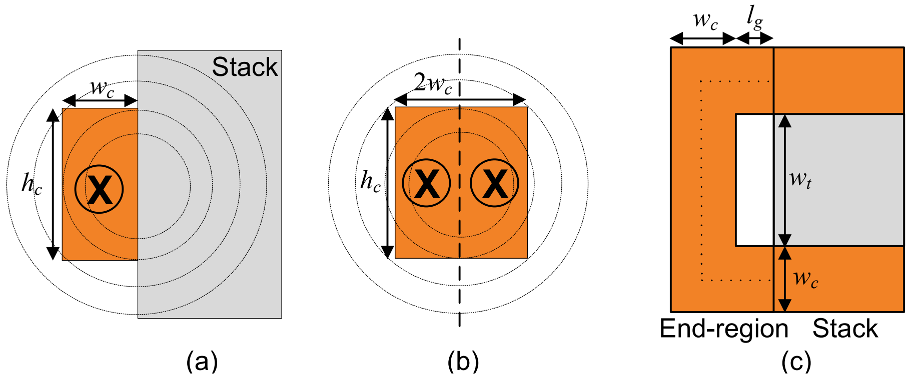

Figure 5: (a) Conductor placed next to permeable lamination stack, (b) two conductors placed next to each other in air to form one large conductor and (c) dimensions for the end-winding inductance calculations.

expected. Furthermore end-effects on the PMs which is caused by fringing fluxes at the magnet-ends can further decrease the magnetic flux circulating through the whole machine magnetic path which further changes the inductance value. It is essential that these are addressed before any machine design optimisation begins.

In Potgieter & Kamper (2012*b*) it is thoroughly explained how to calculate the end-winding inductance of a non-overlap winding PM machine. As mentioned in most cases due to the short end-winding length of the non-overlap winding machines, the end-winding inductance is mostly ignored. There are however some methods reported in literature of how to calculate this parameter for non-overlap winding machines. However, most of these methods as explained in Potgieter & Kamper (2012*b*) does not take the lamination stack into account and the results obtained for the end-winding inductance is far too low. A new method making use of the method of mirror images as explained in Kamper & van der Merwe (1988) is employed in this study.

A common calculation technique as in literature is to combine the two end-region sections of a coil to form a semi-circular coil in air. From the dimensions of the circular coil the per phase end-winding inductance L_e can be expressed from Grover (1946) as

$$L_{e(1)} = \frac{1.9739}{n_a^2}\left(\frac{2a^2}{b}\right) N_c^2 qK. \quad (\mu\mathrm{H}) \tag{1}$$

However, as mentioned due to this formula not taking the lamination stack into account the end-winding inductance is calculated far too low. A different method is thus used by assuming a large circular coil along the circumference of the centre of the stator. The per unit end-winding length inductance of this large circular coil is then calculated. To take the lamination stack into account the method of mirror-images is used. It is found that if a conductor is placed next to a medium of infinite permeability as in Fig. 5(a) the inductance of this conductor will be two times that of the conductor, with two times the conductor width, shown in Fig. 5(b) in air. The formula (1) can now be modified to calculate the per unit inductance of this large coil in air as given in (2) with

$$L_{e(2)} = \frac{1.257}{n_a^2} l_e \left(\frac{2a}{b}\right) N_c^2 qK. \quad (\mu\mathrm{H}) \tag{2}$$

In the case of (2), $a = r_c$ (slot radius), $b = 2w_c$ (slot width) and $c = h_c$ (slot height). However, it is also important to specify the correct end-length (l_e) and the gap between the end winding and the lamination stack (l_g) also needs to be taken into account. To take l_g into account a third analytical approach is developed as given in (3) with

$$L_{e(3)} = \begin{cases} L_{e(2)\ (l_e = w_t + 2w_c + 2l_g,\, b = 2w_c)} & \text{for} l_g < 2.5\ \mathrm{mm}, \\ \{L_{e(1)\ (l_e = w_c + 2l_g,\, b = w_c)} + & \\ L_{e(2)\ (l_e = w_t + w_c,\, b = 2w_c)}\} & \text{for } l_g > 2.5\ \mathrm{mm}, \end{cases} \tag{3}$$

and with $a = r_c$ and $c = h_c$. It was also found that an average of more or less 10 % needs to be added for double layer windings for mutual phase cross-coupling and another 10 % needs to be added to the end-winding inductance if there are other permeable mediums in close vicinity to the end-region as for instance the turbine mounting plate which is common for wind generators. Five machines were used as a case study and if the analytically calculated end-winding inductance is compared to the end-winding inductance calculated by 3D-FE for each machine on average an error of only just more than 2 % is observed.

Although much better results are obtained by taking the end-winding inductance into account the effects of variations in the PM strength and the lamination steel still needs to be taken into account. The largest effect was found to be from the end-fringing in the PMs which is clearly seen if a 3D-FE analysis is done. This means that the PM flux linking the coils will be different than expected. The best way to take this effect into account is to linearly decrease the PM strength (H_m). An initial investigation indicates a ratio of about

$$H'_m = H_m \left(1 - \frac{0.005}{l}\right) \tag{4}$$

where l is the axial stack length in meters of the generator. This new value of the magnet strength is then used in the FE simulation to simulate the performance of the machine, with much better short-circuit results obtained.

3.2 Dynamic SS-PMG Behaviour

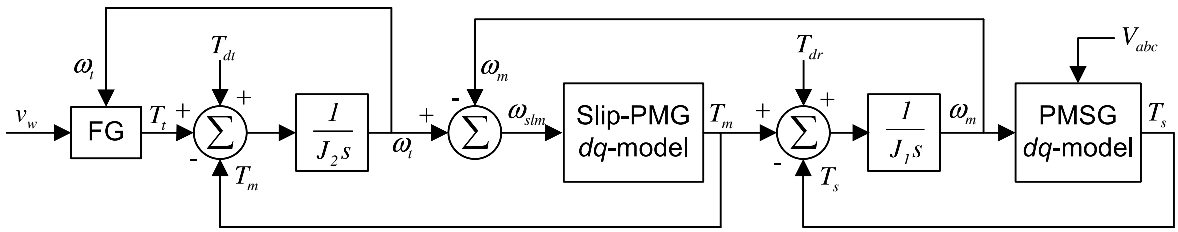

Figure 6: Overall diagram of the dynamic performance prediction of the SS-PMG system.

It is essential for a clear understanding of the dynamic behaviour of the SS-PMG system connected to the grid. Also important here is the behaviour of the generator during grid faults. It is thus important to know which parameters influence the stability of the generator as this will determine many of the design specifications in the optimisation of the slip-PMG and PMSG units. The most important design specifications which will be determined by the stability analysis for the slip-PMG will be the torque ripple size and also the frequency of this torque ripple. It is also necessary to know what is the minimum slip value at which rated torque should occur. If this slip value is specified too low the stiffness of the system increases and there may be too little damping for stable operation. The same applies to the PMSG, but here the most important parameters which will be determined by the stability analysis is the range of the inductance values. This will especially determine the behaviour of the system during grid faults. For the whole system a thorough frequency analysis is needed to see if the torque ripple and other turbine disturbances are filtered. These disturbances might cause unwanted transient phenomenon at the point of grid-connection.

Fig. 6 shows a very basic block diagram overview of the SS-PMG system used to simulate the dynamic behaviour. The function generator (FG) block simulates the wind turbine of which the torque output is determined as a function of the wind speed and the turbine speed. The first part indicates the mechanical and electrical system of the slip-PMG unit which is modelled in the *dq*-reference frame and the second part includes the modelling of the PMSG system also in the *dq*-reference frame. The disturbance torques indicated by T_{dt} and T_{dr} indicates the disturbances caused by the turbine and torque ripple respectively.

3.3 Design Optimisation

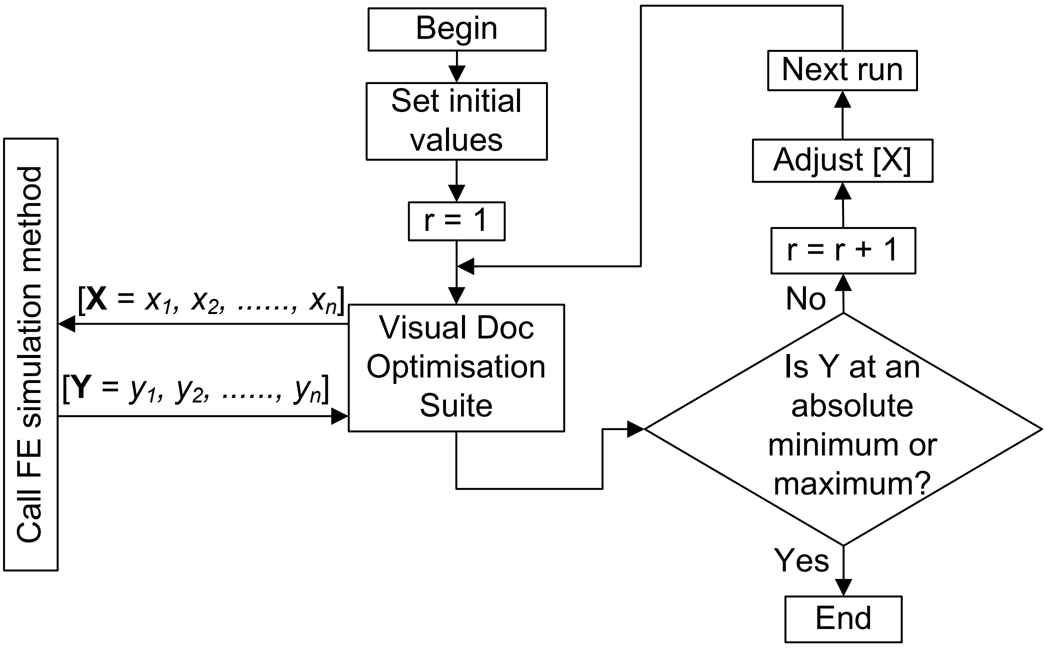

Figure 7: Basic overview of machine design optimisation.

Fig. 7 shows a very basic overview of the design optimisation in block diagram format. Due to the very long time it takes to optimise the generator units using transient FE analysis and due to the large amount of optimisations needed a quasi-static FE simulation procedure is employed. Due to both the PMSG and slip-PMG units being uncontrolled, whereas normally the operating point is known for PM wind generators connected to the grid via a converter a different approach is needed to calculate the performance point of these machines. Typically about three to four static FE simulations are needed.

The performance calculations are done in the *dq*-reference frame. From each static FE simulation the *abc* flux linkages are taken and transformed to the corresponding *dq*-parameters. A first iteration runs the machine at a given current (I_{rms}) and angle (α) to calculate the PM flux linkages, then a second iteration is run to calculate the inductances and then with a third iteration or for more accuracy with a fourth iteration the performance of the machine is calculated. With the *dq*-flux linkages known all the other necessary parameters can be calculated from the *dq*-equivalent circuits and vector diagrams shown in Fig. 8. The *dq*-inductances L_d and L_q can be calculated as

$$L_q = \frac{\lambda_q}{-I_q}; \quad L_d = \frac{\lambda_d - \lambda_m}{-I_d} \tag{5}$$

and the torque can be calculated as

$$T_g = \frac{3}{4}p[(L_q - L_d)I_d I_q + \lambda_m I_q]. \tag{6}$$

With the torque known all other relevant output parameters can be calculated. All the calculations are thoroughly explained in Potgieter & Kamper (2012*a*).

The electrical output power of the SS-PMG is 15 kW, with a torque input of 1000 Nm from the turbine at the slip-PMG side. The overall efficiency should be between 91 % and 92 %. The efficiency of the slip-PMG unit should thus be 97 % which corresponds to a slip value of 0.03. From available turbine data the synchronous speed is given as 150 r/min, which corresponds to a pole count of 40 for the PMSG unit for a 50 Hz system.

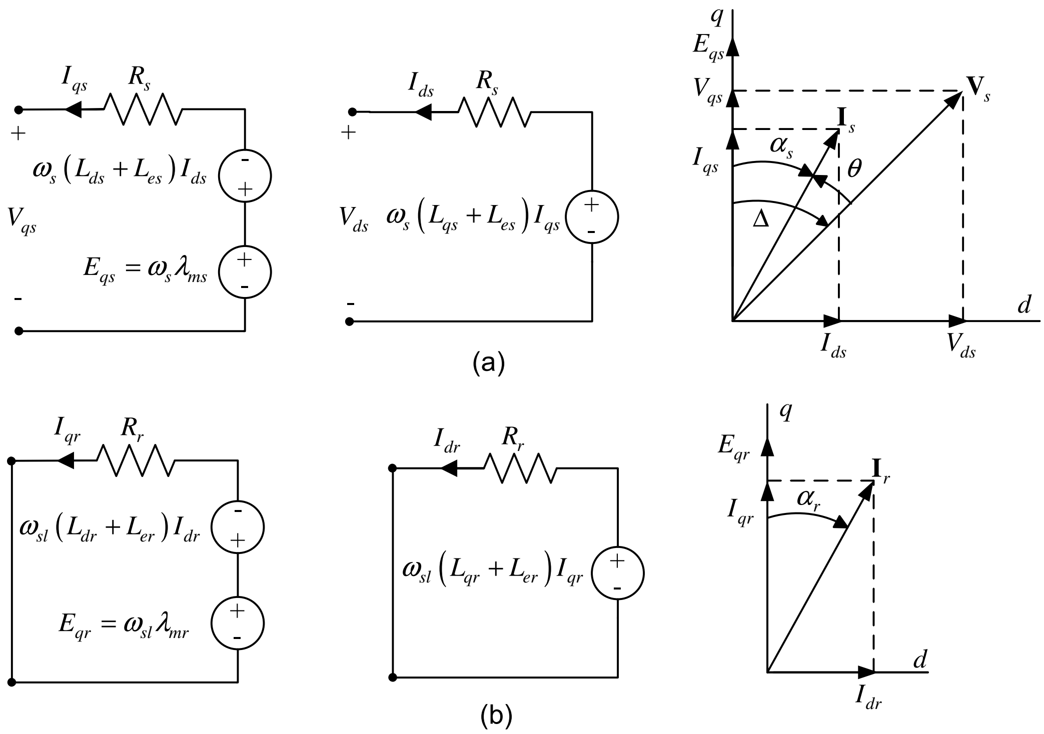

Figure 8: (a) *dq*-Equivalent circuits and vector diagram for the PMSG unit and (b) for the slip-PMG unit.

3.4 PMSG Design

For the design of the PMSG it is important that the exact design requirements are first known. This is why its important to obtain the correct results from the dynamic studies as this will specify the range of certain parameters of the PMSG.

Different topologies needs to be evaluated in order to know which one will be the best suited for this specific application. Thus far three topologies have been identified, a single layer non overlap, a double layer non overlap and a conventional three-phase overlap winding PM generator. These three machines will be optimised for a minimum active mass and PM content. All of them will need to comply to a certain set of design requirements regarding efficiency, power output and torque characteristics.

Regarding manufacturing, the non-overlap windings, especially the SL, are by far the easiest to manufacture as opposed to the conventional overlap windings. However, this needs to be weighed up against the performance of each generator. The SL winding also has the problem of a known large MMF sub-harmonic which could induce significant extra losses. The voltage quality of the SL winding is also a problem which needs to be addressed as this generator is connected directly to the grid. Overlap windings are also prone to have a high torque ripple, which could be a problem. It is important to have the torque ripple as low as possible to curb noise emissions, reduce material fatigue and especially for wind generators it is essential that the no-load cogging torque is as low as possible in order to achieve the required cut in wind speed.

3.4.1 slip-PMG Design

As mentioned a lot of freedom exists in the design of this generating unit. This means that several different generator topologies can be evaluated for possible use. Due to the easier manufacturing methods, the use of Aluminium as an inductor can also be considered. In previous SS-PMG studies only non-overlap slip-PMGs were used. However, the mass of the non-overlap winding machines and also the PM content seems to be too high. The mass and PM content performance can be slightly improved by using a new special type of double-layer winding as proposed in this study for the first time where each winding is individually short-circuited instead of connecting them in series as conventionally done for double layer winding machines.

However, regarding mass and PM content for the same performance conventional overlap windings are shown to perform much better. A new type of winding configuration known as a brushless-DC winding is also proposed for the first time in this study. This type of winding has a far better performance than any of the other types. However, this slip-PMG is extremely difficult to manufacture, whereas the non-overlap windings are relatively easy to manufacture. The brushless-DC winding is also proposed for use as an axial flux slip-PMG, to make manufacturing easier. However, the large attraction forces associated with axial flux machines might be a problem. One of the main drawbacks of the overlap winding slip-PMG is the high torque ripple. The brushless-DC machines on the other hand are found to have a very low torque ripple as shown in Section 4.2.

Furthermore conventional torque ripple mitigation techniques such as skewing is also introduced, to further evaluate the use of overlap windings. This machine can then be manufactured using similar methods as currently employed in the manufacturing of conventional induction machine cage-rotors.

4 Results

This section includes some of the SS-PMG results available. More interesting results resulting from this study on the SS-PMG can also be found in Potgieter & Kamper (2012*a*) and Potgieter & Kamper (2012*c*).

Table 1: Optimisation results of the SL and DL non overlap slip-PMGs.

	Non overlap-SL		**Non overlap-DL**	
	Al	Cu	Al	Cu
T_b, pu	2.00	2.02	2.01	2.11
$\Delta\tau_{NL}$, %	2.54	1.43	1.65	1.94
$\Delta\tau_{L}$, %	3.12	3.91	1.18	1.82
l, mm	131.8	124.7	107.1	90.50
D_i, mm	579.0	593.0	562.0	578.0
M_{PM}, kg	5.57	5.08	5.62	4.48
M_{cond}, kg	12.2	21.5	12.5	23.2
M_{Fe}, kg	43.0	34.5	38.3	33.1
M_{Tot}, kg	60.7	61.1	56.3	60.8
Notes:	Extremely simple construction. Easy use of Aluminium. No contact resistance. High mass and PM content. Long stack length might be a problem.		Easy construction. Easy use of Aluminium. No contact resistance. High mass and PM content, but lower than SL.	

4.1 Optimisation Results

Thus far only optimisation results for the slip-PMG are available. These results are shown in Table 1 for the non-overlap winding slip-PMGs and for the brushless-DC and overlap winding slip-PMGs in Table 2. As mentioned all of these machines need to comply to the specifications given. Clearly the much better performance of the brushless-DC slip-PMGs can be seen with regard to active mass and PM mass. The conventional overlap winding also yields much better results if compared to the non overlap slip-PMGs. Very interesting is also the similar results obtained for both Copper used as conductor material and Aluminium. By using Aluminium instead of Copper the cost of the generator can be significantly reduced.

Table 2: **Optimisation results of the 3-phase overlap and brushless-DC slip-PMGs.**

	Overlap		Brushless-DC radial flux		Brushless-DC axial flux	
	Al	Cu	Al	Cu	Al	Cu
T_b, pu	2.02	2.02	2.03	2.40	2.10	2.39
$\Delta\tau_{NL}$, %	5.56	3.76	1.64	1.97	1.33	0.93
$\Delta\tau_{L}$, %	10.78	9.94	0.44	0.71	2.28	2.61
l, mm	82.0	66.5	62.5	55.0	55.5	44.6
D_i, mm	565.0	577.0	570.0	580.6	490.0	533.2
M_{PM}, kg	3.53	3.43	3.53	3.51	3.62	3.49
M_{cond}, kg	8.99	17.05	7.22	12.38	10.16	16.34
M_{Fe}, kg	28.18	20.14	22.25	15.98	14.97	6.97
M_{Tot}, kg	40.70	40.62	33.0	31.87	28.76	26.80
Notes:	Moderate to difficult construction. Possible Alumi nium casting. Contact resistance a problem. Medium to low mass and low PM content. High torque ripple.		Very difficult construction. Aluminium use might be difficult. Contact resistance a problem. Low mass and PM content. Low torque ripple.		Moderate to easy construction. Easy use of Aluminium. No contact resistance. Very low mass and PM content. Large attraction forces.	

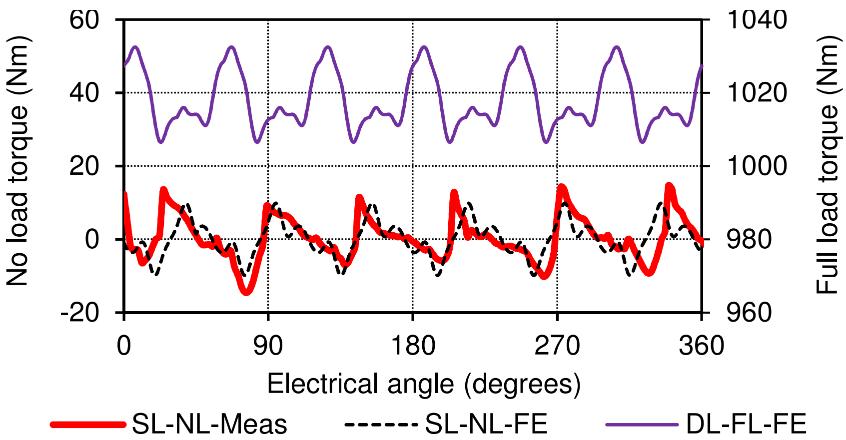

Figure 9: No-load torque ripple for the SL slip-PMG and full-load torque ripple of the DL non overlap slip-PMG versus electrical angle.

4.2 Machine performance results

Fig. 9 shows the measured and FE simulated torque ripple of the manufactured and lab tested non-overlap winding slip-PMGs. The torque ripple results of the built and tested brushless-DC slip-PMG is shown in Fig. 10.

The FE simulated and practically measured torque versus slip curves of all the slip-PMGs that has been manufactured are shown in Fig. 11. It should be noted that all the slip-PMGs practically evaluated has more or less the same active mass and PM content. Clearly the much better torque performance of the brushless-DC slip-PMG can be seen with regard to the non-overlap slip-PMGs.

In Fig. 12 flat topped DC waveform of the brushless-DC slip-PMG is clearly seen as opposed to the non-overlap winding slip-PMGs. The measured grid-current and voltage measured at the stator terminals of the directly grid connected SS-PMG is shown in Fig. 13.

5 Conclusions and Recommendations

The advantages of using a SS-PMG as a wind generator is clearly motivated in this study. This is mainly due to the more robust, simplified less error prone SS-PMG wind turbine sys-

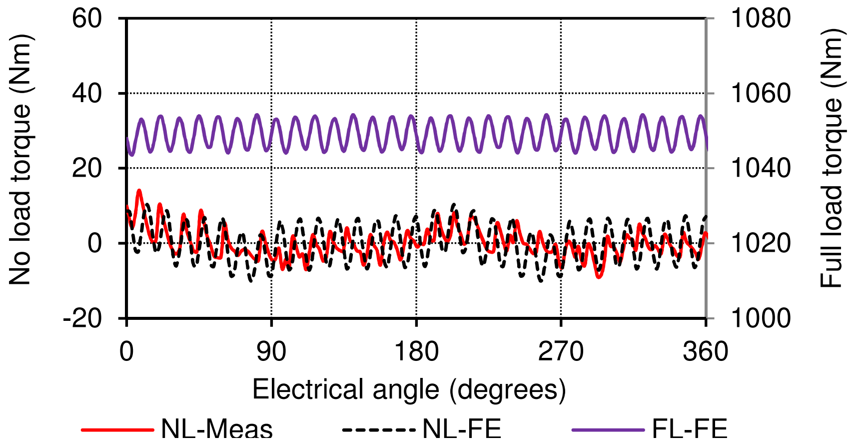

Figure 10: No-load and full-load torque ripple for the brushless-DC slip-PMG versus electrical angle.

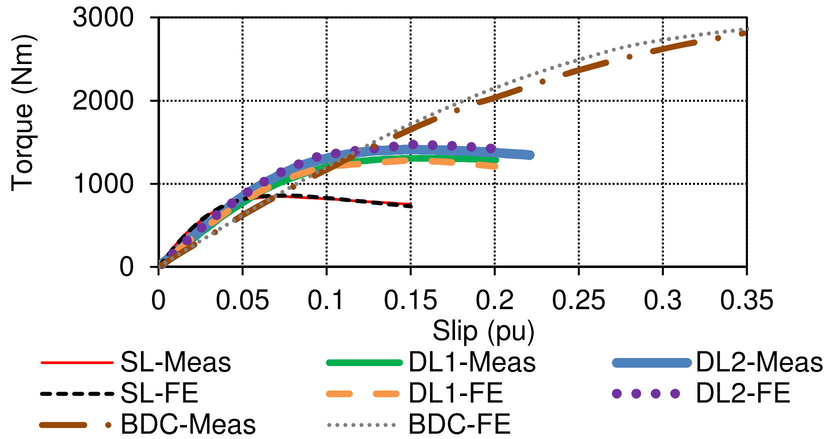

Figure 11: Torque versus slip for the brushless-DC, SL-non overlap, conventional DL-non-overlap and the new concept individually short circuited DL winding slip-PMGs.

tem as opposed to other technologies currently in use. Building on the PMIG tehcnology this generator concept overcomes many of the difficulties previously associated with the manufacturing of such a type of system.

This is also the first known instance of a direct-drive directly grid-connected system which has been successfully manufactured and practically tested in the laboratory and in the field. Preliminary tests on existing prototypes have shown that this generator can be safely connected directly to the grid. To reduce the mass and PM footprint of adding a second generator to the design several new slip-PMG concepts are introduced. This includes the new type of DL winding and also the novel brushless-DC and axial flux brushless-DC slip-PMGs. The brushless-DC slip-PMG yields exceptionally good results regarding mass and PM content if compared to the non-overlap windings. As opposed to the conventional overlap windings, the torque ripple of this type of winding is also found to be extremely low.

Also in this study new developed calculation techniques allows for a much more accurate prediction of the torque profiles and performance of both the slip-PMG and PMSG units. The new analytical technique to calculate the end-winding inductance can also be used accurately for a wide range of concentrated winding machines.

With the concept shown to work properly the main aim is to obtain an efficient fully functioning SS-PMG system comparable to other wind turbine technologies currently in use. Research work is also currently under-way to determine the feasibility of this concept for use in larger utility scale wind turbine systems. More work also needs to be done to determine the best applications for the SS-PMG. Currently this generator seems especially favourable for rural electrification in mini-grids and other locations where it is essential that maintenance is kept at a minimum. Further studies are also needed to determine whether this generator can

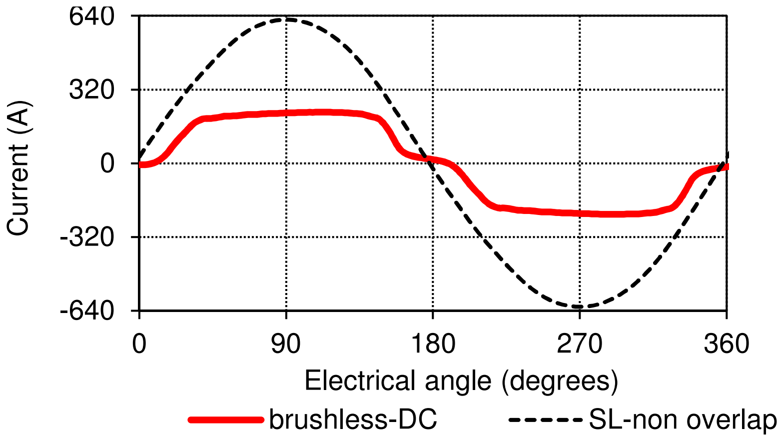

Figure 12: Current versus slip for the non overlap SL and brushless-DC slip-PMGs.

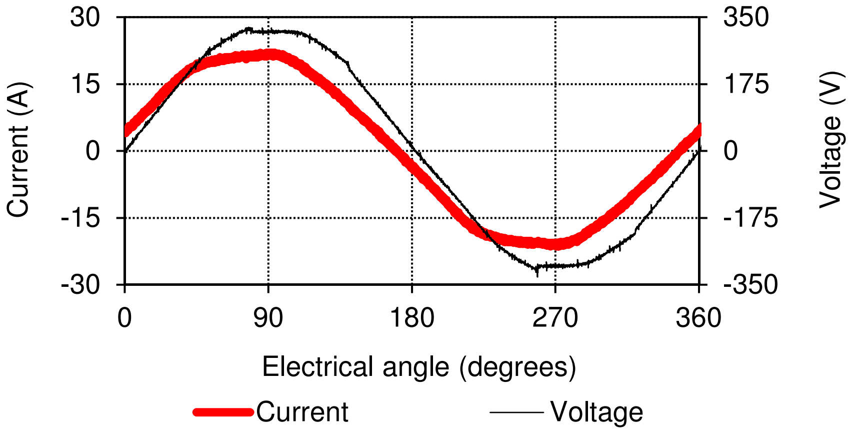

Figure 13: Current versus slip for the non overlap SL and brushless-DC slip-PMGs.

be used as a grid compensator, where it is placed at the ends of long distribution lines to compensate for grid voltage variations.

References

Douglas, J. F. H. (1959), 'Characteristics of induction motors with permanent-magnet excitation', *AIEE Trans. Part III: Power Apparatus and Systems* **78**(3), 221–225.

Fukami, T., Nakagawa, K., Kanamaru, Y. & Miyamoto, T. (2004), 'A technique for the steady-state analysis of a grid-connected permanent-magnet induction generator', *IEEE Trans. on Energy Conversion* **19**(2), 318–324.

Fukami, T., Yokoi, M., Kanamaru, Y. & Miyamoto, T. (2003), 'Performance evaluation of a permanent magnet induction generator', *Electrical Engineering in Japan* **123**(9), 1065–1070.

Gail, G., Hartkopf, T., Tröster, E., Höffling, M., Henschel, M. & Schneider, H. (2004), Static and dynamic measurements of a permanent magnet induction generator: test results of a new wind generator concept, *in* 'Proc. of Int. Conf. on Electrical Machines (ICEM'04)'.

Grabic, S., Celanovic, N. & Katic, V. (2008), 'Permanent Magnet Synchronous Generator Cascade for Wind Turbine Application', *IEEE Trans. on Power Electronics* **23**(3), 1136–1142.

Grover, F. W. (1946), *Inductance calculations: Working formulas and tables*, 1 edn, Dover Publications, New York USA.

Hagenkort, B., Hartkopf, T., Binder, A. & Jöckel, S. (2000), Modelling a direct drive permanent magnet induction machine, *in* 'Proc. of Int. Conf. on Electrical Machines (ICEM'00)'.

Kamper, M. J. & van der Merwe, F. S. (1988), Influence of laminations on axially directed flux in induction motors, *in* 'Proc. International Conference on Electrical Machines (ICEM'88)', Pisa, Italy.

Low, W. F. & Schofield, N. (1992), Design of a Permanent Magnet Excited Induction Generator, *in* 'Proc. of Int. Conf. on Electrical Machines (ICEM'92)', Manchester, United Kingdom.

Muller, H., Poller, M., Basteck, A., Tilshcher, M. & Pfister, J. (2006), Grid compatibility of variable speed wind turbines with directly coupled synchronous generator and hydrodynamically controlled gearbox, *in* 'Sixth International Workshop on Largescale integration of wind power and transmission networks for offshore wind farms', Delft, Netherlands.

Potgieter, J. H. J. & Kamper, M. J. (2012*a*), 'Design of new concept gearless direct-grid connected slip-synchronous permanent magnet wind generator', *IEEE Trans. on Industrial Applications* **48**(3), 913–922.

Potgieter, J. H. J. & Kamper, M. J. (2012*b*), Evaluation of calculation methods and the effects of end-winding inductances on the performance of non-overlap winding PM machines, *in* 'Proc. Int. Conf. on Electrical Machines', Marseille, France.

Potgieter, J. H. J. & Kamper, M. J. (2012*c*), Optimum design and technology evaluation of slip permanent magnet generators for wind energy applications, *in* 'IEEE Energy Conversion Congress and Exposition (ECCE)', Raleigh, NC, USA.

Potgieter, J. H. J., Lombard, A., Wang, R.-J. & Kamper, M. J. (2009), Evaluation of a permanent magnet excited induction generator for renewable energy applications, *in* 'Southern African Universities Power Engineering Conference (SAUPEC)'.

Punga, F. & Schon, L. (1926), 'Der neue kollektorlose Einphasenmotor der Firma Krupp', *Elektrotechnische Zeitschrift* **47**(29), 877–881.

Sedivy, J. K. (1967), 'Induction motor with free-rotating DC excitation', *IEEE Trans. Power Apparatus and Systems* **86**(4), 463–469.

Shibata, Y., Tsuchida, N. & Imai, K. (1996), 'High torque induction motor with rotating magnets in the rotor', *Electrical Engineering in Japan* **117**(3), 102–109.

Shibata, Y., Tsuchida, N. & Imai, K. (1999), 'Performance of induction motor with free-rotating magnets inside its rotor', *IEEE Trans on Industrial Electronics* **46**(3), 646–652.

Thomas, A. J. (2004), A doubly-fed permanent magnet generator for wind turbines, Master's thesis, Massachusetts Institute of Technology.

Tröster, E., Sperling, M. & Hartkopf, T. (2006), Finite element analysis of a permanent magnet induction machine, *in* 'International Symposium on Power Electronics, Electrical Drives, Automation and Motion, (SPEEDAM 2006)'.

Tsuda, T., Fukami, T., Kanamaru, Y. & Miyamoto, T. (2007), 'Effects of the built-in permanent magnet rotor on the equivalent circuit parameters of a permanent magnet induction generator', *IEEE Trans. on Energy Conversion* **22**(3), 798–799.

Vermaak, R., Potgieter, J. & Kamper, M. J. (2009), Grid-connected VSC-HVDC wind farm system and control using permanent magnet induction generators, *in* 'IEEE International Conference on Power Electronics and Drive Sytems (PEDS)'.

Westlake, A., Bumby, J. & Spooner, E. (1996), 'Damping the power-angle oscillations of a permanent-magnet synchronous generator with particular reference to wind turbine applications', *IEE Proc. Electric Power Applications* **143**(3), 269.