

EVALUATION OF PERMANENT MAGNET EXCITED INDUCTION GENERATOR FOR RENEWABLE ENERGY APPLICATIONS.

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Abstract. More efficient and reliable energy conversion methods are constantly being sought for renewable energy applications. The permanent magnet induction generator is a new concept which uses permanent magnets to provide the flux in the machine. This will lead to an improved power factor and a higher efficiency. With this concept the implementation of direct drive and directly grid connected induction generators is now possible. For these machines no gearbox or power electronics are deemed necessary. Maintenance can now be reduced to a minimum, making this a very attractive renewable solution. In this paper the main aim is to further characterise and evaluate the performance and behaviour of this machine type. This is done by designing, constructing and testing a prototype. With this evaluation an indication is given on the viability of the concept. To further validate the results, the machine is compared with an identical, conventional, unmodified, induction generator.

Key Words. Permanent magnet, induction generator, finite element analysis, evaluation, renewable energy.

1. INTRODUCTION

With energy shortages looming globally and the dwindling of fossil fuel resources, as well as the increasing cost of these sources, there is an increasingly growing interest in alternative and renewable energy resources. New technologies are constantly being sought to harness these resources more efficiently, reliably and cost effectively. A generating solution receiving a great deal of attention is direct drive permanent magnet (PM) generators. Unlike induction generators (IGs), the PM generators can be built with large diameters and high pole numbers. Other advantages are their relatively good efficiencies and power factors with respect to IGs.

In developed countries there are more than 3 kW worth of electric motors per person. Most of these are induction machines. The fathers of the induction machine are believed to be Galileo Ferraris (1885) and Nicola Tesla (1886). They built on the work of Michael Faraday, who discovered the electromagnetic induction law, as well as Maxwell's equations. Currently the induction motor is the workhorse of industry due to its robustness, rugged cheap design and standardised sizes [1], [4]. If the advantages of the PM machines can be integrated within the IG, the IG can be transformed into a powerful generating solution.

By adding permanent magnets to the IG design, the magnetizing current can be significantly reduced, leading to a reduction in the machine's reactive power need. This will be especially beneficial for power factor improvement and the obtaining of higher efficiency values. Another important aspect is the high pole, large diameter, direct drive induction generators which can now be used, omitting the need for a gearbox and all its maintenance issues. With the use of an asynchronous induction machine with slip, a soft grid connection is possible [2]. This means that no power electronics are necessary for grid interfacing. A dramatic decrease in cost can now be realised as power electronics can contribute to about 20 % of

the total cost of a wind power setup [3]. Sudden load changes associated with wind power generation, can now be handled far better, because of the slip provided by induction machines. This will improve the stability of the system, as the machine does not need to be synchronised with each load change [2], [3].

Without any grid interfacing, this will result in a fixed speed system. Renewable sources, for example micro hydro systems, the use of ocean currents, as well as fixed wind speed sites, for instance offshore installations, will benefit the most from this concept. These are all fairly constant speed energy sources. Some comparison needs to be made to validate this proposal against other electrical power conversion methods. Factors like, initial installation cost, stability, power loss due to fixed speed, efficiency and the reduced maintenance, need to be taken into account. Another suitable application for the PMIG is high voltage DC transmission. A single solid state converter is used for all the generators in a cluster, posing less of a drawback for fixed speed devices [3], [5], [13]. The PMIG concept can be implemented in a doubly-fed induction generator (DFIG) as well, where the rotor frequency is changed according to the wind speed. The DFIG drive system can operate at a much wider speed range, using only a small solid-state converter, but a more expensive wound rotor [3], [9].

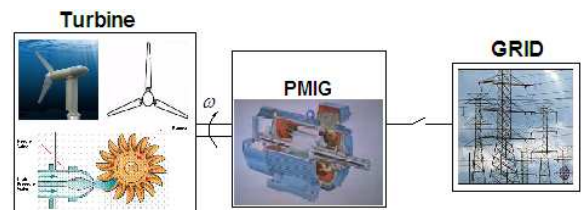


Figure 1: The PMIG system interface.

2. THE PMIG CONCEPT

2.1. Overview

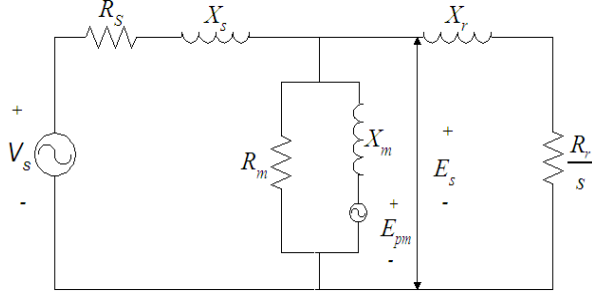


Figure 2: Equivalent circuit of the PMIG.

The basic working principles of the PMIG are mostly the same as for the ordinary induction machine. With the conventional induction machine flux is induced, by drawing magnetizing current from the grid. A second rotor, mounted with permanent magnets provides the flux in the IG's new PM counterpart. This PM rotor is mounted on a freely rotating shaft to provide alternating flux. The poles of the PM rotor will now coincide with the magnetic poles induced in the stator field. Interfacing between the PM rotor and the stator acts in the same way as in a PM synchronous machine. The main rotor operates in asynchronous mode as it still follows the rotating stator field with slip.

As indicated in Fig. 2 the equivalent circuit for the PMIG is very similar to the normal induction machine's equivalent circuit. The flux provided by the permanent magnets can be modelled as an internal voltage source, E_{pm} , in series with the magnetizing reactance. The iron-loss resistance, R_m , can be ignored by approximation; this resistance has a much higher value relative to the magnetizing reactance, X_m . By placing magnets in the flux circuit the equivalent air gap is increased considerably. From equation (1) it can be observed that the magnetizing reactance will be reduced quite significantly, as X_m is inversely proportional to the equivalent air gap length, δ'' , and the square of the number of poles, p . The magnetizing current, I_m , can be decreased substantially according to (2) by having the netto magnetising phase voltage E_s close to E_{pm} . In (1), f_l is the grid frequency, W_l is the number of turns in series per phase, k_w is the fundamental winding factor, d_l is the machine diameter and l_c is the core length [5], [10].

$$X_m = \frac{6 f_l W_l^2 k_w^2 d_l l_c \mu_0}{p^2 \delta''} \quad (1)$$

$$I_m = \frac{E_s - E_{pm}}{X_m} \quad (2)$$

The rest of the circuit parameters will change according to the chosen machine lay-out as stipulated in Fig. 3. From the equivalent circuit and equation (2), theoretically the magnetizing current can be reduced to zero if E_{pm} is equal to E_s . If the magnetizing current is reduced by this much, the power factor and efficiency of the machine will increase accordingly. If

a voltage higher than the grid voltage is induced by the permanent magnets, capacitive excitation can even be realised.

2.2. Different PMIG topologies

Several mechanical configurations can be used in the PMIG. The magnet rotor can be placed either inside the squirrel cage rotor, between the main rotor and stator, or outside the stator. These lay-outs are shown in Fig. 3, with configurations 1, 2 and 3 as mentioned respectively. Each of these configurations will influence the machine characteristics in a different way. By placing the magnet rotor inside the original rotor, only the rotor's parameters will be changed, leaving the parameters of the stator unchanged. A reduction in the rotor yoke will decrease the value of the rotor leakage reactance. This in turn will influence the torque-speed profile of the machine [4]. By placing the magnet rotor between the stator and rotor, both the stator and rotor characteristics will be changed. Either a larger stator or a smaller rotor is now needed. To match the performance of the ordinary induction machine, this will result in a larger diameter machine to realise the same power output. By placing the magnet rotor on the outside, the stator yoke is basically removed, reducing the stator leakage reactance. Better matching of the grid voltage and E_{pm} might now be obtained, because the voltage drop across the series stator leakage reactance can now be countered to some extent.

With the configurations shown there are still other possibilities regarding the position of the rotor and stator. For example the stator can be placed on the inside and the primary rotor on the outside. Several variations are thus possible for the stator, primary rotor and the PM rotor, with respect to their positions in the assembly. Construction wise an easier solution could be an axial flux induction machine. More freedom regarding the placement of the PM rotor might be obtained in this case.

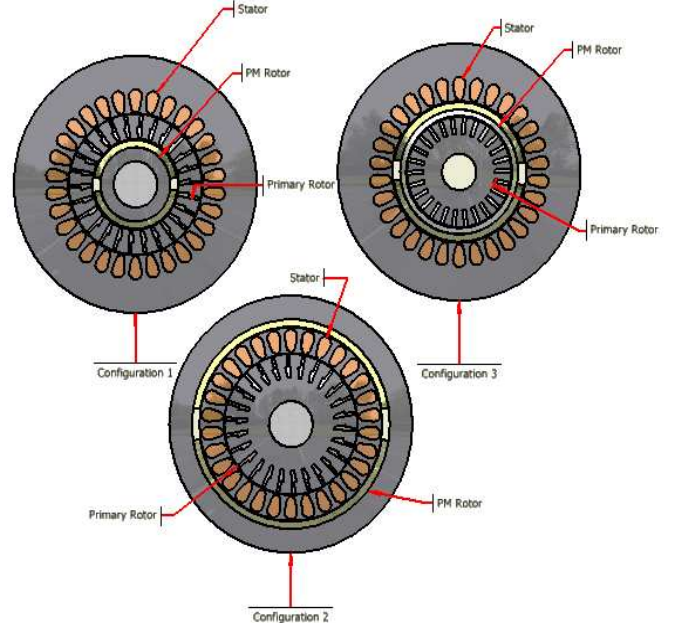


Figure 3: Different configurations which can be used for the PMIG.

3. PROTOTYPE PMIG

3.1. Description

To gain a more thorough understanding of the PM induction machine's behaviour, an experimental prototype was constructed. For this experiment an ordinary 2-pole, 9 kW induction machine was used. This induction machine was modified to accommodate the permanent magnets.

From the different mechanical configurations it was deemed the easiest to modify the existing squirrel cage rotor, leaving the rest of the machine unchanged. This decision was influenced by time, cost and ease of construction. The magnet rotor was thus mounted against the shaft inside the squirrel cage rotor. A separate bearing configuration was used in order to have the new rotor, rotating mechanically freely.

Better results could have been obtained if different configurations or other machines were used. For instance, higher pole number machines could have been used. Higher pole number machines would have given a better indication of the viability of the high pole PMIG. The machine configuration used is also not the most favourable choice. Placement of the PM rotor on the shaft, inside the squirrel cage, results in a limited magnet area. By using different configurations and making the flux area larger, better results could have been obtained. For instance the magnet rotor could be placed between the stator and the main rotor. However this will de-rate the machine regarding power output. The other option was to place the magnet rotor on the outside. From a mechanical viewpoint this would be more expensive, as the outside stator yoke needs to be machined. However the main aim of this study was to gain practical knowledge on the machine behaviour, with the use of a low cost experiment. This knowledge will be used in future applications of the PMIG.

3.2. Design Approach

A magnetic design was needed to obtain the rated performance of the machine. A theoretical approach can be used to estimate the flux per pole. From this the magnet thickness can be computed. The new machine, however, will be different from the original machine, because of the modified rotor. In this case the normal theoretical approach might not be accurate enough. A more valid estimate can be made from finite element analysis. As a first approach the original machine is simulated without any modifications. At no-load the magnetizing current is the only current drawn by the machine; the machine is thus simulated at no-load using no-load current. The PM machine with its PM rotor is also simulated by means of finite element analysis. Under no-load conditions, the new PM machine needs to give the same simulation results as the original machine.

3.3. Finite Element Analysis

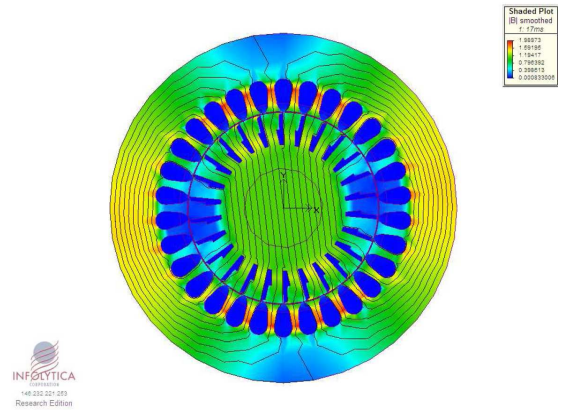


Figure 4: Finite element analysis of the unmodified machine.

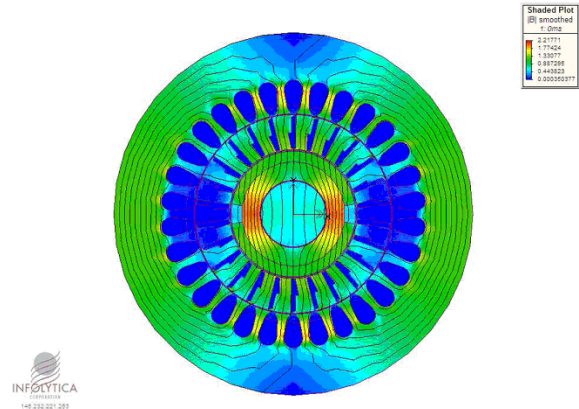


Figure 5: Finite element analysis of the PM induction machine with PM rotor.

When simulating the original machine, the coils are excited by using the specified no-load currents. The flux linkage (λ), per phase voltage and the flux density in the air gap (B) are then determined. Next the PM machine is simulated for various magnet configurations. Several different magnets with varying height (h) and grade are used. The magnet pitch and the second air gap length (A_{g2}) are also variable parameters in the design. Fig's. 4 and 5 indicates the finite element results.

After several iterations a suitable magnet configuration was decided upon. At the end a trade-off was made between both mechanical and performance considerations. The best suited outcome was a magnet thickness of 6 mm and a 0.9 magnet pitch. The second air gap length was constrained at a minimum value of 1 mm. Due to an error on the PM manufacturer's side, the magnets were received with incorrect dimensions. To accommodate the incorrect sized magnets a 0.73 magnet pitch had to be used. However this still gave fairly good results compared to the original configuration. The results were verified by two different finite element packages, Maxwell version 12 and Magnet version 6.

To match the original machine the magnets need to produce an RMS voltage of at least 400 V. As can be seen from the results in Fig. 10 only about 70% of this value is reached by using the current configuration. The simulated results are a little lower than the rated operating voltage. This might be because the correct BH-curves could not be obtained from the

machine manufacturer for the material used in the machine. Larger magnet heights and higher grade magnets do not improve the results significantly, as can be seen from Fig's. 6 - 8. This is due to the small diameter of the magnet rotor if it's placed on the shaft. A large amount of flux is now forced into a small area, consequently saturating the machine. Fig. 9 shows the entire harmonic spectrum of the flux density in the primary air gap.

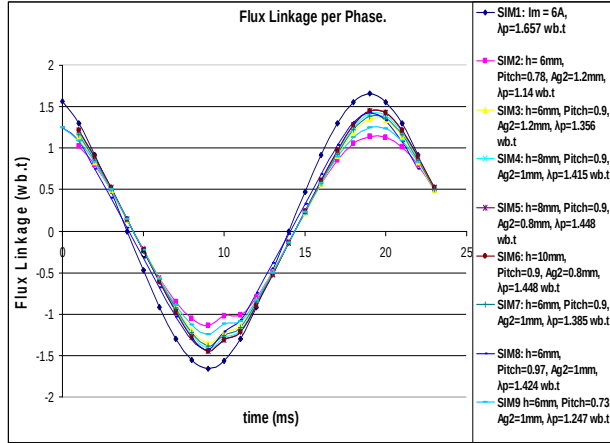


Figure 6: Flux linkages for different iterations followed.

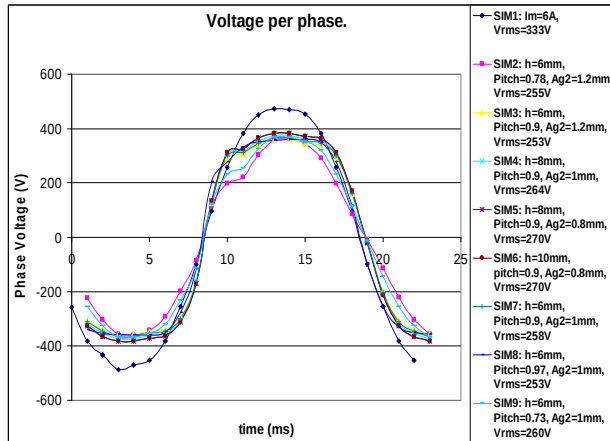


Figure 7: Voltages for different iterations followed.

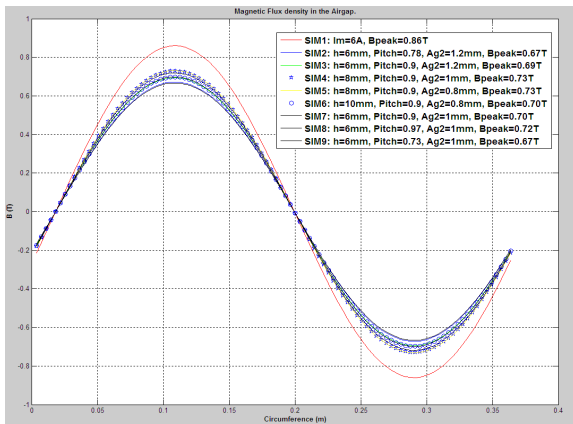


Figure 8: Fundamental flux density waveforms in the primary air gap for different iterations followed.

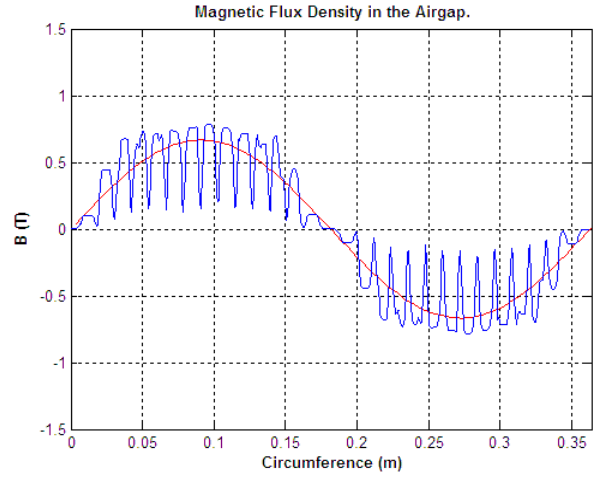


Figure 9: Flux density in the air gap of the PM induction machine, shown with its fundamental wave.

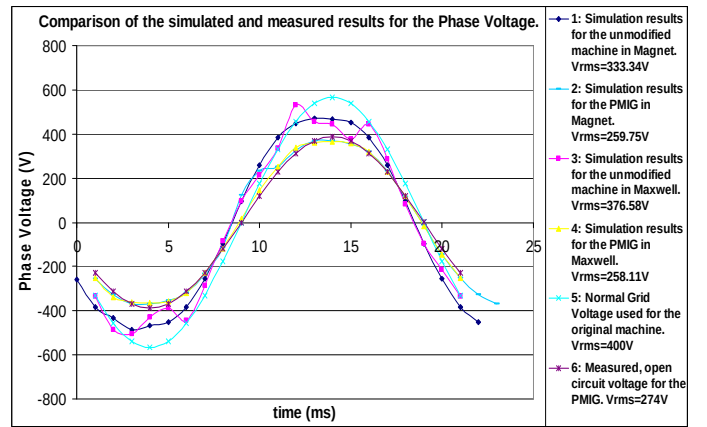


Figure 10: Comparison of the simulated and measured results of the phase voltage at no-load.

3.4. Testing of the PMIG

For the lab test setup a same-sized induction machine was used as a prime mover for the modified PM induction machine. The PMIG was connected to the grid and the driving motor was fed from a variable speed drive. For adequate comparison all tests were done on both the PMIG and the standard IG.

An open circuit test with the PMIG rotated at synchronous speed by the prime mover, revealed an open circuit voltage of 274V_{RMS}. This is in effect the internal voltage induced by the permanent magnets. By means of an auto transformer, tests were done at different grid voltages. The best results and most stable operation were obtained at grid voltages of 274 V and lower. For stable operation a small amount of magnetizing current is still needed in the machine. To pull the rotating PM rotor into synchronism with the stator rotating field, an attractive force between the stator field and the PM rotor is necessary. At lower grid voltages the PMIG has a capacitive power factor and is found to deliver reactive power into the grid.

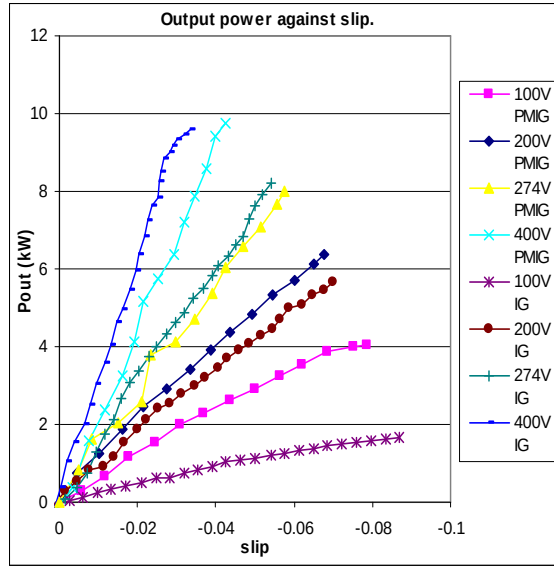


Figure 11: Output power against slip for the different grid voltages.

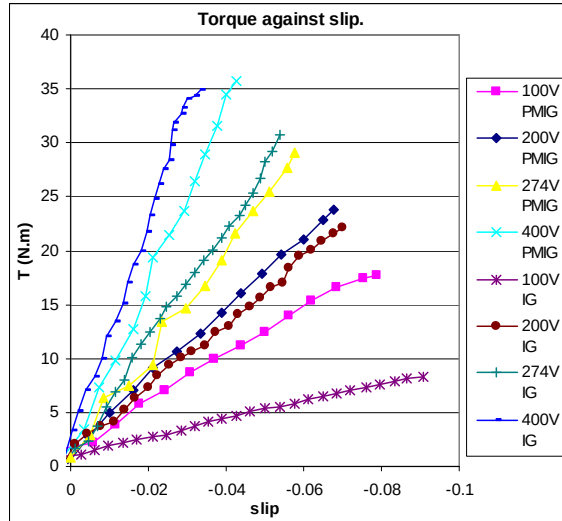


Figure 12: Torque against slip at different grid voltages.

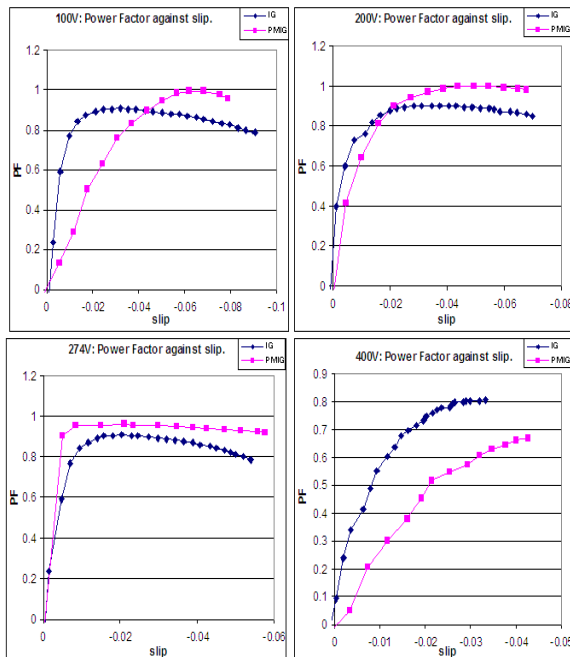


Figure 13: Power factor against slip with grid voltage a parameter.

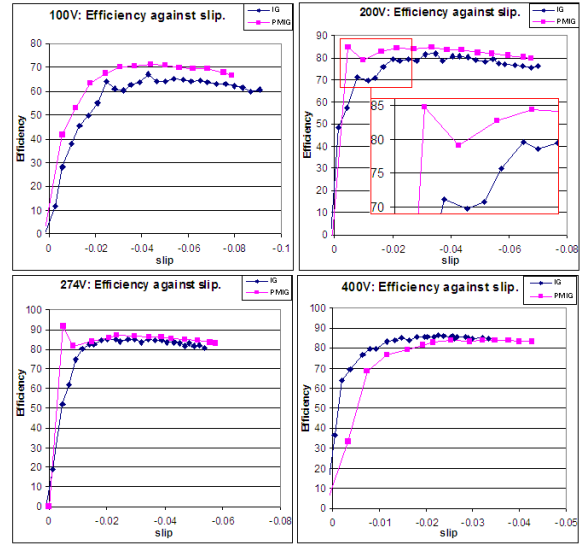


Figure 14: Efficiency against slip with grid voltage a parameter.

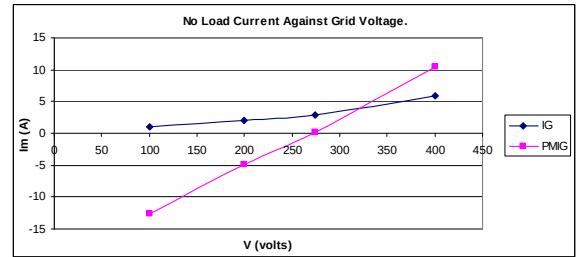


Figure 15: No-load current versus grid voltage.

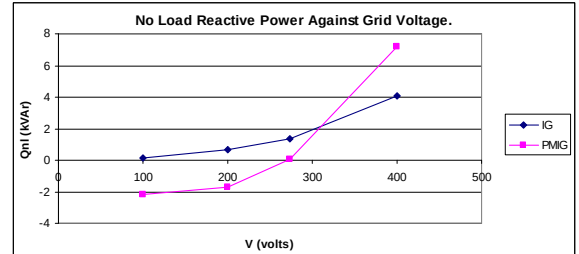


Figure 16: No-load reactive power demand versus grid voltage.

From the results in Figs. 11 – 14 it can be seen that the PMIG performs much better than the IG at voltages lower than 274 V. The power performance curves in Fig. 11 show a higher output power for the PMIG at lower voltages, which makes it a higher density machine [7]. Observing Fig. 14 the PMIG poses quite an attractive efficiency; in some cases an average efficiency of about 5% higher than the IG is obtained. The PMIG operates at unity power factor at some voltages and slip values as shown in Fig. 13.

For grid voltages higher than 274 V the advantages of the PMIG start to deteriorate; as can be seen from the no-load results in Figs. 15 and 16 there is a cross over point at about 274 V. At this point the magnetizing current is about zero. With a deviation in grid voltage from 274 V, the magnetizing current rises sharply as shown in Fig. 15.

From these results the conclusion can be drawn that it is absolutely critical for the internally induced PM voltage to be close or equal to the grid voltage. As mentioned earlier the increased magnetizing current can be explained by equations (1) and (2). From

equation (1) the magnetizing reactance is inversely proportional to the effective air gap length. For the standard IG the radial air gap is 0.55 mm. For the new PMIG, there is another air gap of 1 mm plus the magnet height of 6 mm. All these adds up to a resulting 7.55 mm and a roughly 14 times increase in the equivalent air gap, decreasing X_m by 14 times in turn. The magnetizing current will follow suit and will increase rapidly with larger differences between the PM internal voltage and the grid voltage shown in Fig. 15. The rotor leakage reactance is influenced as well, because almost all of the rotor yoke was removed. This will decrease the rotor leakage reactance, resulting in a different torque-slip performance.

During tests at speeds close to synchronous speed, dynamic oscillations were experienced with the PMIG. It is clear that the PM rotor struggles at these conditions to synchronize itself with the stator field, probably due to cogging torque between the two rotors. At higher slip values this was not a problem and stable operation was obtained. In further designs, special care should be taken to reduce all forms of cogging torque between the two rotors.

4. CONCLUSIONS

Although only an elementary evaluation of the PMIG is done in this paper, conclusions can be drawn on the advantages and questions of implementing PMIGs, as follows:

- The PMIG has a considerable advantage over the normal IG with regard to power output, power factor and efficiency. Measured results obtained from both the IG and the PMIG confirm the better performance of this generator type.
- For best PMIG performance it is extremely important that the internal voltage induced by the magnets be closely equal to the rated supply voltage.
- There are still some machine behaviours which need to be investigated. The dynamic behavior of the new machine needs to be characterized more thoroughly. In [2] the dynamic behaviour of the PMIG is evaluated in much more detail.
- To gain a more valid comparison, other mechanical configurations can be evaluated as well. Construction wise axial flux PM induction machines can be considered as an alternative.
- The main drawback regarding this machine type is the constructional complexity.

Relatively little literature exists on the PMIG and only a few small prototypes have been built. However from this literature the concepts and theories are fairly complete. From the evaluated prototype analysis and the studied papers, the proposed high pole, large diameter induction machine should definitely be an option for future investigation. For several renewable sources this could prove to be especially beneficial. To extract energy from these sites economically, low maintenance solutions are an absolute necessity. As there is no gearbox or power electron-

ics the initial cost and maintenance of such an installation will largely be reduced. From this proposed project a true reflection of the viability of this concept will be obtained.

5. REFERENCES

- [1] Ion Boldea, Syed A. Nasar, *The induction machine Handbook*, CRC Press, 2002.
- [2] Gabriele Gail, Thomas Hartkopf, Eckehard Tröster, Michael Höffling, Michael Henschel, Henning Schneider, "Static and Dynamic Measurements of a permanent magnet Induction Generator: Test Results of a New Wind Generator Concept", *Springer Netherlands*, June 2007.
- [3] B. Hagenkort, T. Hartkopf, A. Binder, S. Jöckel, "Modelling a Direct Drive Permanent Magnet Induction Machine", *ICEM*, 2000.
- [4] M. Godoy Simões, Felix A. Farret, *Renewable Energy Systems: Design and Analysis with Induction Generators*, CRC Press, 2004
- [5] M.J. Kamper, "Permanent magnet induction generator", EMLab Report, Stellenbosch University, Sept 2008.
- [6] W.F. Low, N. Schofield, "Design of a Permanent Magnet Excited Induction Generator", *Proc. ICEM 92*, Manchester University, Vol3 pp 1077-1081, 1992
- [7] Tadashi Fukami, Kenichi Nakagawa, Yasunori Kanamaru, Toshio Miyamoto, "A Technique for the Steady-State Analysis of a Grid-Connected Permanent-Magnet Induction Generator", *IEEE Transactions on Energy Conversion*, Vol. 19, No. 2, June 2004
- [8] Toshihiro Tsuda, Tadashi Fukami, Yasunori Kanamaru, Toshio Miyamoto, "Effects of the Built-in Permanent Magnet Rotor on the Equivalent Circuit Parameters of a Permanent Magnet Induction Generator", *IEEE Transactions on Energy Conversion*, Vol. 22, No. 3, September 2007
- [9] Andrew Joseph Thomas, "A Doubly-Fed Permanent Magnet Generator for Wind Turbines", *Master dissertation*, Massachusetts Institute of Technology, June 2004
- [10] M.J. Kamper, "The design criteria and development of a design program for squirrel-cage induction motors with use in the load region.", *Master dissertation*, University of Stellenbosch, 1987.
- [11] T. Wildi, *Electrical Machines, Drives and Power Systems*, Fifth Edition, Prentice-Hall International, 2002.
- [12] W.F. Low, N. Schofield, "Design of a Permanent Magnet Excited Induction Generator", *Proc. ICEM 92 Manchester University*, Vol3 pp 1077-1081, 1992.
- [13] Cristoph Meyer, Markus Höing, Anders Peterson, Rik W. Doncker, "Control and Design of DC Grids for Offshore Wind Farms" *IEEE transactions on industry applications*, Vol. 43, No. 6, November/December 2007.