# Design of permanent-magnet generators for wind turbines

J. Rizk M. Nagrial

School of Mechatronic, Computer and Electrical Engineering
University of Western Sydney, Nepean
P.O. Box 10, Kingswood, NSW 2747
AUSTRALIA
Email: j.rizk@uws.edu.au

## Abstract

*There has been much interest and studies in high efficiency wind generators with permanent magnet excitation due to the increasing availability of permanent magnet materials, especially Nd-Fe-. The present paper is aimed to outline the design, analysis of such a PM generator. The generator that is being used will be an 8-pole permanent magnet generator rated at 5 kW and using NdFeB for the field excitation. The details of the permanent magnet generator are also presented.*

## 1. Introduction

A totally renewable energy based electricity generation system for Australia – even in broad concept – is a complex task presenting major challenges. Until now, Australia has relied exclusively upon sources of "stored" energy whether they are coal, natural gas or hydro. As a result, it has been possible to maintain a reliable electricity supply without incorporating a large quantity of costly energy storage. However Australia's reserves of "stored renewable energy sources are limited. Under these circumstances it will probably be necessary to rely largely upon intermittent sources (e.g. solar and wind) to produce most of Australia's electricity needs and to store surplus energy for use at times when such sources are unavailable [1].

In Australia, a program of the department of Primary Industries and Energy (DPIE) supports the renewable energy. Under this program, the Federal Government has provided funds to promote the use of renewable energy, especially for stand alone power systems in remote and rural areas in Australia. About 20 000 rural households rely on diesel or petrol generators to supply their power needs. Anyone who has experienced these systems, which are usually, needed most of the day, will be aware that they are intermittent, noisy, and demand considerable attention [2-4]. In contrast, the renewable energy systems can provide power 24 hours a day cleanly and silently. However renewable systems for remote areas do have the relatively high up front cost ($15 000 to $50 000 depending on size)[5].

In the area of wind energy, the energy authorities in Australia have been undertaking an active wind energy program for several years [6-10]. The program has included wind monitoring, analysis of existing wind data, installation and testing of small wind generators in remote homestead power systems, and installation of up to 100 kW wind generators. The Ten-Mile Lagoon wind farm at Esperance on Western Australia's south coast is the largest wind farm. This wind farm has nine Vesta V27 wind turbines with a total output of 2.025 MW. Total project cost, including transmission line, was $5.8 million, and electricity generation cost over the life of the wind farm is estimated at 8-cents/kWh [5].

The largest individual wind generator in Australia is the 150 kW Windmaster at Malabar, Sydney, New South Wales. A 60 kW pilot wind generator situated at Breamlea, near Geelong in Victoria, is producing 95,000 kWh of electricity a year, enough to meet the needs of 20 houses. Wind farms are vast areas of land dotted with hundreds of wind generators, which usually feed electricity directly into the supply network. Large sections of the southern Australian coast are ideal wind-generation sites

Wind turbines can be divided into two basic configurations depending on the position of the rotor: horizontal axis and vertical axis (or Darieus type) wind turbines (HAWTs and VAWTs, respectively). HAWT are the most commonly employed and manufactured. Both types use aerodynamic lift to extract power from the wind and have the same sub-systems [9-18].

Due to recent developments in permanent magnet materials, especially Nd-Fe-B, high efficiency PM generators can be manufactured for wind applications. The present paper is aimed to outline the design, analysis of such a PM generator. The generator is an 8-pole permanent magnet generator rated at 5 kW and using NdFeB for the field excitation. This is being designed using a new finite element package developed by MSC-Ansoft. The generator will be coupled to the blades via a 1:5.5 gearbox. This will give a higher rotational speed to the generator to allow it to generate more electricity at lower wind speeds.

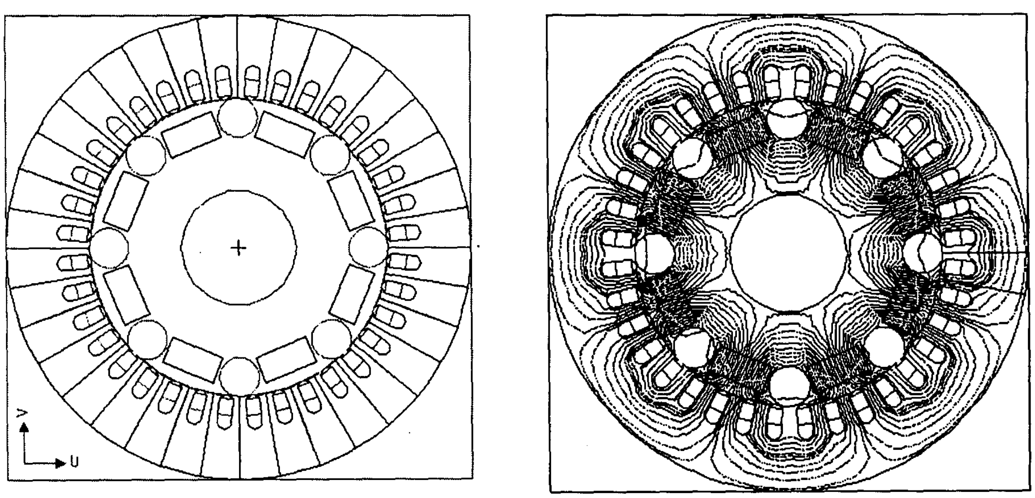
## 2. Finite Element Analysis

The finite element method is a numerical method of solving linear and non-linear partial differential equations. It offers an accurate and powerful design tool, allowing material properties, nonlinearities and structural details to be taken into account. The method basically involves the discretisation of the machine cross section into smaller finite elements. The spatial variation of magnetic potential throughout the machine is described by a non-linear partial differential equation derived from Maxwell equation.

The finite element method (FEM) can be used to change the structure of the machine, the material properties, and the excitation in the rotor and the stator of machine [18, 19]. The solution of a continuum problem by the FEM process always follows an orderly step-by-step process. The first step is to divide the continuum or solution region into elements. A variety of element shapes may be used, and different element shapes may be employed in the same solution region. The finite element model contains information about the device to be analysed such as geometry (subdivided into finite elements), materials, excitations, and constraints. The material properties, excitations, and constraints can often be expressed quickly and easily, but geometry is usually difficult to describe. The finite elements can be very small where small geometric details exist, such as air gaps and can be much larger elsewhere.

Before the system equations are ready for solution, they must be modified to account for the boundary conditions of the problem. Each degree of freedom at a grid point may be unconstrained (unknown) or constrained. The assembly process gives a set of simultaneous equations that we solve to obtain the unknown nodal values of the problem. If the problem describes steady or equilibrium behaviour then we must solve a set of linear or non-linear algebraic equations. If the problem is unsteady, the nodal unknowns are a function of time, and a set of linear or non-linear ordinary differential equations must be solved.

The solution of the system equations can be used to calculate other important parameters. For example, in electromagnetic problems, the nodal unknowns are the components of magnetic flux density. From these components the induction, the torque, and other electromagnetic parameters can be calculated [20]. Fig. 1 shows the cross section and the flux distribution of the designed machine and Fig. 2 shows the magnetic flux density around the core.




a) b)

Figure 1: Cross section of the wind generator a) and the flux distribution b)

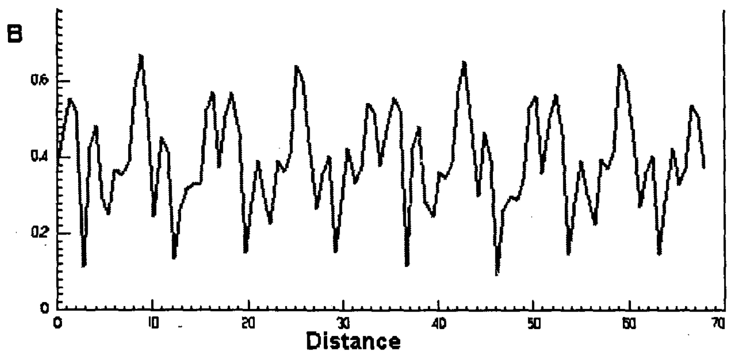



Figure 2: Magnetic flux density in the stator yoke

## 3. Permanent magnet generators

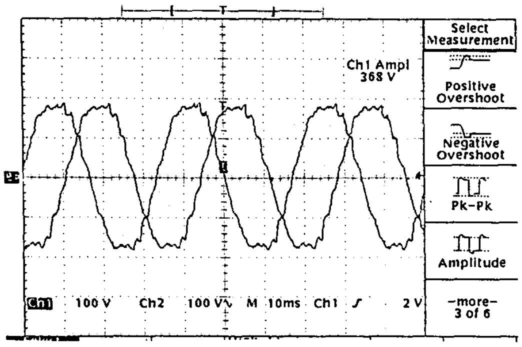
Permanent magnet (PM) machines are a well-known class of rotating and linear electric machines used in both the motoring and generating modes. PM machines have been used for many years in applications where simplicity of structure and a low initial cost were of primary importance. More recently, PM machines have been applied to more demanding applications, primarily as the result of the availability of low-cost power electronic control devices and the improvement of permanent magnet characteristics. In general, modern PM machines are competitive both in performance and cost with many types of machines.

The term permanent magnet machine is used to include all electromagnetic energy conversion devices in which the magnetic excitation is supplied by a permanent magnet. The energy converters using permanent magnets come in a variety of configurations and are described by such terms as motor, generator, alternator, stepper motor, linear motor, actuator, transducer, control motor, tachometer, brushless dc motor, and many others. Permanent magnet machines are rapidly finding numerous applications as alternators, automotive applications, vehicular electric drive motors, small appliances, and control motors, printed circuit motors and computer and robotics applications. The stator of the machine is identical to the stator of a multiphase AC machine. The new component is the rotor, which in contrast to conventional rotors relies on permanent magnets as the source of excitation rather than an electric current in windings. The optimum rotor configuration, rotor electromagnetic and mechanical design, and the stator electromagnetic design must be matched to achieve a higher efficient machine of the desired load characteristics, high power factor, and high efficiency and performance.

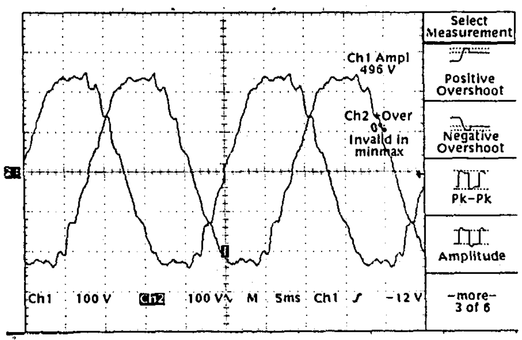
The PM machines can be surface mounted or exterior and interior machines [18-20]. In buried or interior PM machines the machine is robust, rugged and well-suited for flux weakening control for a wide speed-torque range, essential for many applications. The surface-mounted PM machine has magnets at the airgap surface and is liable to damage at high speeds or even in the assembly and fabrication process. The rotor structure for an interior PM rotor will tend to have a smooth rotor design similar to or better than induction machines. Thus, windage losses will be equal to or lower than those of conventional induction machines. In this paper we present the performance of designed interior permanent magnet machine. The stator employed is of an equivalent induction motor, rated at the same power. The dimensions of PM generators are given in Appendix A. Figure 3 show the sinwave of generated voltage at different frequency. Further work is continuing to test the performance under realistic wind energy applications.

## 4. Conclusions

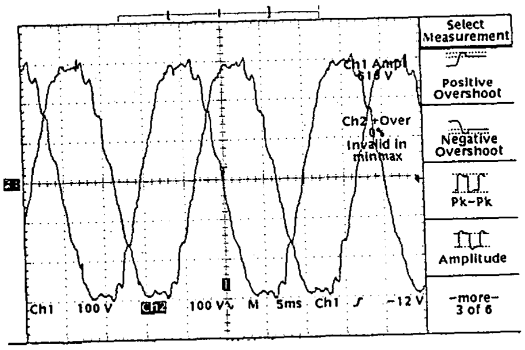
A permanent magnet wind generator is analysed using the finite element method. The simulation results are being used in the fabrication of the machine. The fabricated machine's configurations are, also, shown. The initial preliminary results show the performance as predicted by finite element analysis



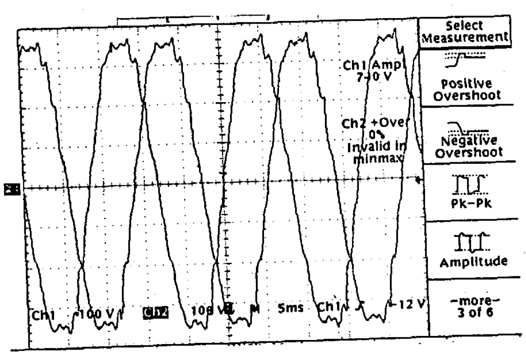

a) at 450 rpm




b) at 600 rpm




c) at rated speed, 750 rpm




d) at 900 rpm

Fig. 3: EMF of the generator at different speed

## 5. References

[1] Griffiths A., *Renewable Electricity for Australia,* Mark Stevens Energy Division, Australian Commonwealth Government Printer, Canberra, 1993.

[2] Remmer D. and Dymond M. Actual Cost Analysis with an approach to efficiency improvements in SECWA operated systems. Murdoch University Energy Research Institute, NERWIA, Perth, Australia, 1992

[3] Phillips N, Nayar V. Sadler B. Applications of renewable energy hybrid systems in conventional mini power stations Solar'91, Australian and New Zealand Solar Energy Society, Adelaide, 1991

[4] Remmer D. Economic analysis of unsubsidised remote area power supply systems electric energy conference, the Institution of Engineers, Brisbane, Australia, 1992

[5] Green S., The *Australian Renewable Energy Industry*, Department of primary industries and energy, Australian Commonwealth Government Printer, Canberra, 1994.

[6] Survey on present and future contribution to the Australian economy, Net Energy program, Energy division ""Australian federal department of primary industries and energy DPIE, April 1998.

[7] Lemon J. H. Ecologically Sustainable Development (ESD) working groups. Final report, energy production, Canberra, 16-18 April, 1991

[8] Kaneff S. Renewable Energy options for sustainability. PP 48-100 Canberra: Center for resources and Environmental studies Australian National University.

[9] Wyckmans M, *"HVDC Light Opens up New Business Opportunities"*, Proceedings, Electric Energy Society of Australia, 1999 Annual Conference

[10] *Wind Energy Technical Information Guide.* SERI, Golden Colorado, USA, December 1989.

[11] World Energy Council *New Renewable Energy Resources*, Kogan Page Limited, 1994.

[12] Paul Gipe, *Wind energy comes of age*, John Wiley & Sons, INC, 1995.

[13] Grosveld, F. W., 1985 "Prediction of Broadband Noise from Horizontal Axis Wind Turbines", AIAA Journal of Propulsion and Power, Vol. 1, No 4.

[14] Richardson, D. R and M[c]Nerney, G. M. Wind Energy Systems. IEEE, March, 1993

[15] Eggleston, D.M and Stoddard, F.S. Wind Turbine Engineering Design. Van Nostrand Reinhold, 1987.

[16] Nacfaire, H. Grid-Connected Wind Turbines. Elsevier Applied Science Publishers LTD, 1988.

[17] Jenkins, N. Engineering Wind Farms. Power Engineering, April 1993.

[18] Rizk J. and Nagrial M. , Analysis and design of permanent magnet machines using finite element method, Power Systems World '97, Sep. 6-12, 1997, Baltimore, PP USA, IMO3.2-1 – IMO3.2-7

[19] Rizk J. and Nagrial M. (1997) "Finite Element Modeling of permanent magnet machines Third International Conference on Modeling and Simulation (MS'97),), Melbourne, Australia, pp. 295-299, Oct. 29-31

[20] Rizk J and Nagrial M, Design of permanent-magnet generators for wind turbines, Australasian

Universities Power Engineering Conference, University of Northern Territory, (AUPEC '99) 27-30 September 1999.

# APPENDIX A
# GENERATOR SPECIFICATIONS

| | |
|---|---|
| Poles number | 8 pole |
| Rated power, kW | 5 kW |
| Rated speed | 750 Rpm |
| Rated voltage, v | 415 v |
| Stator inner diameter, mm | 165 |
| Length of stator stack, mm | 100 |
| Air gap length, mm | 0.6 |
| Stator slots | 36 |
| No of turns/slot | 96 |
| Phase resistance, Ω | 3.7 Ω |
| Magnet dimensions, mm | 15x30x100 |