# DEVELOPMENT OF A DIRECT-DRIVE ELECTRICAL TRANSMISSION SYSTEM FOR A KENYAN MANUFACTURED VERTICAL AXIS WIND TURBINE

***P. O. Akello[1], F. X. Ochieng[1] and J. Kamau[2]***
*[1]Institute of Energy and Environmental Technology, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya*
*[2]Department of Physics, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya*
*E-mail: philipodhis@gmail.com*

**Abstract**
The major reason for the continued low penetration of Small Wind Turbines (SWTs) in Kenya is the high cost of the technology particularly the drive train (gearbox and/or generator). Subsequently, the main objective of this research was to design and develop a direct-drive generator that eliminates the need of gearbox, is affordable/low cost and easy to manufacture and assemble. Secondly the research also sought to determine the optimal economic cost of production of the generator. In achieving this, the methodology used involved: computational electro-mechanical design using FEMM 4.2 software, followed by prototype development and testing. In addition, stratified random sampling, questionnaires and face to face interviews of SWT manufacturers was also done. Materials used included permanent magnets, coil windings, steel rotor discs, used vehicle hub bearing, generator mounting frame, polyester resin, epoxy hardener and talcum powder. The results of the research are in form of 1 kW direct drive Axial Flux Permanent Magnet (AFPM) generator, which costs between 5 – 20% cheaper than the existing SWT transmission systems in the market. Its performance ranges above average as compared to the current ones and its manufacturing process technology is simpler and faster than the existing approaches. In conclusion the use of AFPM direct drive generator reduces transmission system costs of SWTs which can greatly accelerate the adoption of vertical axis SWTs in rural off-grid regions of Kenya. The generator is also quite easy to construct, operate and maintain by people with basic technical skills. Its adoption will also create employment opportunities in the manufacturing and service delivery sectors.

**Key words**: Renewable energy, small wind turbines, vertical axis wind turbines, direct drive axial flux permanent magnet generator, Finite Element Magnetic Method (FEMM)

## 1.0 Introduction

### 1.1 Permanent Magnet Direct Drive Generators

Increasing energy demands and global warming, caused by increasing environmental pollution, call for the use of renewable energy resources. Among them, wind energy is currently assumed as the lowest risk, with proven technology and no greenhouse-gas emissions or waste products. By end of 2009, the capacity of wind energy power plants had reached 158GW worldwide (Madani, 2011). The interest in producing electricity from wind puts certain demands on the electrical machines and drives. This challenge is what has led to much technological advancement in induction machines and permanent magnet generators.

One of the areas where technological advances have played a major role in the last years is the development of innovative, direct driven, variable speed generators for wind turbines. The generator is an important component in a wind turbine, since it converts the mechanical energy in the rotating wind turbine to electricity. Small scale wind power applications require a cost effective and mechanically simple generator in order to be a reliable energy source. Direct-drive generators fulfill this requirement by eliminating the need of gearbox in wind turbines. Gearless wind turbines are becoming increasingly popular (Jöckel, 1996), because they prevent the drawbacks associated with the gearbox including oil leakage, gear costs, gear maintenance and gear losses.

For direct drive, the popular machine option is the Permanent Magnet (PM) synchronous machines (Wenping *et al*., 2012). PM machines are electromagnetic energy conversion devices in which the magnetic excitation is supplied by a permanent magnet. Energy converters using permanent magnets come in a variety of configurations and are described by such terms as motor, generator, alternator, brushless dc motor, and many others. Permanent magnet machines are rapidly finding numerous applications as alternators, automotive applications, small appliances, computer and robotics applications among others. The stator of the machine is identical to the stator of a multiphase AC machine. The new component is the rotor which relies on permanent magnets as the source of excitation rather than an electric current in windings of conventional rotors. The advantages of PM machines over electrically excited machines can be summarized as follows according to literature (Polinder *et al*., 2006):

(i) Higher efficiency and energy yield.
(ii) No additional power supply for the magnet field excitation.
(iii) Improvement in the thermal characteristics of the machine due to absence of the field losses.
(iv) Higher reliability due to the absence of mechanical components as slip rings.
(v) Lighter and therefore higher power to weight ratio.

The main disadvantages of PM machines are high cost of PM, difficulties in manufacturing and demagnetization of PM at high temperatures. 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.

### 1.2 Statement of the Problem

According to International Electrotechnical Commission (IEC) Standard, a Small Wind Turbine (SWT) can be defined as a system of 200m$^2$ rotor swept area or less that converts kinetic energy in the wind into electrical energy. SWTs have been available in Kenya for more than 10 years. However, despite the huge potential for SWTs alongside the stringent need for rural electricity, the pace of adoption in many rural areas is still low.

Further, the SWT sector is still limited to few companies and pilot projects, and this has led to only a limited number of SWTs installed in Kenya, of which a significant amount of them are malfunctioning. A major reason for the continued low penetration is the high cost of technology involved, particularly the drive train (gearbox and/or generator). This study focused on the development of direct drive generator and electrical system expected to lower the overall cost of SWTs in Kenya, by eliminating the gearbox and also through a low cost but efficient generator design using locally available materials. In the process, the adoption of SWTs in Kenya is expected to accelerate.

### 1.3 Research Objectives

The main objective of the study was to design and develop an electrical transmission system including a permanent magnet generator working with a Vertical Axis Wind Turbine (VAWT) that can operate in low wind speed sites. The specific objectives of the study are:

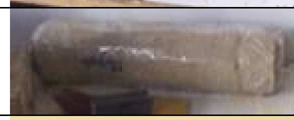
(i) To design and develop a direct-drive generator using locally available components.
(ii) To integrate a transmission and control system that will work seamlessly with the direct drive generator.
(iii) To verify the generator performance through measurement and field tests.
(iv) To determine the economic cost of production of the generator.

## 2.0 Materials and Methods

### 2.1 Materials

Table 1 shows a summary of the main materials used in the fabrication of the generator:

*Table 1: Main materials used for fabricating the generator*

| Material | Picture |
|---|---|
| Rotor Disks |  |
| Magnets (NdFeB N40, 46mm x 30mm x 10mm) |  |
| Magnet (Winding) Wire, Gauge 16 |  |
| Fibre cloth |  |
| Mounting Frame |  |

| | |
|---|---|
| Used Car Hub (Toyota 110) |  |
| Mounting Studs (M12 x 50mm) |  |

Other materials include resin, talcum powder, hardener, nuts and washers.

### 2.2 Design Methodology

This section gives details of how the 1kW Axial Flux Permanent Magnet (AFPM) Generator was constructed for charging 24V battery.

#### 2.2.1 Selecting Generator Main Parameters

The design began by selecting the generator main parameters which are shown in Table 2:

*Table 2: Generator main parameters*

| Parameter | Value |
|---|---|
| Output Power | 1kW |
| Rated Voltage | 48V |
| Rated Speed at cut-in wind speed (1-3m/s) | 150RPM |
| Pole Number | 12 |
| Phase Number | 3 |
| Magnet dimensions | 46mm x 30mm x 10mm |
| Car Hub diameter | 140mm |

#### 2.2.2 Generator Modeling and Simulation in FEMM 4.2 software

Computer software was used to design and test (optimize) the machine before its fabrication. This is commonly referred to as Finite Element Analysis (FEA). FEA is a flexible, reliable and effective method for the analysis and synthesis of power-frequency electromagnetic and electromechanical devices. There are several Finite Element Method (FEM) simulation packages that are now available. One such package is Finite Element Method Magnetism (FEMM 4.2). FEMM 4.2 is a suite of programs for solving low frequency (hence low speed) electromagnetic problems on two-dimensional (2-D) planar and axisymmetric domains.

The actual generator was modified to the flat 2-D model since FEMM 4.2 does not model in 3-D. Later, FEMM will be used to determine electromechanical parameters of the generator and these will be compared with the measured values. Figure 1 below shows a section of the 2-D model of the generator in FEMM 4.2.

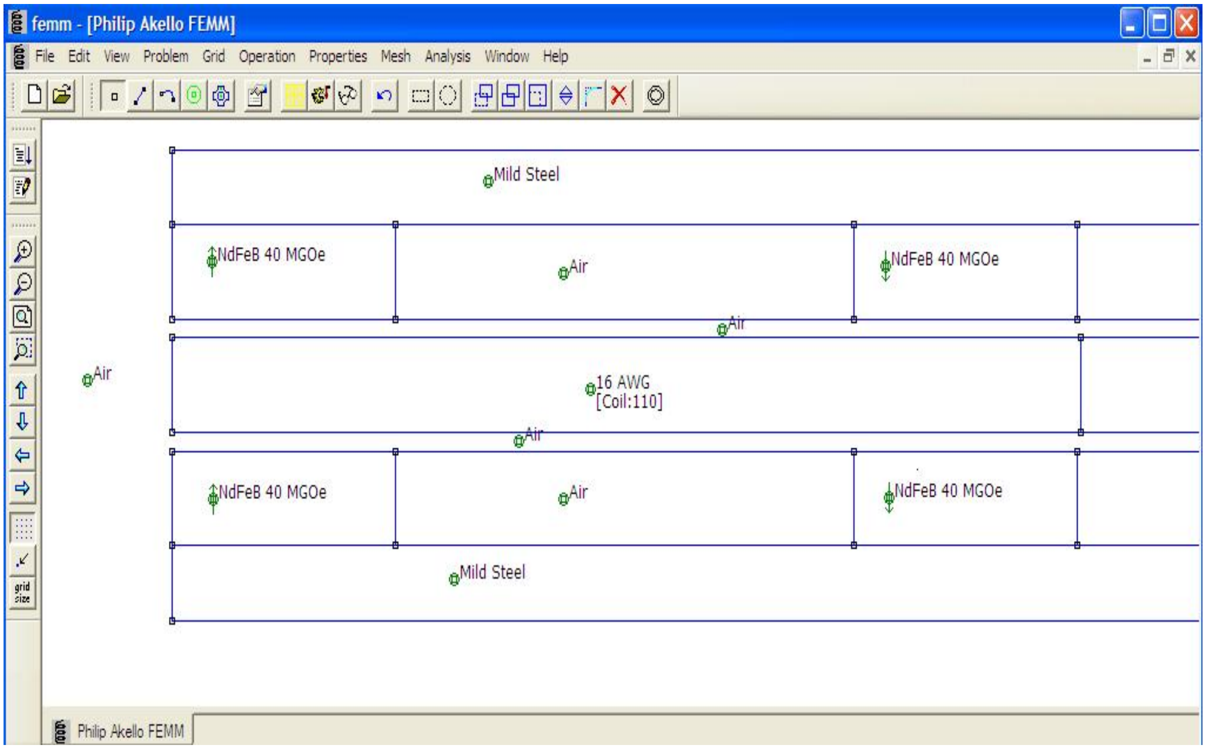



*Figure 1: A section of 2-D Generator Model in FEMM 4.2*

### 2.2.3 Design Calculations

Several calculations to determine dimensions and parameters were performed. Some of these equations were gathered from valid books and papers, but some of them were devised. From the calculations, the following dimensions were derived as shown in Table 3:

*Table 3: Generator dimension design parameters*

| Parameter | Value |
| --- | --- |
| Inner rotor disk radius | 124mm |
| Outer rotor disk radius | 170mm |
| Rotor disk diameter | 340mm |
| Rotor disk thickness | 8mm |
| Stator thickness | 10mm |
| Stator diameter | 480mm |
| Air-gap length | 1mm |
| Effective air-gap | 32mm |
| Number of coils | 9 |
| Number of turns per coil | 110 |

### 2.3 Fabrication Process

#### 2.3.1 Mould Preparation and Casting of Stator and Rotor Disks

The shapes of the stator and rotor disks were marked in two separate plywood of reasonable thickness, marking the mounting hole centers. The stacks – which are the boards serving as the lid and base of mould- were then cut. Figure 2 shows finished mould for stator and rotor respectively.

*Figure 2: Finished stator and rotor moulds*

A coil-winding machine was then made from pieces of 12 mm ply wood mounted on a threaded stud. Coils were formed from four pins made from three inch nails which are spaced to form the shape of the magnet (46mm x 30mm). The sides of the coils were supported by two cheek-pieces held 10mm apart by a central spacer, with a handle attached to one cheek piece. Each cheek has deep notches for slipping in insulation tape around the finished coil. 9 pieces of coil were wound on this machine, after which they were taped when the right number of turns were attained. The coils were then connected in 3-phase star shaped before soldering them at the points of connections. The figure below shows pictures of coils after winding, connection and soldering.

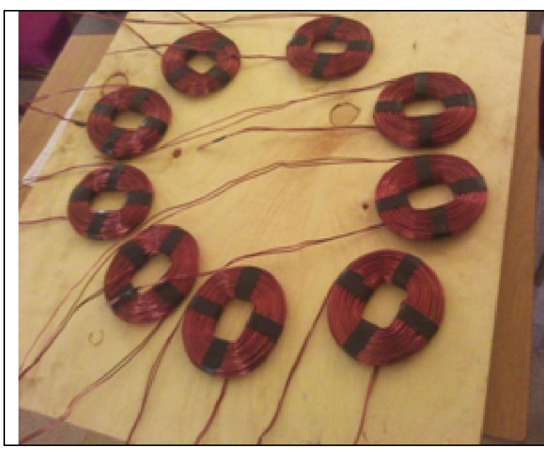


*Figure 3: Stator coils*

After cutting two sheets of fibreglass cloth, Stator casting began by mixing polyester resin (200ml), epoxy hardener (3 ml) and talcum powder for heat dissipation. Wax was applied to stator mould base followed by a little resin, one sheet of fibre cloth before placing the coils. The resin mixture was then poured over the coils so that it soaked in between the coils. A second sheet was applied after preparing another resin batch, while banging the mould to release air bubbles. A lid was then screwed on top of the mould and left for 24 hours before loosening the screws to remove the stator mould. Three mounting holes equally spaced were then drilled as shown in the Figure 4.

*Figure 4: Complete stator before and after painting*

The rotors were moulded next, beginning with magnets placement on the disks. The magnets were placed such that a magnet with a north pole on one face is adjacent to a south pole on the other. The use of a magnet jig cut out from plywood ensured that each magnet was equidistant from the adjacent one. These disks were then moulded in a similar manner to the stator, the only difference is that one sheet of fiberglass cloth was used and this was placed on top of the magnets. Figure 5 shows pictures of magnet jig and dry rotor disks after moulding and painting.

*Figure 5: Magnet jig and finished rotor disks*

**2.3.2 Assembling the Generator**

Apart from the stator and rotor disks moulds, other requirements before mounting are the mounting frame, car hub, studs, nuts and washers. Necessary tools including spanners and pliers were needed for this task. First, the car hub was greased before being mounted onto the frame. This was followed by the back rotor, stator and front rotor respectively. Appropriate air-gap (1mm) between each rotor disk and the stator was observed. Figure 6 shows the complete AFPM generator.

*Figure 6: Assembled AFPM generator*

### 3.0 Results and Discussion

Initial generator performance tests were carried out by turning the generator by hand at around 60 rpm (once per second) before using a fixed speed AC motor with the ratings 0.25hp, 0.18kW, and 630 rpm. Voltage Measurements were taken at no-load test using a digital multimeter. Figure 7 shows the generator test set-up with the motor.

*Figure 7: Generator test-set up*

The results were as follows:

| Speed (rpm) | AC Voltage (V) |
|---|---|
| 60 | 6.9 |
| 630 | 68.2 |

This is an on-going project and further performance tests in the field are going to be done. These are therefore initial test results.

The AC voltage indicates the generator output voltage at any given speed. The DC output from the battery is normally higher by a factor of about 40% than the AC voltage, less a fixed amount of around 1.5 volts DC, due to the fixed voltage drop in the rectifier (Piggott, 2003). The 40% difference occur owing to the fact that the AC reading is an average (that is root mean square) value, while the rectified DC is the peak voltage available.

From the above explanations, the AC voltage, $V_c$, required to start charging a 24-volt battery (which is the design requirement for this project), can therefore be computed as follows:

**24VDC = (1.4 x $V_c$) – 1.5**
**$V_c$ = <u>18.21</u>**
From the test results, a generator speed of 60 rpm produces AV voltage of about 6.5V.
Therefore, $V_c$ will be attained at (18.21 x 60/6.9) = 158 rpm.

The generator will therefore start charging the 24-volt battery at a speed of 168 rpm.

Speed in m/s and rpm are related by the following equation:
**m/s = πd/60 x rpm**
where πd is the circumference of the rotor disk.
**Speed in m/s = π x 0.34 x 158/60 = 2.8m/s**

The wind speed at which the generator will start charging the battery is 2.8m/s.

## 4.0 Conclusion

Research statistics indicate that most Arid and Semi-arid areas in Kenya have an average wind speed of 4m/s. The AFPM generator is therefore expected to perform well under these wind speed conditions given that it begins battery charging from a low wind speed of about 2.8m/s. this generator is therefore appropriate for use in both rural and even urban off-grid sites with low wind speeds. So far the cost of the generator is far below that of the existing systems. In the end, this is expected to lower the overall cost of the wind turbine, resulting in a cheaper turbine compared with what is currently available in the Kenyan market. The generator is also quite easy to construct, operate and maintain by people with basic technical skills. This is also expected to accelerate the adoption of SWTs in Kenya, creating employment in the process to many unemployed youth.

**Acknowledgement**

I acknowledge the support of National Council for Science and Technology (NCST) for financing this project, as well as Jomo Kenyatta University of Agriculture and Technology (JKUAT) for availing the necessary facilities that aided the development of this generator.

**References**

Finite Element Magnets Method (FEMM 4.2). (2013). *www.femm.info/wiki/Download*. Retrieved on 22/5/2013.

Jöckel, S. (1996). *Gearless wind energy converters with permanent magnet generators - an option for the future*? Proceedings of European Union Wind Energy Conference, EWEA, Göteborg, Sweden: pp. 414-417.

Madani, N. (2011). *Design of a permanent magnet synchronous generator for a vertical axis wind turbine,* Royal Institute of Technology University, Stockholm, Sweden: Master Thesis.

Piggott, H. (2003). *Permanent magnet alternator theory session for ITDG wind power course*, Hambantota, Sri Lanka.

Polinder, H., Bang, D.J., Li, H., and Chen, Z. (2006). *Concept report on generator topologies, mechanical and electromagnetic optimization.* Delft University of Technology, Delft, Netherlands.

Wenping, C., Xie, Y.M and Tan, Z. (2012). *Wind Turbine Generator Technologies*, from Advances in Wind Power, InTech, Rijeka, Croatia: pp. 177-204.