The Design of a Small Scale Wind Turbine Generator

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Abstract: The energy harvested by the wind is a function of both the blade design and the wind resource which is site dependent. The extracted energy may be used to drive mechanical devices or stored for future use. There are many types of energy storage facilities but for a small scale wind turbine, battery storage is adequate. Electricity generation works on the principle of electromagnetic induction. Electricity can be generated using the synchronous or induction machine. For simplicity, the field winding may be replaced by permanent magnets to produce the magnetic field flux. Permanent magnet wind turbine generator has been designed and the design has adopted minimum air gap to enhance magnetic flux generation and cost reduction. Preliminary bench test has been carried out and the results obtained on a single phase arrangement are quite satisfactory.

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1. Introduction

The power in the wind is available for harvesting depends on the location and the wind resource, a function of the wind speed as well as the swept area of the rotating turbine blades, a design function. For a given site therefore, the faster the wind speed or the larger the rotor blades the greater the energy to be extracted from the wind. In other words, the turbine power production depends on the interaction between the rotor blades and the wind and it is this interaction that is important in a wind turbine blade design. The power harvested may be used to drive mechanical devices or stored for future use. There are various methods of storing energy including pumped-hydro and the flywheel all under the mechanical type, heated fluid in thermal storage and electrical storage ranging from lead acid battery through to superconducting magnetic energy storage (Achara, 2014). For the purpose of a small scale wind turbine, where simplicity is the watch word, battery storage is adequate. Battery storage is one way of overcoming the unpredictability of the availability of wind resource. Before the energy extracted from the wind is stored or used in electrical form, it has to be converted into electricity.

1.1 The Electricity Generation

The wind turbine generator is responsible for converting the rotational mechanical power harvested from the wind into electricity that can be grid-tied, used in distributed systems, charge batteries and for residential supplies. The conversion may be achieved using any of the following electromechanical devices including direct current machines usually referred to as dynamo, synchronous machines and induction machines. All these machines work on the basis of Faraday's law of electromagnetic induction through the interaction between the coil windings and the magnetic flux, (Bhadra et al, 2009, (see figure 1).

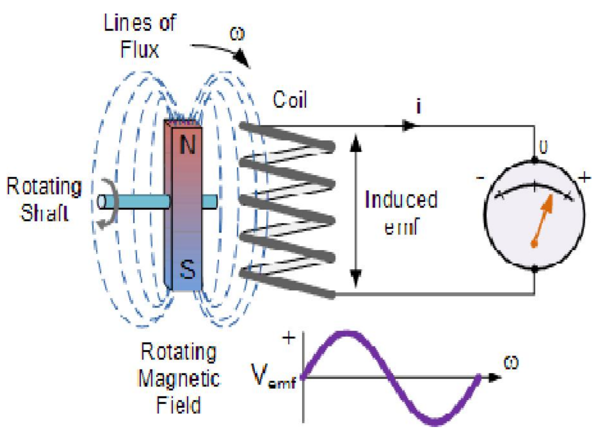

Figure 1. The Basic Principle of Generating Electricity

The operation of the wind turbine electric generator depends on the flow of electrons past electric coils or the other way round where the coils of wire move past electromagnet field. This interaction between the electromagnetic field and coils of wire induces electromotive force (emf). For a given magnetic flux, the voltage generated increases as the number of turns on the coil increases. For a given number of turns, the emf induced is proportional to both the strength of magnetic flux and speed of rotation. The direction of the magnetic lines of flux and the direction of conductor movement are used to determine the polarity of the generated voltage.

2. The Electric Generator

The wind turbine generator can be classified based on the mode of generation of the magnetic flux. These are the permanent magnet and the wound-field generators. Most residential and other small wind turbine generators use permanent magnets to create the required magnetic field as the machine rotates. These high strength magnets are usually made from rare earth materials such as neodymium (NdFe) which provides constant magnetic field, simpler and more rugged construction without the need for field windings. Wound field requires an external energy source to generate the magnetic field but has the ability to adjust the field flux and therefore the power to match the varying wind resource.

The transmission of the mechanical energy from the rotor blades to the electric generator can be achieved either by direct drive or gear box connection through the main shaft. The direct drive arrangement is simpler and more efficient but the generator rotor shaft and bearings are exposed to the full weight and rotational force of the rotor blades. On the other hand, the use of a gearbox allows for better matching of components but suffers from mechanical efficiency loss in the gearbox. Therefore the type of wind turbine generator selected for any particular location would depend on the wind resource of the site and the characteristics of the electrical machine in relation to the wind speed. The cut-in speed defines the speed above which the wind turbine electric generator starts to produce electricity and would produce the maximum rated power just before the cut-out or furling speed. Within this range the power generated is proportional to the cube of the freestream wind speed. Mechanical or electric speed sensors may be applied to stop wind turbine or guard against over-speeding.

2.1 Types of Electric Generators

Both the synchronous generator and the *Induction Generator* have similar fixed stator winding arrangement which, when energised by a rotating magnetic field, produces a single phase or a three-phase output voltage. However, the rotors of the two machines are quite different with the rotor of an induction machine having either the squirrel cage or wound rotor.

2.1.1 Asynchronous (Induction) Machines

The three-phase induction machine is the most widely used rotating machine in industry. The single phase version is also used in many domestic applications where the use of electric motors is needed (WWFL 2014).

The induction machine gets its name from the way it is operated (Hansen 2010) and (CHIRAS 2008 & 2009). An external AC is provided to the stator winding but none to the rotor winding. The AC in the rotor of an induction machine is as a result of induction from the stator. An induction motor is also classified as an asynchronous machine and its speed is slightly less than the synchronous speed. The induction machine has many advantages including ruggedness, inexpensive, easy to maintain, wide variation in size and speed which varies +only by few percentage points. The machine has its flaws and these are indicated in the design section.

The application of a three phase voltage across the stator windings of the induction machine gives rise to the flow of a three phase current which produces a rotating magnetomotive force mmf) (ECE 2014). The rotation of the stator mmf is dependent on the number of poles (p) of the stator winding. The poles occur in pairs. The stator mmf rotates at a rate of 2/p revolution per period (stator current period, $T = 1/f$). The synchronous speed (n_s) is defined by the speed of the stator mmf rotation, therefore:

$$n_s = 120f/p \ (rpm)$$

where f is the frequency of the

stator current.

The rotating stator mmf is applied to the rotor through the air gap. There are two types of rotor, the squirrel cage and the wound rotors. The conductors are held in the slots of the laminated core mounted on the machine shaft. For emf to be induced in the rotor conductors, the rotor must operate at a speed lower than the synchronous speed of the stator. The difference between the synchronous speed and the rotor speed (n) is referred to as the slip speed (n_{slip}). Therefore:

$$n_{\mathrm{slip}} = n_s - n \ (rpm)$$

The slip (s) is the slip speed when normalised and is defined as

$$s = (n_s - n)/n_s$$

The asynchronous machines rotate below synchronous speed when used as a motor, and above synchronous speed when used as a generator. The induction generator requires power which is provided by the grid if grid-tied but in standalone, additional capacitors are connected to the windings for self-excitation. A further requirement for the standalone is the availability of some residual magnetism in the rotor laminations.

2.1.2 Synchronous Machine

The stator core and windings of the three phase synchronous machine is identical to those of the induction machine. Like the stator of the induction machine, the function of the synchronous machine stator is to provide a rotating mmf to the rotor. However the rotor of the synchronous machine is different from that of the induction rotor. The rotor of the synchronous machine is a rotating electromagnet and has the same number of poles as the stator. The rotor windings carrying DC current create the poles of the synchronous machine rotor. The synchronous machine therefore requires both AC and DC for excitation of the stator (armature) and the rotor (field) windings respectively (Chilvers 2014). There is a tendency for the magnetic fields of the stator and rotor to align themselves. Under steady state conditions with given constant AC frequency f, the machine speed (n) is equal to the synchronous speed (n_s), that is:

$$n = n_s = 120f/p$$

The fundamental difference between induction machine and the synchronous machine is that the rotor currents of the induction machine are induced whereas those of the synchronous rotor are not.

2.1.3 The Permanent Magnet DC Generator

The DC motor may be converted to a generator by mechanically running it at a speed higher than the designed motor speed. This can be achieved through rotating the armature using energy harvested by the wind turbine rotor blades. Since in a conventional DC machine the stator carries the field winding and the rotor the armature winding, the output electric power is taken on the armature through a commutator, slip-rings and carbon brushes. DC generators for wind turbine applications have the disadvantage that a separate direct current power source is needed to excite the shunt field. However, this disadvantage can be overcome by replacing the field inding with permanent magnets to create a Permanent Magnet DC Generator (PMDC generator).

The purpose of this study is to design a cheap and simple wind turbine generator for use by rural communities.

3. The Design

It has been noted that the induction machines are associated with some disadvantages and these include difficulty in controlling the speed, very high starting current which may be many times higher than the full load current, the low lagging power factor when the machine is lightly loaded and the provision of slots to hold the conductors on the laminated core. When the machine is operated as a standalone additional capacitors and residual magnetism are also needed. For the synchronous machine both external AC and DC are required for excitation of the stator and rotor windings. Furthermore these machines, in most cases, require the use of slip rings and commutators which will only add to the complexities, (Piggott 1997) and (Bartmann & Fink, 2009).

Under normal circumstances, the design of the DC generator requires separate DC to excite the field windings. However this can be avoided by the use of permanent magnets. The use of permanent magnets also has the advantage that the design responds to changes in wind speed very quickly because the strong stator field is always available.

Since permanent magnets are very expensive, it will be necessary to minimise the air-gap in order to reduce the quantity of magnets required and maximise efficiency.

As a result of the flaws and complexities in the induction and synchronous generators design, this study has opted to a version of the permanent magnet design in which the stator windings are sandwiched by two rotor disks. This design is simple and the cost of permanent magnet has come down significantly. The choice is a trade-off between simplicity and cost. The target users, the rural folks, for easy maintenance do not want complexities in design and for affordability want reasonable priced product.

Piggott and [Batmann & Fink] have adopted the similar approach in their designs but failed to quantify for repeatability, the strength of the magnets used except to say that they are strong magnets.

3.1 The Permanent Magnet

The importance of the permanent magnet in this design cannot be over-emphasised since it is the magnet that creates the magnetic flux that enables the mechanical energy of the spinning shaft to be transferred to electric energy. The formulation of neodymium, iron and boron magnet (NdFeB) to be used in this design is reported in 2009 to be the most powerful magnet available. The development of neodymium-iron-boron (NdFeB) at 35MGOe maximum energy product (B-Hmax) is credited to General Motors, Sumitomo special metals and the Chinese Academy of Sciences. The quality and strength of magnets are measured by the maximum energy product in megagauss oersted (MGOe). Magnets are usually rated, for example N45 with the number designating the BHmax and the letter the material from which it is formulated. The theoretical maximum grade of NdFeB is N64 [B & Fink]. Recently manufacturers have started quoting the pull strength of magnets a function of the mass and surface area of a given magnet. This parameter, for repeatability, is important in the study and design of the wind turbine generator.

3.2 The Generator

The generator consists of the rotor and stator. The rotor is made up of two discs carrying the permanent magnets that produce the magnetic field flux.

Figure 2 shows the stator sandwiched between the rotor discs. The stator carries the coils through which the generated electricity is collected. The permanent magnets are each of pull strength 10.9kg and are each drilled and countersunk for fixing onto the rotor discs.

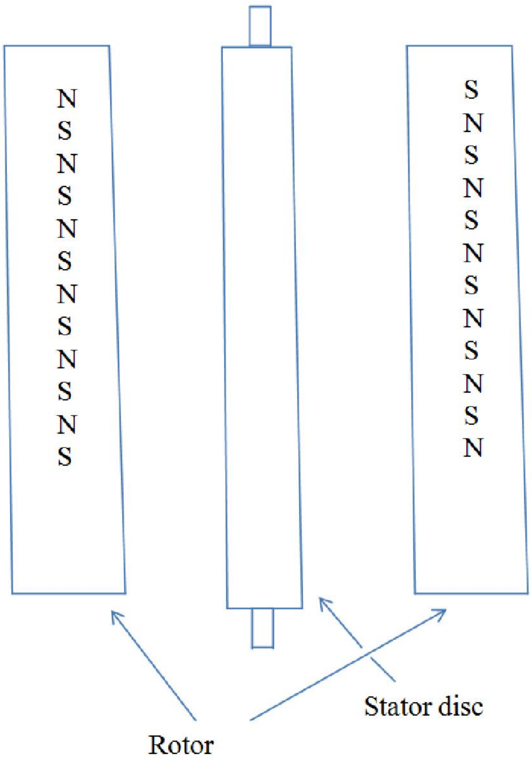

Figure 2: The Permanent Magnet Generator 2 Disk Arrangement (Schematic).

3.2.1 The rotor

Each of the rotor pair is 250mm in diameter and 10mm thick and carries 12 neodymium permanent magnets. The magnets are each located at the intersection of a 100mm radius circle inscribed on the rotor disc and the 30^{o} equal division of the disc into 12 places. Figure 3 shows this arrangement. These intersection points are each drilled with 4 mm bit and tapped to take a 5mm screw. Permanent magnets drilled in this way are more costly compared with similar plain undrilled type. There are two methods of fixing the plain undrilled magnets: casting in resin with fibreglass sheet cover or banding with metal on the outer side and filling the inner part with resin. It is necessary to alternate the poles of the magnets as shown in the figure. It may be necessary to first create a template in order to maintain accuracy in the fixing of the magnets. The same alternating arrangement used in fixing the permanent magnets on the 100mm radius circle is also used between the two mild steel discs whereby each magnet on one disc in alignment with the opposite magnet on the other disc is of opposite pole see figure 2.

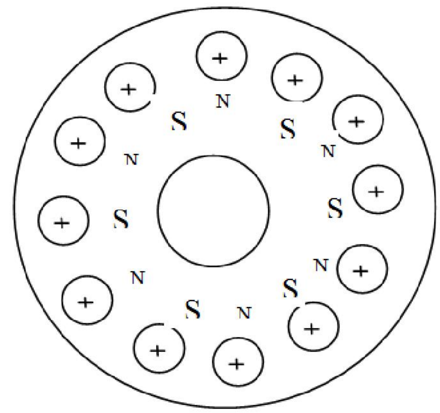

Figure 3: A Rotor Disc Carrying 12Magnets (Schematic)

3.2.2 The Stator

The stator carries 9 coils as shown iin figure 4 against the twelve magnets carried by each of the rotor discs. The coils are star connected.

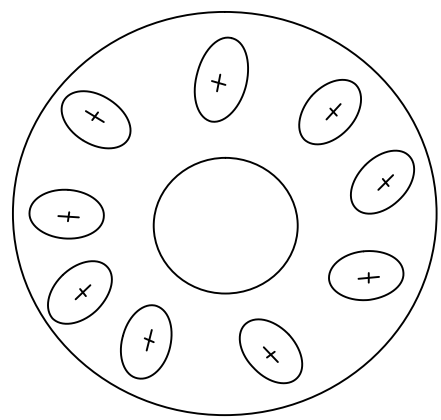

Figure 4: Stator Disc Carrying 9 Coils (Schematic)

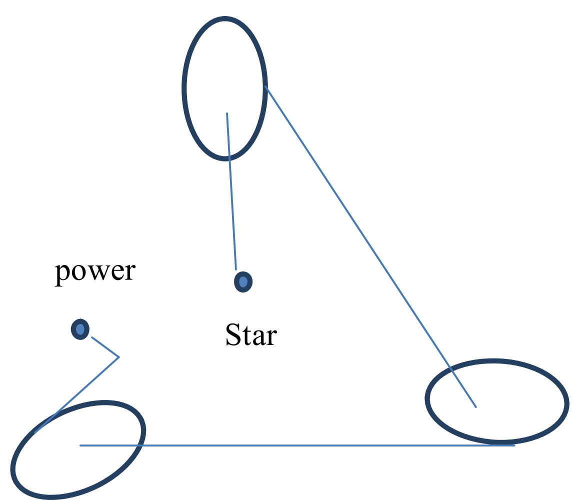

Figure 5: Single Phase Star Connection

Since there are only 9 coils, each phase in a three phase arrangement would connect three coils in series and the centreline of each coil will be displayed 40^o relative to the next one. The stator, since is stationary carries in addition, brackets for fixing it on the housing. Figure 5 shows the single phase star connection arrangemens. The three phase will be the single phase repeated three times but with the 3 star ends all connected together.

4. Discussion

Permanent magnet generators are generally lighter than wound stator machines for a given power rating and have better efficiencies because there are no field windings and field coil losses. Also, as the stator is provided with a permanent magnet pole system, it is resistant to the effects of possible dirt ingress. However, if not fully sealed, the permanent magnets will attract ferromagnetic dust and metallic swarf which may cause internal damage.

The permanent magnet generator is a good choice for small scale wind turbine systems as they are reliable, can operate at low rotational speeds and provide good efficiency especially in light wind conditions as the cut-in point is fairly low.

The voltage generated by a permanent magnet generator is determined by a number of factors including the magnetic field strength of the permanent magnet, the number of turns of the armature and the rotational speed of the armature. In the absence of commutating brushes and slip rings, the permanent magnet generator does not require regular maintenance as the other versions that carry carbon brushes which not only require regular replacement as they wear out but also have the tendency to produce electrically conductive carbon dust in the machine. Part of the simplicity in the design of the permanent magnet generator is the mounting of the turbine blades directly on the generator shaft without the complication of gearing and the associated losses. With brushless permanent magnet generator, there is no need for DC current excitation as in the synchronous machine. However, relatively speaking magnets are still quite expensive and to reduce the quantity required for a given design, the air gap between the two rotor plates is minimised for maximum efficiency and cost reduction. Although the permanent magnet design is simpler, more durable, it does not allow control of magnetic flux production hence excitation because the rotor flux attains its maximum efficiency at one pre-defined wind speed.

Safety is an issue in the handling of neodymium magnets because they are very strong and can cause serious personnel injuries. In assembling the generator, it is advisable to place a wooden wage on the rotor disc resting on the table with the magnets facing up as a precaution against the two discs carrying opposite magnetic poles jamming together and smashing personnel fingers. It is as well necessary to remove all sharp steal objects within the vicinity that the assembling is taking place. The neodymium magnets are very brittle that they will break by a simple knock or drop so it is necessary to handle with care. Ensure that two of the magnets never get near each other otherwise one may never pull them apart. If accidentally they glue together pulling them apart may not work the best bet would be to wring or twist them with luck they may come apart.

5. Conclusion

1. Permanent magnet wind turbine generator has been designed.
2. Preliminary bench test based on the singe phase built has been carried out and the results are promising.
3. As a cost reduction measure, the quantity of neodymium permanent magnet used has been significantly reduced by reducing the air gap to the barest minimum before the rotor discs start rubbing on the stator coils.

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