

# AN AXIAL-FLUX PERMANENT-MAGNET GENERATOR FOR A GEARLESS WIND ENERGY SYSTEM

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**Abstract**— The paper discusses the development of an axial-flux permanent-magnet generator for a gearless wind energy system which aims to demonstrate the feasibility of integrating wind and photovoltaic energy converters for the generation of electricity and to achieve optimum exploitation of the two energy sources. The merits of an axial-flux generator topology are discussed with reference to the particular requirements of an electrical generator for a direct-coupled wind turbine application. The design, construction and test results of a 5 kW, 200 rev/min permanent-magnet generator, to form a 10 kW pilot power plant in combination with a 5 kW photovoltaic array, are presented.

## I. INTRODUCTION

Wind turbines and solar energy make significant and increasing contributions to electric utility networks as the power generated is renewable and pollution-free. However, both sources are variable and either source alone cannot supply isolated loads unless a suitable storage battery is incorporated in the system. Integration of wind and photovoltaic sources, which are generally complementary, should reduce the net variation of input power and therefore also reduce the required size of storage battery. The proposed system configuration [1] comprises a direct-coupled, variable-speed wind turbine driving a 5 kW permanent-magnet generator, a 5 kW photovoltaic array, and a double-input, single-output power electronic interface which connects the generating units to the utility circuit and is operated to achieve optimum exploitation of the two energy sources.

Conventional generators for wind turbine systems operate best at high speed and require step-up gearboxes. However, the gearbox of a wind power plant is expensive, subject to vibration, noise and fatigue, and needs lubrication as well as maintenance at appreciable cost. In recent years the idea of a gearless wind energy system has gained momentum and a number of alternative concepts have been proposed for direct-coupled electrical generators for use in grid-connected wind turbines; some smaller stand-alone machines also use direct-coupled generators. Some direct-drive examples are:

- The Eole Darrius-type vertical-axis 4 MW turbine (91 m tall, 64 m equatorial diameter) using a direct-coupled hydro-type synchronous generator with wound poles (Canada).
- The Enercon E-40 500 kW grid-connected, direct-coupled, variable-speed machine using a radial-field, synchronous generator with wound poles (Germany).
- The small Marlec battery charging machines using an ironless-stator, axial-flux, permanent-magnet generator (UK).

Proposals for direct-coupled grid-connected generators include transverse-flux and radial flux permanent-magnet machines. In this paper, an axial-flux permanent-magnet generator named Torus [2] is presented for a direct-drive, variable-speed wind turbine application. The paper describes the perceived advantages of the Torus configuration and discusses the design characteristics of a 5kW, 200 rev/min, 28 pole machine. The results of experimental tests carried out on a prototype are given and evaluated, in comparison with predicted performance.

## II. THE TORUS CONFIGURATION

The Torus machine is a slotless, toroidal-stator, double-sided, axial-flux, disc-type, permanent-magnet, brushless machine. Fig. 1 shows the basic layout. A simple toroidal strip-wound laminated stator core carries a slotless toroidal winding which may have any chosen number of phases. The rotor comprises two mild steel discs, one on each side of the stator, carrying axially-polarised magnets. The active conductor lengths are the radial portions facing the magnets. It is seen that the machine effectively comprises two independent halves, lying either side of the radial centreline. The name Torus was adopted to indicate the toroidal nature of both the stator core and the stator winding. The salient features of the Torus machine can be summarised as follows:

- The topology of the machine leads to a short axial-length and thus to a high power-to-weight ratio and makes it possible to integrate the generator directly with the wind turbine to form a very compact generating set.

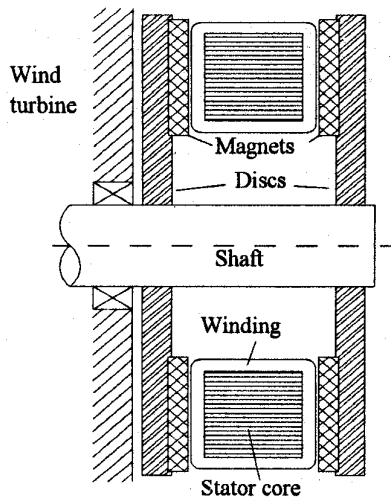


Fig. 1 Layout of Torus machine

- The disc rotors and magnets act naturally as fans, so good ventilation and cooling of the stator winding are achieved even at low rotational speed and hence the machine can operate with high electric loading.
- The slotless, air-gap winding gives low values of mutual and leakage inductances. The axially-directed end-winding lengths are relatively short, yielding low resistance. Hence, the voltage regulation under load is acceptable for the application.
- The absence of slots leads to a very low-noise machine with negligible cogging torque. Vibration and high-frequency rotor losses associated with stator slot openings are also eliminated.

The design of a Torus machine is characterised by the following principal parameters:

- Stator core outer and inner diameters
- Number of poles
- Magnet material and thickness
- Number of stator phases
- Number of turns per coil
- Conductor size

The remaining dimensions together with the electrical parameters follow from this set of design variables.

### III. GENERATOR DESIGN AND CONSTRUCTION

The overall specification for the generator, after rectification, was:

- Nominal power 5 kW
- Nominal speed 200 rev/min
- Nominal dc output voltage 150 V
- Nominal dc output current 33 A

The generator must fit within a nacelle of defined size. Analysis and design considerations of the Torus configuration have been reported previously [2]. Many alternative designs were studied using a computer program incorporating electric, magnetic and thermal models of the Torus configuration. The targets for the generator are based on the desire for low cost and high efficiency. The selected values of principal design details are given in Table I. Some aspects which were given special

TABLE I  
PRINCIPAL DESIGN DETAILS

Number of poles	28
Number of phases	3
Number of winding layers	4
Outer diameter of stator core	465 mm
Inner diameter of stator core	275 mm
Axial thickness of stator core	20 mm
Magnet material	Sintered Nd-Fe-B, Crumax 3714 $B_r$ : 1.25 T, $(BH)_{max}$ : 37 MGOe
Magnet thickness	12.7 mm
Magnet mass	15.8kg
Total machine mass	98.5kg

consideration in the prototype design are discussed briefly below.

#### *Permanent-magnet material*

Several types of permanent-magnet material have been used in electrical machines including Alnico metal alloys for pilot exciters for large turbine generators, ferrite for small low cost motors and rare-earth alloys such as  $\text{SmCo}_5$  and Nd-Fe-B used in compact high performance motors. For minimum cost, possible designs using ferrite magnets were investigated but no satisfactory solution was obtained within the diameter constraint. In order to meet the diameter restriction and the target for high efficiency, use of Nd-Fe-B magnets was found to be necessary.

#### *Pole number*

Where a d.c. output is required, as in the present case, the a.c. output of the generator is rectified so no particular frequency of machine emf is demanded. A high number of poles may therefore be chosen to give light-weight rotor and stator cores, leading to high power-to-weight ratio. Extremely high pole numbers are avoided because they give excessive leakage of magnet flux. After consideration of many alternatives, 28 poles were chosen which corresponds to an output frequency of 46Hz when the turbine speed is 200 rev/min.

#### *Winding layers*

For economy of construction, a low number of winding layers is preferred. The conductor size is restricted to limit eddy current losses in the air-gap winding.

Fig. 2 shows a rotor disc, utilising available sizes of rectangular magnets. The photograph in Fig. 3, taken during manufacture, illustrates the arrangement of the stator winding.

### IV. PERFORMANCE PREDICTION

Generator efficiency is determined by the power losses which include the following principal components:

- $I^2R$  loss in the stator winding
- Eddy current losses in the air-gap winding
- Iron loss in the stator core
- Friction and windage loss

The loss at low speed and intermediate power is important because the wind turbine spends only a small proportion of

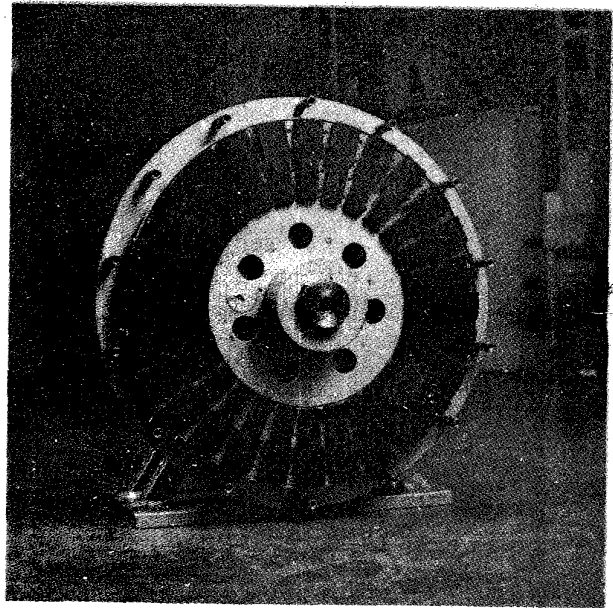


Fig. 2. Inner rotor of 5kW generator

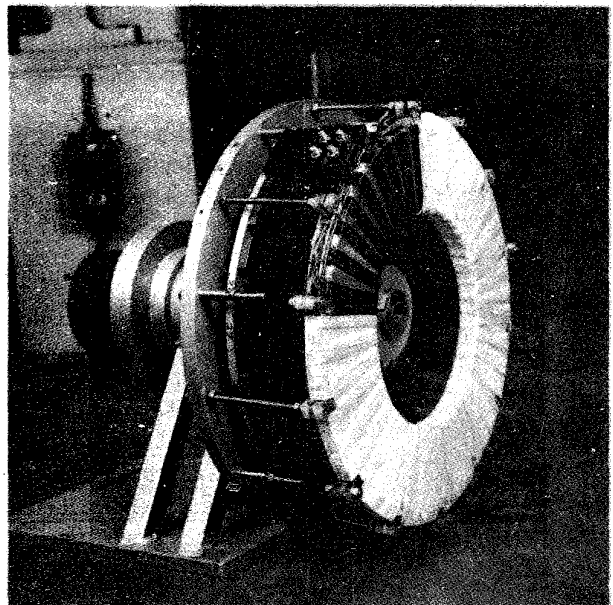


Fig. 3. Parts of the 5kW generator

its working life at full power. In the present system, however, reduced-speed operation at low power reduces the iron and other losses which are independent of load current thereby greatly improving the part-load efficiency.

**TABLE 2**  
**PREDICTED GENERATOR PERFORMANCE AT 200 REV/MIN**

Current, A	3.3	10	20	30	33.3	36.7	40
Voltage, V	180.8	176.0	167.9	157.2	152.5	146.9	140
Power output, W	603	1760	3359	4716	5084	5386	5600
$I^2R$ loss, W	9	82	356	926	1223	1603	2096
Eddy loss, W	12	11	11	9	9	8	7
Iron loss, W	91	91	91	91	91	91	91
Copper temp, °C	26.7	32.5	54.1	99.1	122.6	152.6	191.6
Efficiency, %	84.4	90.5	88.0	82.1	79.4	76.0	71.9

**TABLE 3**  
**EFFICIENCY AND POWER OVER THE SPEED RANGE**

Speed, rev/min	200	180	160	140	120	100	80	60
Shaft power, kW	6.41	4.67	3.28	2.20	1.38	0.80	0.41	0.173
Output power, kW	5.08	3.73	2.66	1.81	1.14	0.66	0.33	0.129
Efficiency, %	79.3	79.8	81.1	82.1	82.6	82.3	80.7	74.5

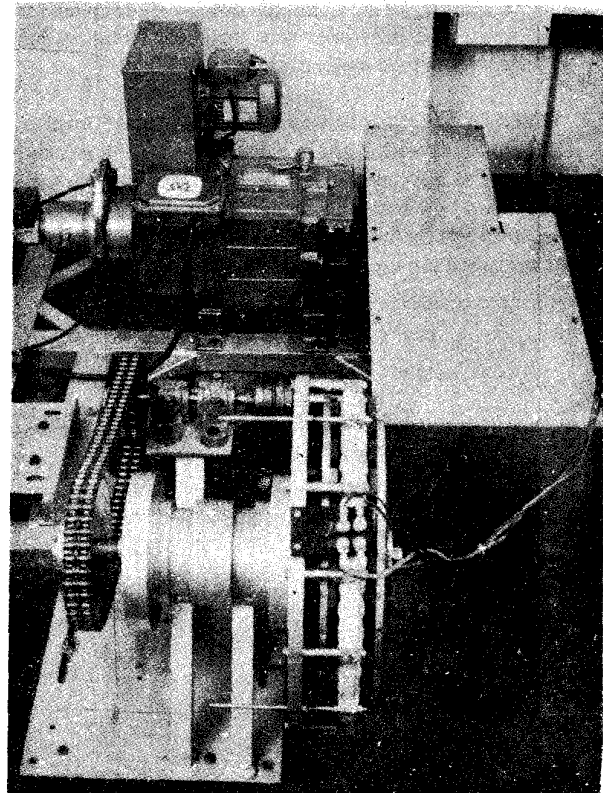
The eddy current loss is proportional to speed<sup>2</sup>, flux density<sup>2</sup> and wire diameter<sup>2</sup>. At reduced power, the eddy current loss becomes relatively more important, but in the proposed design it is small because thin wire is used for the winding. Iron loss varies approximately in proportion to speed. Rectifier loss is proportional to the dc current and hence to speed<sup>2</sup>. Being a direct-coupled, low-speed machine, the windage and friction losses are very small.

The system permits variable-speed operation with shaft power proportional to speed<sup>3</sup>. The generated voltage is proportional to speed and so the current is proportional to speed<sup>2</sup> and the  $I^2R$  loss is proportional to speed<sup>4</sup>. At low speed the  $I^2R$  loss is therefore less important. Losses also determine the winding temperature. Class-H materials are now standard and permit operation at up to 180°C. High loss could be tolerated but would conflict with the need for high efficiency. The prediction program incorporates a comprehensive lumped-parameter thermal resistance model to derive winding temperature from predicted loss.

Table 2 gives the computed generator performance at the nominal speed of 200 rev / min, with 20°C ambient temperature.

Table 3 gives the computed power and efficiency over the operating speed range, taking into account the wind turbine characteristic and the variations of loss components.

## V. TEST RESULTS AND EVALUATION



**Fig.4. Generator test rig.**

Fig. 4 shows the test rig in which the Torus generator was driven by a d.c. motor through three stages of speed reduction. The first two stages used belt drives, but, owing to the high torque at the generator shaft, it was found necessary to change to a chain drive in the final stage in order to avoid excessive belt slip. Torque was measured by a transducer between the second belt drive and the chain drive.

The attractive force exerted by one magnet disc upon the stator during assembly was very large, being approximately 10kN. This necessitated special attention to mechanical design details and a carefully controlled assembly procedure using jacking screws. Adequate stiffness was essential to maintain an air-gap clearance of 1.5mm between the faces of the winding and the rotors.

In open-circuit tests the waveshapes of emf in a single-turn search coil wound around the stator core, and also of the stator phase and line voltages (Fig. 5), were shown to be very close to sinusoidal. Harmonic analysis of the line voltage waveform showed that the largest harmonic component, which was the fifth harmonic, was as low as 0.6%. This result was different to previous Torus machines [2] in which trapezoidal magnets with constant angular width were used to obtain trapezoidal emf waveform. The difference was attributed to the variable angular width of the magnets, as seen in Fig. 2.

Generator performance was measured when driven at 200 rev/min, firstly with 3-phase resistive load. The measured efficiency at 5kW output was 83.9% which is regarded as good for a low-speed machine. This figure is slightly pessimistic as the losses in the chain drive are included in the measured input power.

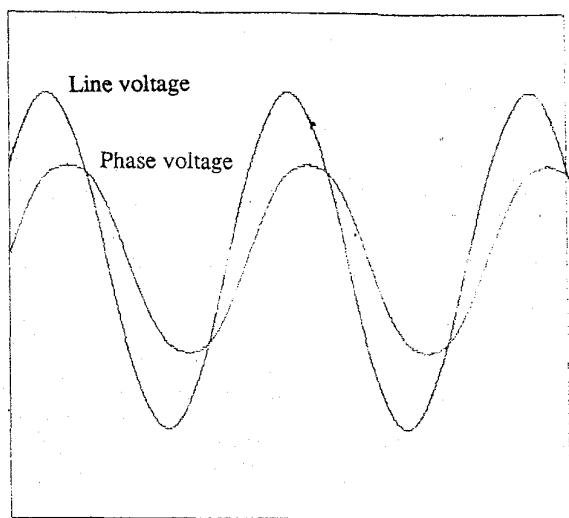


Fig. 5. Open-circuit voltage waveshapes

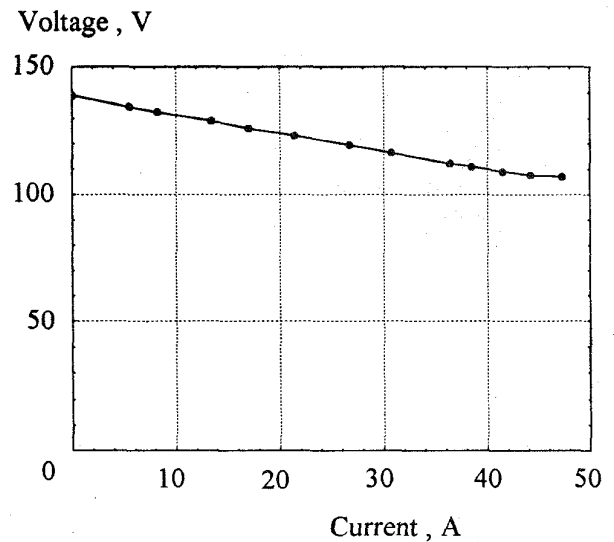


Fig. 6. Measured d.c. voltage regulation characteristic with resistive load

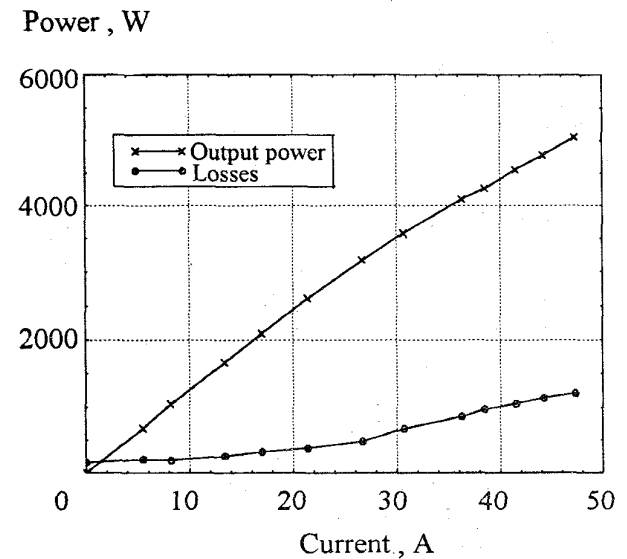


Fig. 7. Measured variations of d.c. output power and losses with resistive load

Figs. 6 and 7 give the measured performance with output via a diode bridge rectifier to a resistive load. The d.c. output voltages were 139V on no-load and 107V on rated 5kW load. These were less than the predicted values shown in Table 2, for the following reasons:

- the sinusoidal emf waveshape yields lower d.c. voltage than the trapezoidal emf waveshape which was assumed at the design prediction stage.
- the average remanence of the delivered magnets was 1.17T which was less than the specified value of 1.25T which was assumed at the design stage.
- the effective air-gap length was increased because the actual winding thickness of 5.9mm was greater than the original designed value of 4.4mm.

The reduced value of output voltage required increased current (47A) at the rated output power. However, the measured efficiency was 80.7% at this point, exceeding the design prediction of 79.4% even though the latter figure did not include losses in the rectifier and chain drive. This improvement was attributed to the observed sinusoidal waveshape of induced emf which produced a winding current with better form factor. Fig. 8 illustrates the waveforms of phase voltage and phase current.

## VI. CONCLUSION

The prototype machine described in the paper is, to the best of the authors' knowledge, the largest of this configuration which has yet been constructed. Despite a number of practical difficulties, mainly of a

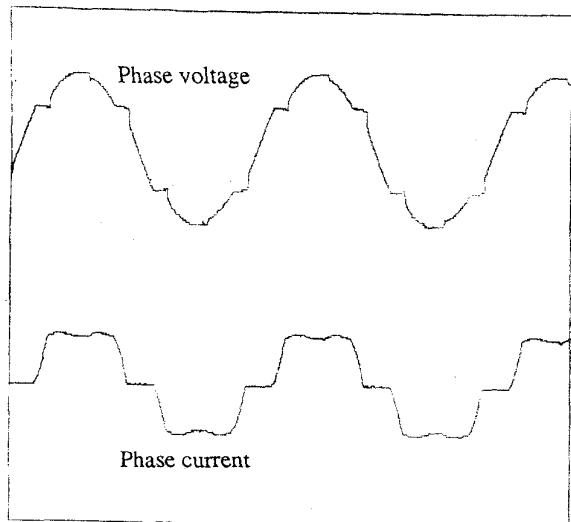


Fig. 8. Waveshapes of voltage and current in a phase winding with rectified output to resistive load.

mechanical nature, the measured performance of the prototype 5kW, 200 rev/min Torus generator was very good. Deviations from the predicted performance were explained in terms of variations of design details.

## VII. ACKNOWLEDGMENTS

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## APPENDIX

### Consideration of Axial Force

A critical feature in large Torus machines is the axial force between the stator and each rotor disc. The force is unbalanced during assembly and may create mechanical instability in operation unless the bearings and mechanical supports are adequately stiff. It is therefore interesting to consider how a design may be modified to alleviate the axial force whilst still delivering the specified torque with tolerable power loss.

Assuming sinusoidally-distributed flux density  $B$  and electric loading  $J$ , torque is given by

$$T = \pi J R_1 (R_2^2 - R_1^2) B \quad (1)$$

and the axial force between the stator and one rotor disc is

$$F = \pi (R_2^2 - R_1^2) B^2 / 4 \mu_0 \quad (2)$$

where  $B$  and  $J$  are peak values and  $R_1$  and  $R_2$  are respectively the inner and outer radii of the stator core.

$$\text{Hence } F = (B/R_1 J 4 \mu_0) T \quad (3)$$

This indicates that a machine with large diameter, low flux density and high electric loading is preferable when axial force is a critical parameter. The copper loss in the

active part of the stator winding is the largest component of loss and is given by

$$P = 2\pi\rho J^2 R_1(R_2 - R_1)/w \quad (4)$$

where  $\rho$  is the effective resistivity of the winding taken over the complete winding thickness  $w$ . Combining equations (1), (2) and (4) yields

$$P = \rho T^2 / (2\mu_0 w R_1 F) \quad (5)$$

Clearly, a compromise has to be reached between size reduction and loss reduction. A large diameter and a thick stator winding offer advantages but increased size may not be mechanically acceptable. A preferred approach for large outputs may be a multistack arrangement.