

Research Report

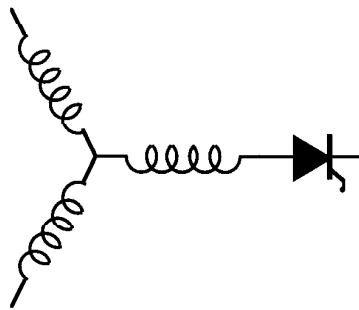
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**Design and Construction of a Permanent Magnet
Axial Flux Synchronous Generator**

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Abstract.- This paper presents the design characteristics, special features, and manufacturing aspects of a permanent magnet axial flux synchronous generator. This machine is aimed for applications in the low power low speed range (5 kVA, 500 rpm). A central stator configuration is selected for the construction of the axial flux generator, so that the stator leakage inductance is significantly reduced.

I. INTRODUCTION

Electric generators using axial flux configuration were developed almost 150 years ago. However, their applications have always been limited to fractional power due to the construction difficulties, specially the heat dissipation from the armature windings [1]-[3]. However, compared to traditional machines using radial flux distribution, axial flux generators present the following advantages:

- i) Better efficiency.
- ii) They operate with similar magnetic flux density in all the magnetic circuit, which translates in a better utilization factor of the magnetic core. Also, the axial flux construction takes advantage of the anisotropic characteristic of the oriented grain silicon iron [4].
- iii) Axial flux configuration allows the construction of compact electric generators with a large number of poles (low rated frequency).

So far no significant effort has been done to develop axial flux permanent magnet synchronous generator for operation in micro-generating systems. In this paper, a complete design procedure for such electric machine is developed and the manufacturing aspects for the construction of a 5 kVA 500 rpm, 50 Hz prototype is shown. The innovative aspects of the axial flux synchronous generator presented in this paper are the following:

- i) The bulk and the lateral covers of the generator are made with a non ferromagnetic alloy. This reduces the stator leakage inductance and the corresponding magnetic losses. A bronze-aluminum material is used (90% copper and 10% aluminum), since this material is more resistant and lighter than the traditional bronze. Also, the bronze-aluminum is easier to cast in induction or Morgan furnaces.

- ii) Preliminary studies have shown that the efficiency improvement of the axial flux generator is around 5%.

Moreover, due to the absence of the increasing speed mechanism, the overall system efficiency of the micro-generating station increases between 20 and 50%.

- iii) Permanent rare earth magnets (neodymium-iron-boron) are used in order to avoid the slip rings to supply the field rotor windings. This allows the construction of shielded and more compact units.

It is important to emphasize that even though small units of axial flux generators have been implemented and reported in the technical literature [1], they are inadequate for industrial applications. The principal problems of such prototypes dealt with the reduced number of poles which results in larger stator windings making impossible the construction of power shielded units. The design of axial flux generators with a larger number of poles for applications in micro-generating systems represents a new technological development and design of these machines.

II. GENERAL DESCRIPTION OF THE GENERATOR

For the construction of the axial flux generator a two airgap central stator configuration was chosen in order to cancel the longitudinal forces over the rotor pieces.

In Fig. 1 the central stator topology of the generator is shown. The permanent magnets are embedded in the rotor lateral pieces mounted on the shaft. A yoke of silicon iron sheets closes the magnetic circuit by the back side of the magnets.

The stator is composed by teeth formed by stacks of silicon iron sheets arranged in radial form in which the three-phase

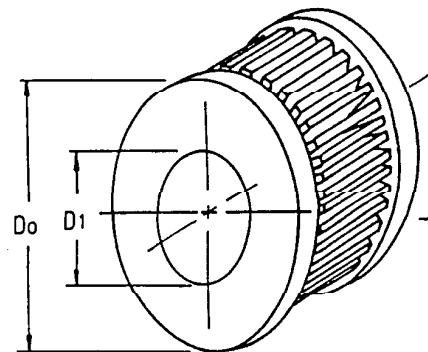


Figure 1: Topology of the Axial Flux Generator

winding is housed. These teeth are fixed by two bronze disks in their ends, this geometry allows to obtain "open" slots with low leakage reactances and minimal losses of material at the moment of the pattern-making. Moreover, a skewing of the teeth with one slot pitch is considered in order to avoid the cogging torque.

A. Windings

The stator windings must fulfill the following requirements:

- Avoid wire crossing specially in the external part of the end winding.
- Reach the best copper utilization factor in the slots.
- Obtain a sinusoidal distribution of the mmf in order to avoid torque pulsations.
- The winding factor has to be high enough so that the rated power of the generator is not reduced.

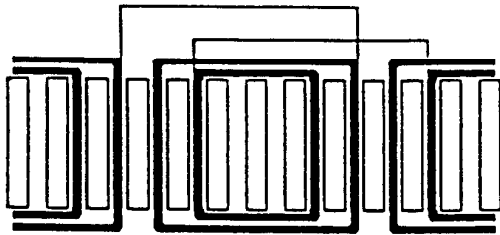


Figure 2: Linear representation of the windings

The construction of two concentric windings as shown in Fig. 2 satisfies most of the above requirements. The mmf generated by the winding can be expressed by the Fourier series:

$$mmf(x) = \sum_{n=1,3,\dots}^{\infty} b_n \sin(nx) \quad (1)$$

For a maximum value of mmf(x) equals to 1 the Fourier coefficients are shown in Table I.

TABLE I
FOURIER COEFFICIENTS OF THE MMF PRODUCED BY A PHASE WINDING

n	b _n	n	b _n	n	b _n
1	1.065	9	0	17	0.017
3	0	11	-0.097	19	-0.015
5	-0.057	13	-0.82	21	-0
7	0.041	15	0	23	0.046

The winding factors for the fundamental component of the mmf are defined by the following expressions:

$$f_1 = \frac{\sin(q\alpha_r / z)}{q\sin(q\alpha_r / z)} \quad \text{and} \quad f_2 = \sin\left(\frac{y}{\tau} 90^\circ\right)$$

where:

- f₁ is the distribution factor
- f₂ is the pitch factor
- q = 2 number of slots per phase and per pole
- α_r = 30° electrical degrees corresponding to one slot
- y = 4 coil span in number of slots
- τ = 6 polar pitch in number of slots

In this case f₁ = 0.966 and f₂ = 0.866. These factors were calculated for a two layer winding corresponding to the conventional generator. Finally the winding factor (f₃) is given by:

$$f_3 = f_1 \cdot f_2 = \frac{\pi}{4} b_1 = 0.8365$$

It must be noticed that the winding does not generate a third harmonic and that the fifth and seventh harmonic components are small. Thus the flux distribution results almost sinusoidal since the dominant reluctance harmonic generated by the slot (due to the saliency of the stator teeth) is the sixth. When the reluctance harmonic and the harmonic component generated by the winding have the same frequency the cogging torque increases.

Figure 2 shows that the copper wire occupies about 2/3 the space of the slots which results in an utilization factor equals to 0.46 for wire with circular cross section and 0.60 for wire with square cross section. In conventional generators the winding utilization factor is in the range of 0.50 to 0.55 for wires with circular cross section.

B. Electromagnetic Design

The magnetic circuit corresponding to a pair of poles is formed by the teeth of the stator, two airgaps, four permanent magnets and two rotor yokes.

The determination of the permanent magnet width was done by using traditional electromagnetic calculations. Also the rotating field power was maximized, which results in equal cross sections of teeth and slots.

III. CONFIGURATION OF THE AXIAL FLUX GENERATOR WITH PERMANENT MAGNETS

Figure 3 shows the general drawing of the prototype. The principal parts of the generator are the followings:

- | | |
|--------------------------|-------------------------|
| 1. Bulk of the generator | 6. Bearing |
| 2. Lateral cover | 7. Shaft |
| 3. Permanent magnets | 8. Holding stator disk |
| 4. Rotor yoke | 9. Stator teeth |
| 5. Rotor lateral piece | 10. Stator holding ring |

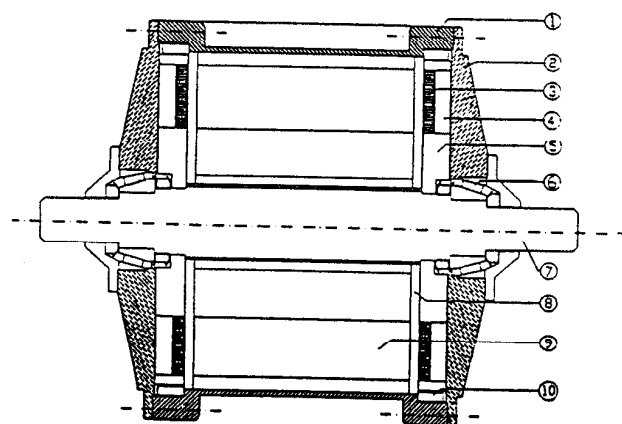


Figure 3: Configuration of the axial flux generator

IV. CONSTRUCTIVE ASPECTS OF THE AXIAL FLUX GENERATOR

Figure 4 shows a photograph of the generator stator. The three phase winding is formed by six sections of molded coils in this way one phase is formed by two sections connected in series. The general connection procedure is "abcabc", which equalizes the leakage inductances.

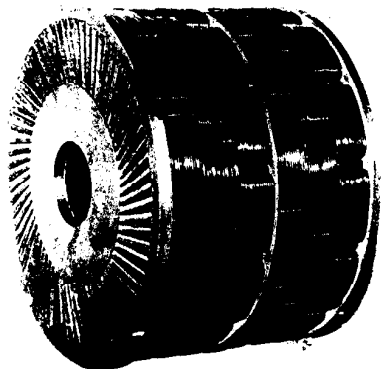


Figure 4: Stator of the generator with windings

The use of permanent magnets allows the shielded construction of the machine. Also reduces its longitudinal size. Figure 5 shows the external aspect of the permanent magnet axial flux generator (external diameter: 36 cm, length of the frame: 45 cm)

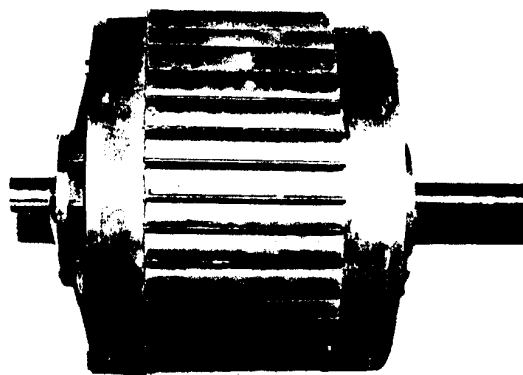


Figure 5: Permanent magnet axial flux generator

V. CONCLUSIONS

The paper presented the design characteristics of an axial flux generator with central stator rated 5 kVA, 500 rpm, 50 Hz. The excitation system consists of Nd-Fe-B permanent magnets, so a high power density is obtained.

Efficiency of the generator is about 96 % and the use of bronze in its construction improves the heat dissipation (the frame was constructed of a non-ferromagnetic alloy due that the internal part of the bulk is close to the end turns of the stator windings). Also the use of bronze presents a good mechanical rigidity and corrosion resistance.

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