

Permanent magnet axial-flux generator with toroidal winding

Ants Kallaste, Aleksander Kilk
Tallinn University of Technology
Ants.Kallaste@ttu.ee, Kilk@cc.ttu.ee

Abstract

This paper analyzes of toroidal winding permanent magnet axial-flux wind generator. Special attention is paid on peculiarities and output characteristics. The experimental generator has been designed and constructed on the base of this construction approach. Testing experimental generator allows to compare test result with simplified calculation method and is also possible to optimize the permanent magnet generator construction

Keywords

Generator, permanent magnet, axial-flux, toroidal winding, calculation method

Introduction

Permanent magnet (PM) machines have been replacing other types of electrical machines in many places. Higher reliability of PM materials, their higher energy density, their greater corrosion resistance and the demagnetizing influence are the main causes of developing PM generators. New PM materials are also less sensitive to temperature changes. In recent years contemporary power electronics of high efficiency, high reliability and decreasing cost offers the possibility to change the output voltage and frequency of the generator to match the system needs.

The main requirements for wind-generators designing are as follows:

- Simple construction
- Light weight
- Low speed
- High output power
- Variable-speed generation
- Low cost.

For changing wind energy to electrical energy, different PM generator construction solutions are analyzed. In addition to some construction solutions similar to classical hydro- and turbo-generators, which are working on radial fields in air-gap, also axial flux machines are used [1]. Generator constructions may also differ in winding and magnet arrangement.

The construction idea of the PM generator in this paper bases on the axial flux machine analysis [2]. As the construction of the machine seemed to be

very complicated and difficult to produce, a different solution with toroidal winding was researched. The main requirements for the new solution were: simple construction and ability to function as a directly driven wind-generator. It was also important to get sinusoidal voltage and current waveforms. To meet these requirements, the flux density surrounding the active parts of winding must change according to cosine dependency. Based on these principals and ideas the authors designed in 2003 a new generator, where 2 stators and 1 rotor are used in every phase. According to a patent research, carried out by authors in 2005, the generator construction was not actually a new solution, because a similar idea was described before [3].

1 Machine overview

The generator has a sandwich-type construction. There is a rotor placed between two identical stators and phases are arranged on a shaft next to each other. The phases are identical and independent. On a figure 1 can be seen one phase active parts.

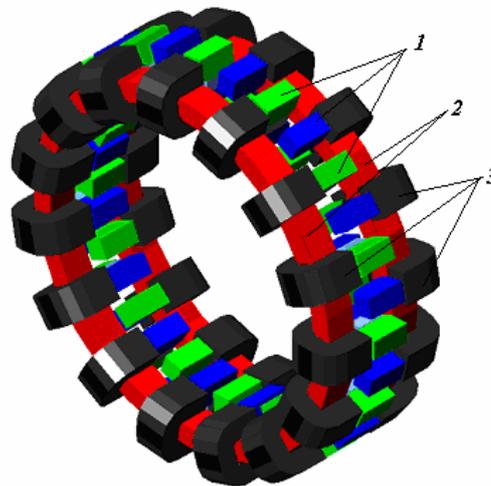


Fig.1. One phase active parts of a generator. 1 – rotor poles, 2 – torus winding, 3 – U-shape magnetic core

Every generator phase has two identical stators and one rotor between them. On the stator there are 15 U-shaped magnet cores. The central parts of the magnetic cores form slots for torus-windings. Magnet cores are placed symmetrically on the axial end surface of stator. Every central part of the U-shaped cores forms one elementary slot. The positions of the magnet cores of the first and second

stator are not identical – the magnet cores of the first stator are shifted by one core-width step compared to the cores of the second stator. Every stator has one or more torus-winding(s) in its slots.

Active part of a rotor consists of permanent magnets and rotor poles. NdFeB permanent magnets are placed between rotor poles. Rotor poles direct magnet fields through the air-gap from rotor to stator. There are 30 rotor poles symmetrically fixed to the rotor disc, and for every stator slot there is one pair of poles. Rotor disc has to be made of diamagnetic and preferably non-conductive material. Around the perimeter of the rotor the direction of magnetic flux in the one rotor pole is opposite of the flux direction in the next rotor pole. For example: NS, then SN, and then NS etc (Fig. 3). This type of construction enables magnetic flux around the elementary slots change according to cosine function.

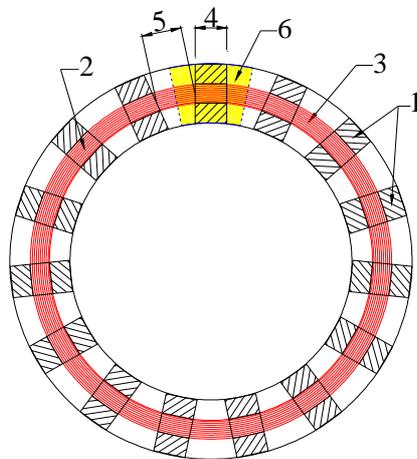


Fig.2. Active part of a stator consisting of 15 elementary stator zones, 1 – U-shaped magnetic core, 2 – stator slot, 3 – torus-winding, 4 – active part of a winding, 5 – passive part of a winding, 6 – elementary stator zone

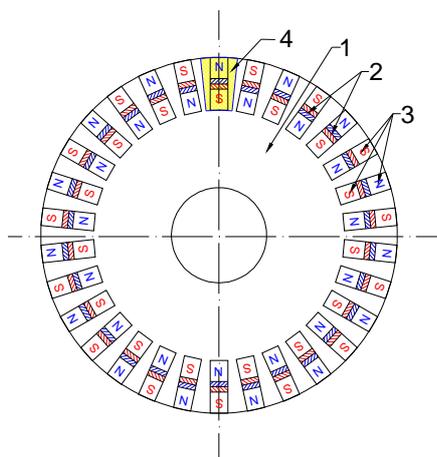


Figure 3. Rotor: 1 – rotor disc, 2 – permanent magnets, 3 – rotor poles, 4 – elementary rotor

2 Operating principles

The permanent magnets on the rotor are used to create an activating field for changing mechanical energy to electrical energy. The magnetic flux of the

permanent magnet (Figure 4) goes through a closed contour, what is formed by:

- 2 pairs of rotor poles,
- The permanent magnet of the rotor,
- 2 air gaps,
- A magnetic core of the stator

The active part of the stator is formed by a U-shaped magnetic core and a torous winding, what is placed in a slot.

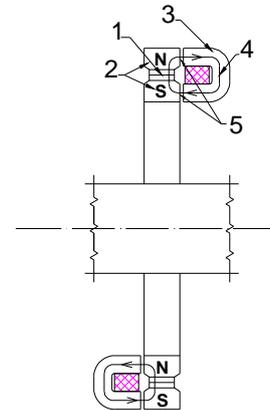


Fig. 4. Fragment of the active part of the generator. 1 – PM, 2 – rotor poles, 3 – stator core, 4 – magnetic flux, 5 – air gap

Figure 5 explains the operating principles of the generator. If the rotor is rotating to the direction indicated in Fig. 5 with speed ω , then the flux density value in the closed magnetic circuit will change. When the active parts of the rotor and the stator are in parallel positions, then the magnetic flux value is in its peak level. The magnetic flux value decreases to zero, when the pairs of rotor poles move forward by a half the width of an active part of the stator. If the pairs of rotor poles move further from this location, the magnetic flux will change its direction. The magnetic flux will be maximized again, when the active parts will reach new parallel positions, and all the process will be repeated. The faster the rotor rotates, the faster the magnetic flux changes and the higher will be the value of induced electromotive force (EMF) amplitude.

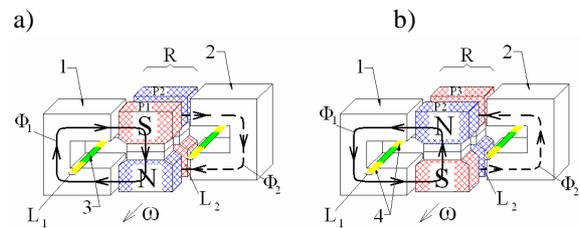


Fig. 5. Fragments of active generator parts describing the direction change of the rotor magnetic flux: a – direction of magnetic flux on first and second elementary generator at starting position; b) direction of magnetic flux after rotor has turned by one pole step (3 – active winding, 2 – end winding).

3 Generator analysis

The analysis of the generator was performed to find the best calculation method. The steady-state analysis was performed as first step to get the first cut of design criteria. Magnetic equivalent circuit was first used for magnetic analyses. The finite-element analysis was performed to refine the magnetic analysis. Finally, a dynamic analysis was performed in the laboratory to validate generator performance under dynamic condition.

A three-phase PM generator consists of three identical single-phase generators. Every single-phase generator consists of one rotor and two identical stators. Each stator consists of z elementary stator and each rotor of $2z$ elementary rotor zones. For example: if one stator of a three-phase generator equals $z = 15$ elementary stators and one rotor equals $2z = 30$ elementary rotors, then a single-phase generator consists of 30 generator sections (let's name them elementary generators), and a three-phase generator consists of $3 \times 2z = 6z$ identical elementary generators. In our example it means, that the generator consists of $6z = 6 \times 15 = 90$ elementary generators.

The explanation of the nominal characteristics of the elementary generator is as follows. Let the nominal power of a three-phase generator be 9 kW. Then the calculation of the generator will be identical to a calculation of a $9000 \text{ W} : 90 = 100 \text{ W}$ elementary generator. According to that, in case the power equals to 100 W, nominal current $I_n = 10 \text{ A}$ and there are $N = 10$ elementary wires, the nominal voltage of an elementary wire is $U_{ne} = 1 \text{ V}$. Nominal voltage of a stator winding of the described generator equals:

$$U_n = z \cdot U_{ne} \cdot N = 15 \cdot 1 \cdot 10 = 150 \text{ V}$$

To find out the induced EMF into windings, we have to calculate the maximum flux density in the air-gap. The maximum flux density depends on the demagnetization characteristic of the permanent magnet (given by the remanence flux density B_r and the coercive force H_c , and by the geometry of the air-gap). The quality of the permanent magnet can be estimated by the value of B_r multiplied by H_c . The higher the $B_r \times H_c$ value is the higher is the energy product of the permanent magnet. The air-gap between the magnet poles decreases the flux density compared to the remanence flux density in a closed magnetic circuit

To analyze the magnetic circuit, the finite-element method was used to compute the flux density in the generator components. The main purpose is to get the overall picture of the leakage flux and saturation level in different parts of the generator, the iron losses in the components of the generator, and the worst case of demagnetization on the permanent magnet.

From generator magnetic field analyses was found that it is not enough to study only two dimensional magnetic fields because of leakage flux in third dimension. Three dimensional analyse result can be

seen on figure 7. The figure 7 is for generator with 1 mm air gap.

The distribution of magnetic flux density in air gap (1 mm) between rotor and stator pole is represented in the Figure 8

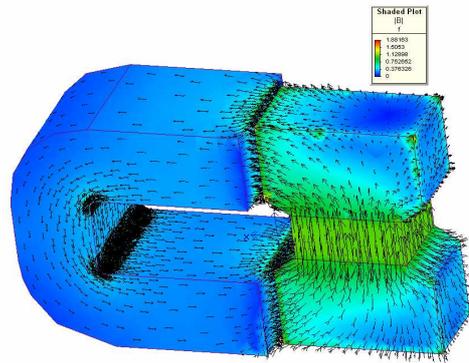


Fig.7. Flux density on the surface of elementary generator

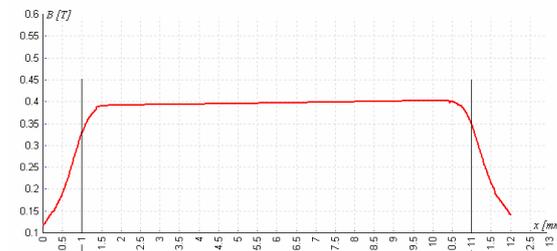


Fig.8. Distribution of magnetic flux density in air-gap of generator

From magnetic analyse was found that the leakage flux forms quite a considerable part of the flux and it depends on the air gap. Dependence is presented on the figure 9.

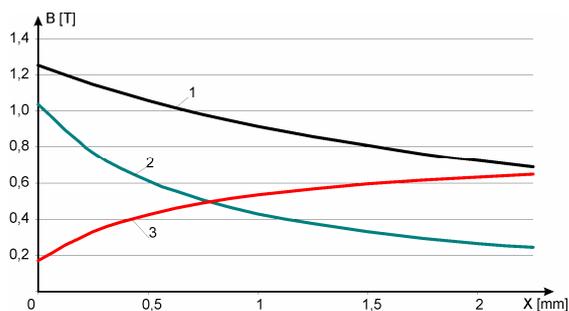


Fig.9. Air gap flux density dependence on air gap with 1– flux density without leakage, 2– flux density with leakage, 3 – leakage flux

The simplified equivalent circuit of the winding is described in Fig. 8. The equivalent circuit of the generator consists of:

- E – the induced EMF,
- r – the resistance,
- x_σ – the leakage reactance,
- x_s – equivalent reactance.

Load consists of impedance Z_l and series-compensating capacitor x_c . The vector diagram of the equivalent circuit is on the Fig. 10. The active and reactive resistances of armature reaction are not described on the equivalent circuit.

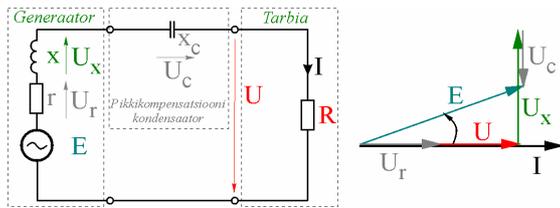


Fig.10. Simplified equivalent circuit of the generator with series-compensating capacitor (a) and vector diagram (b)

4 Experimental study of generator

The experimental model of a PM generator with torus-windings was built and tested (figure 11). The purpose of the experiment was to study and analyze both the electromagnetic processes as well as the main operating characteristics of the PM generator. As an aim of experimental study it was to compare the experimental data with the results of design and calculation. It was not our intention to optimize construction of the PM generator.

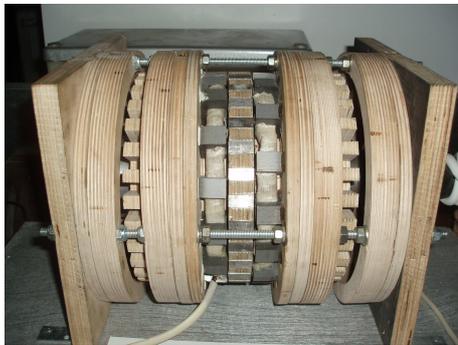


Fig.11. Picture of experimental model generator

We tested the generator in some different load conditions to analyze the influence of load character to the load characteristics of the PM generator. The generator was driven by asynchronous machine, what was fed via a frequency converter. The open circuit voltage waveform was captured with the scope (Fig. 12). We can see on the Fig. 12 that the waveform is quite similar to the sine wave and the total harmonic distortion THD is relatively low.

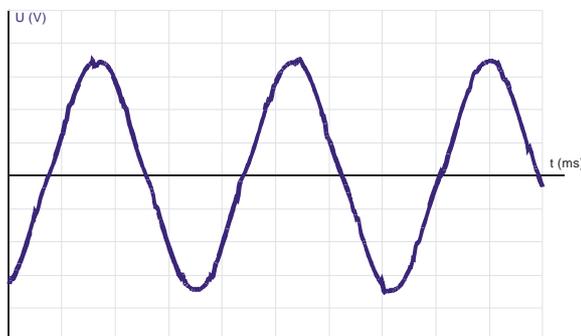


Fig.12. The open circuit voltage waveform, if the air-gap is 2 mm and the frequency 50 Hz

The load characteristic of the voltage-current of the generator is quite soft. End-windings of the generator are relatively long, making the inductance of the torus-windings relatively high. To compensate the inductance of the generator winding, when it was loaded, we added a capacitor to the resistive load. The capacitor gave us much better external characteristic. Voltage-current characteristic with the inductance of the generator compensated by the capacitor is presented on Fig. 13.

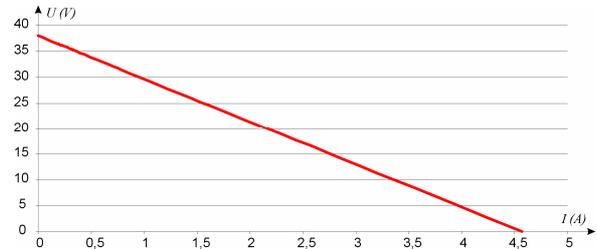


Fig.13. The voltage-current load characteristic with the inductance of the generator compensated by the capacitor

5 Conclusion

On the basis of the experiment the constructional solution of the axial flux PM wind generator with U-shaped magnetic cores and torus-windings was tested and analyzed. A mathematical methods of the PM generator analyzes were studied and the results were compared with experimental data. Different between mathematical method and experimental result was small. Also this type of generator has relatively high flux leakage it has very simple construction.

References

1. PEETERS, E., VAN TICHELEN, P. Design Considerations of an Axial Flux Permanent Magnet Machine with U-Shaped Stator, EPE-PEMC 2002, Cavtat&Dubrovnik, Croatia, CD, 2002.
2. WEH, H., MAY, H. Achievable Force Densities for Permanent Magnet Exited Machines in New Configurations, Proc. of ICEM, 1986.
3. MULJADI, E., BUTTERFIELD, C. P., WAN, Y. Axial-Flux modular Permanent-Magnet Generator with a Toroidal Winding for Wind-Turbine Applications. IEEE Transactions on Industry Applications, Vol. 35, No 4, July/August 1999.