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Performance Comparision of Internal and External Rotor Structured Wind Generators Mounted from Same Permanent Magnets on Same Geometry

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Introduction

In order to convert wind power into electricity, many types of generator concepts have been proposed and used [1]. Most of the low speed wind turbine generators presented are permanent-magnet (PM) machines. These have advantages of high efficiency and reliability, since there is no need of external excitation and conductor losses are removed from the rotor [2, 3].

Recent studies show a great demand for small to medium rating (up to 20 *kW*) wind generators for stand-alone generation-battery systems in remote areas. The type of generator for this application is required to be compact and light so that the generators can be conveniently installed at the top of the towers and directly coupled to the wind turbines.

Compared to a conventional, gearbox coupled wind turbine generator, directly coupled generators has a series of advantages, such as a much reduced size of the overall system, a rather low installation and maintenance cost, flexible control method, quick response to the wind fluctuation and load variations, etc. However, a directly coupled generator needs to have a very low-speed operation to match the wind turbine speed and, at the same time, to produce electricity in a normal frequency range (10-60 *Hz*).

Potentially, permanent magnet (PM) generators offer a high efficiency in operation and a simple and robust structure in construction because no field current and winding are used [4–6]. Basically, radial-flux PM generators can be divided into internal and external machines, according to rotor direction in the air gap. The availability of modern high energy density magnet materials, such as NdFeB, has made it possible to design special topologies [1, 2]. The machine topologies considered in this study include the conventional internal rotor radial-flux construction, external rotor radial-flux construction; the two machine structures compared are built with surface mounted magnets by applying the same NdFeB.

The criterias used for comparison are torque density, vigorous material weight, outer radius, total length, total volume, generated power and efficiency. These criterias are identified as being critical for the efficient deployment of generators in wind turbines. The basis for the comparison is highlighted to make the comparison fair and reasonable. The design equations are based on finite element analysis and verified by Ansoft *Maxwell* and *Rmxprt* softwares.

Permanent magnet materials

The properties of PM materials have got great influence on the performance of PM machines. These are used for excitation in machines for the application ranging from robotics to standard commercial drive to energy generating systems.

PM machines have various advantages such as high efficiency and power factor, high torque to weight ratio, brushless construction etc. It is equally important to know that which type of design and configuration is used in an electrical machine. The application requirement decides the type of PM material used due to cost, size and weight. It is very important to consider operating temperature range, external demagnetizing field, weight constraint and space limitation at design stage itself. Commercial type PM motors use ceramic or polymer–bonded neodymium–ironboron magnets.

The two machines compared in this study are three phase PM generators which use the same number of pole pairs, PM geometry and characteristic for direct drive wind turbine applications. Fig. 1 illustrates the permanent magnet geometry. Table 1 determines the electrical parameters obtained for permanent magnet to be used in both internal and external generator types.

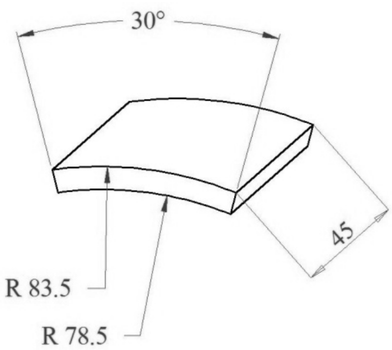

Fig. 1. Permanent magnets' geometry (measures in mm)

Table 1. Permanent Magnets' electrical parameters

Number of pole pairs:	5
Residual flux density (Tesla):	1.23
Coercive force (kA/m):	890
Maximum energy density (kJ/m^3):	273.67
Relative recoil permeability:	1.09981
Demagnetized flux density (Tesla):	0.0888
Recoil residual flux density (Tesla):	1.23
Recoil coercive force (kA/m):	890

For high performance motors, where the size and weight constraints are present, there sintered rare earth magnets are used. In applications, where the motor or generator is exposed to extreme environment, Alnico is preferred in these machines.

The use of Nd–Fe–B based PM material makes it possible to design and develop an electrical machine of any size excited by fully or partially by these permanent magnets. Alnico magnets can carry flux densities equivalent to soft magnetic irons but they are easily demagnetized due to lower values of coercive force as compared to ceramic magnets. Ceramic magnets are cheap but limited by low maximum energy density product.

It is due to lower values of retentivity. Rare earth PM materials such as samarium cobalt alloys have relatively more desirable magnetic properties, but these are expensive. Except the polymer bonded rare earth magnets, ferrites and cobalt based metallic magnets are physically hard and brittle. Its applications are specific to select the particular PM material but recent trends are to use Nd-Fe-B rare earth magnets due to its highest energy density and residual flux density amongst available PM materials [7-11]

Compared machine structures

Radial-flux PM Generator with Internal Rotor. This is a kind of typical radial-flux generator, as shown in Fig. 2, with the permanent magnet poles rotating inside the stationary armature windings. The stator is made up of electrical grade steel laminations with distributed windings. The rotor is cylindrical in shape with a shaft on which the bearings are mounted.

There are two magnets providing the MMF required in a pair of poles, which can effectively resist the demagnetization caused by the armature reaction in a sudden short circuit. The air-gap flux density is closely related to the magnet remanence and the magnet working point. It is difficult to get high air-gap flux densities with low remanence magnets in this configuration [12]. Fig. 3 shows 3D completed view of an internal rotor machine. On the other hand, Table 2 determines main electrical and dimensional parameters of the internal machine.

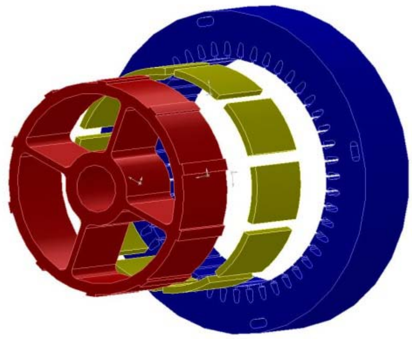

Fig. 2. Rotor iron, permanent magnets and stator stack of an internal rotor machine

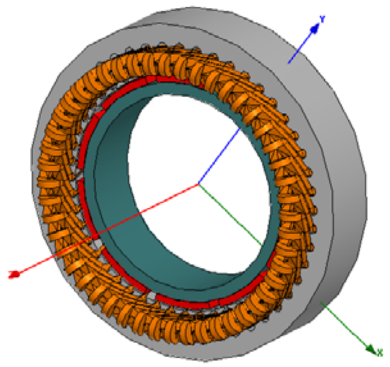

Fig. 3. Completed view of the internal rotor machine designed

Table 2. Main electrical and dimensional parameters of the internal machine

	EXPLANATION	VALUE
P	Rated power	1500 W
n	Reference speed	400 rpm
T	Rated torque	37.8 Nm
U_{ph}	Rated phase voltage	24 V
I_{ph}	Rated phase current	20.38 A
l_{PM}	Thickness of PM	5.0 mm
G_{PM}	Mass of PM's	0.74 kg
Q	Number of stator slots	48
p	Number of pole pairs	5
g	Length of the air-gap	1 mm
D_{out}	External diameter of the stator stack	231 mm
D_{in}	Internal diameter of the stator stack	169 mm
L	Length of the stator stack	45 mm
N_{ph}	Number of coil turns in series per phase	480

Radial-flux PM Generator with External Rotor. As illustrated in Fig.4, the wound stator in the external rotor configuration is stationary, located in the center of the machine, while the magnets are mounted evenly along the internal circumference of the rotating drum supported by front and rear bearings. Fig.5 shows completed view of the design of the external rotor machine.

Table 3. Main electrical and dimensional parameters of the external machine

	EXPLANATION	VALUE
P	Rated power	1000 W
n	Reference speed	400 rpm
T	Rated torque	31.8 Nm
U_{ph}	Rated phase voltage	24 V
I_{ph}	Rated phase current	14.85 A
l_{PM}	Thickness of PM	5.0 mm
G_{PM}	Mass of PM's	0.74 kg
Q	Number of stator slots	36
p	Number of pole pairs	5
g	Length of the air-gap	1 mm
D_{out}	External diameter of the stator stack	155 mm
D_{in}	Internal diameter of the stator stack	65 mm
L	Length of the stator stack	45 mm
N_{ph}	Number of coil turns in series per phase	360

The magnetic circuits are the same as those in the conventional internal rotor radial-flux PM generator. But the blades of the wind turbine can be conveniently bolted to the front face of the drum to realize the direct coupling between the wind turbine and the PM generator.

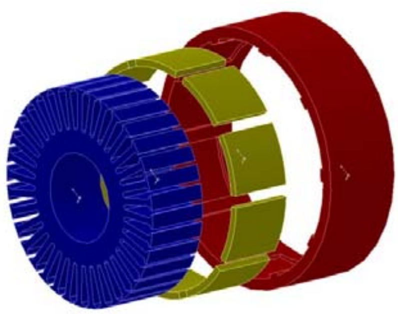

Fig. 4. Stator stack, permanent magnets and rotor iron of an external rotor machine

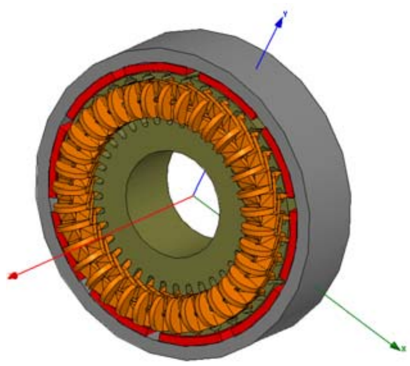

Fig. 5. Completed view of the external rotor machine designed

Because of the enlarged periphery of the external rotor drum, the multi–pole structure can be easily accommodated, and therefore the total length of the magnetic path is reduced. As the rotor is directly exposed to the wind, the cooling condition is improved for the magnets, so that the resistance to high temperature demagnetization is enhanced [12].

Main electrical and dimensional parameters of the external machine are determined, as seen from Table 3.

Results

The results of the comparison are given as phase voltages induced in graphics and tables for internal and external rotor PM generator. Those will be explained in the following sections:

A. Induced Phase Voltages under load for internal and external rotor PM generator. Fig. 6 and 7 illustrate the induced phase voltages of each machine type under load. Both machine types induce similar peak phase voltages value due to applying the same number of coil turn in one slot.

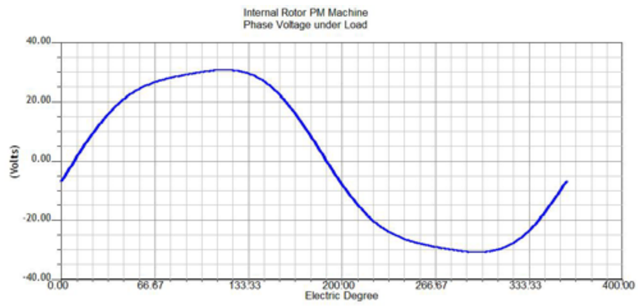

Fig. 6. Internal rotor PM machine phase voltage under load

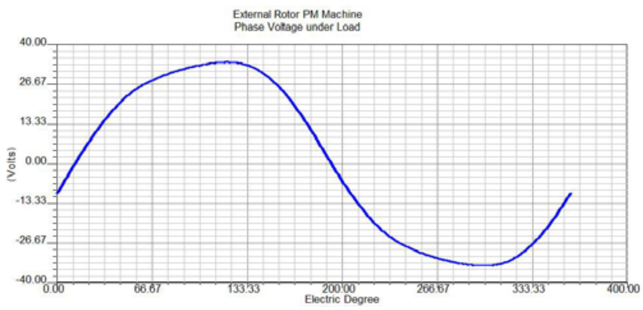

Fig. 7. External rotor PM machine phase voltage under load

Winding Currents under load for internal and external rotor PM generator. Fig. 8 and 9 illustrate winding currents produced under load of the each machine type. As shown in the figures, internal rotor configuration produces higher winding current for the same magnet. In the internal rotor configuration, applying the larger radius side to the stator induces higher current in stator windings.

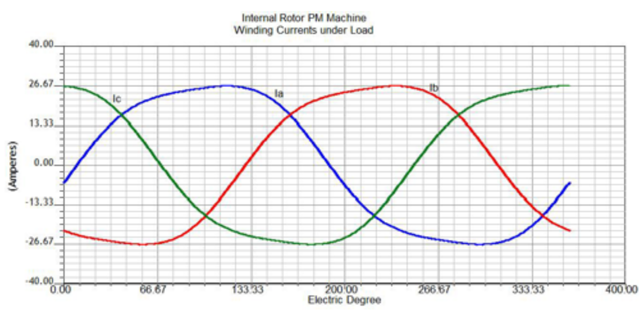

Fig. 8. Internal rotor PM machine winding current under load

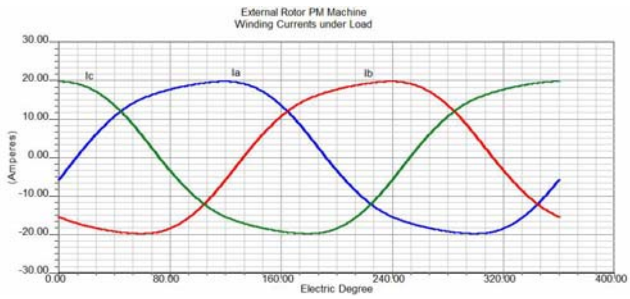

Fig. 9. External rotor PM machine winding current under load

Airgap Flux Density for internal and external rotor PM generator. For both machine types lenght of air-gap is limited as 1 milimeter. Internal rotor PM machine maximum air-gap flux density (Tesla) is 0.881335 and it is 0.769404 for the external rotor PM machine. So, the internal rotor configuration creates higher flux density in the air gap than the created flux density in the external rotor configuration.

Fig. 10 and Fig. 11 illustrate the air-gap flux density both internal and external machine configurations under no-load.

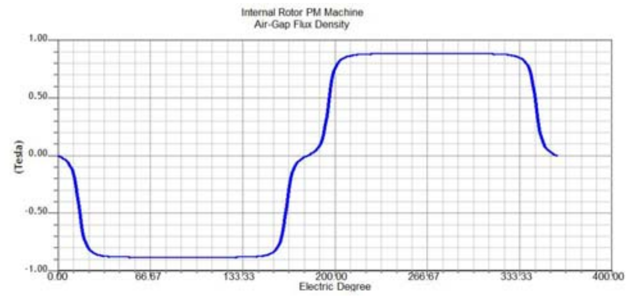

Fig. 10. Internal Rotor PM machine air-gap flux density under no-load (Tesla versus electric degree)

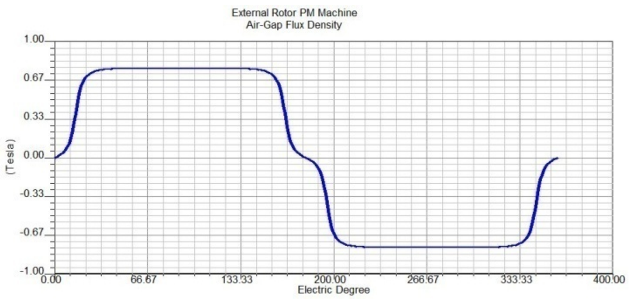

Fig. 11. External rotor PM machine air-gap flux density under no-load (Tesla versus electric degree)

Output Power versus Speed Comparison for internal and external rotor PM generators. It is assumed that the average speed (400 *rpm*) is applied for both machine types due to direct drive configuration. The two machine types have 5 pole pairs and the synchronous speed is 600 *rpm* for 50 *Hz*. The machines considered in this study are designed to operate at reference speed 400 *rpm* and 33.3 *Hz* to provide lower speed for direct drive applications.

Fig. 12 illustrate the output power vs. speed graph for the internal and external rotor PM machines. The internal rotor PM machine provides higher output power at reference speed but the internal rotor PM machine has larger volume and cost.

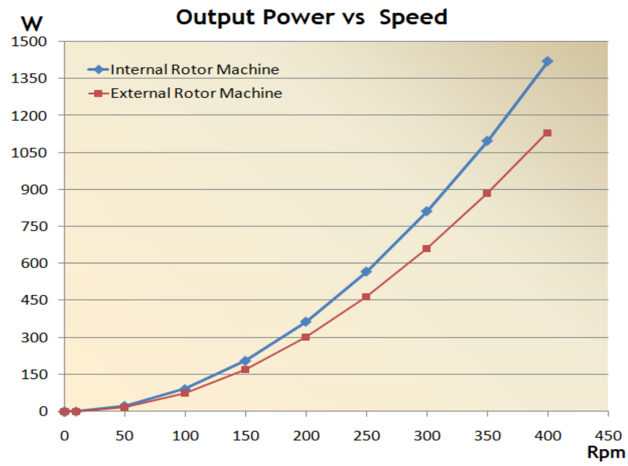

Fig. 12. Output power vs speed values for internal and external rotor PM machine

Material Comsumption based comparation. Table 4 illustrates the material comsumption based comparison between internal and external rotor PM machines. The consumption datas could be seen from the table.

Table 4. Material comsumption based comparation

MATERIAL COMSUMPTION	Internal Rotor	External Rotor
Armature copper density (kg/m^3):	8900	8900
Permanent magnet density (kg/m^3):	7800	7800
Armature core steel density (kg/m^3):	7800	7800
Rotor core steel density (kg/m^3):	7870	7870
Armature copper weight (kg):	3.980	2.362
Permanent magnet weight (kg):	0.744	0.744
Armature core steel weight (kg):	5.699	3.431
Rotor core steel weight (kg):	1.404	1.557
Total net weight (kg):	11.82	8.095
Armature core steel consumption (kg):	20.72	8.762
Rotor core steel consumption (kg):	1.404	1.557

The internal rotor PM machine has higher weight value although it generates higher output power. The external rotor machine has lower copper weight and armature core steel weight (*kg*) due to compact configuration.

Thorough Comparison based on full load data. In Table 5, the machines' electrical parameters are shown thoroughly. According to these parameters, the configurations can be easily compared for the required parameter.

The external rotor PM machine type has high armature thermal load, copper loss and current density. Cause of having higher losses, it has lower efficiency. But this configuration has smaller volume, lower cost and short circuit current.

The Internal rotor PM machine type which has the same PM geometry and characteristics has higher output power and rated torque. Lower load resistance, armature current density, armature thermal load and total losses are the main advantages of this type configuration. Having high efficiency is another advantage. Beside these advantages, this configuration has larger volume and more cost value.

Table 5. Parameters and Full Load Data for internal and external rotor machines

PARAMETERS	Internal Rotor	External Rotor
Load resistance (ohm)	1.152	1.728
Load line voltages (V)	23.48	25.66
RMS line current (A)	20.38	14.85
RMS phase current (A)	20.38	14.85
RMS phase voltages (V)	23.48	25.66
Armature thermal load (A^2/mm^3)	107.90	187.46
Specific electric Loading (A/mm)	27.64	32.94
Armature current density (A/mm^2)	3.90	5.68
Iron-core loss (W)	18.10	13.99
Armature copper loss (W)	147.88	186.50
Total loss (W)	165.98	200.50
Output power (W)	1420.4	1132.9
Input power (W)	1586.4	1333.4
Efficiency (%)	89.53	84.96
Apparent power (VA)	1435.8	1143.9
Power factor	0.989	0.990
Rated torque (Nm)	37.87	31.83
Short circuit current (A)	95.90	50.56

Conclusions

From the data presented in the previous sections, it is inferred that external rotor PM machines have a smaller volume, lower output power, lower efficiency, higher armature thermal load, higher armature current density by applying the same PM geometry and characteristic for a given power rating. This is true for all the investigated power ratings and it is possible to get higher output power and torque by applying the internal rotor configuration for the same PM geometry and characteristic.

The external rotor PM configuration is superior to the internal rotor PM configuration. However, internal rotor constructions has higher output power and torque. The external rotor configuration also has lower total weight and cost. The former also has advantages such as ease of installation and cooling. Therefore the external rotor construction is more suitable to be applied in wind power systems. For most of the comparisons, the low speed constructions are superior to the high speed constructions, which means that multi-pole PM generators are preferred in the application of small, gearless, low speed wind system.

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In this study, internal and external rotor radial-flux machine constructions built with surface mounted by applying the same NdFeB were compared according to torque density, vigorous material weight, outer radius, total length and volume, generated power and efficiency. Induced phase voltages and winding currents under load, airgap flux density, output power versus speed and material consumption for internal and external rotor PM generators have been obtained as the results of comparison. It was inferred that external rotor PM machines have a smaller volume, lower output power and efficiency, higher armature thermal load and current density than internal rotor PM machines by applying the same PM geometry and features for a given power rating. Therefore it was seen that the external rotor construction was more suitable to be applied in wind power systems because of external rotor structured PM machines have lower total weight and cost. Ill. 12, bibl. 12 (in English; summaries in English, Russian and Lithuanian).

И. Таример, Ц. Осак. Сравнение производительностей ветровых генераторов, построенных на основе постоянных магнитов той же геометрии // Электроника и электротехника. – Каунас: Технология, 2009. – № 4(92). – С. 65–70.

Составлены компьютерные программы для расчета электронического потенциала в двумерных анизотропных средах, когда источник тока: точечный, в форме круга и в форме диска. Полученное семейство кривых продемонстрировало изменение электрических констант зависимости от анизотропии, расстояния между электроническими потенциалами на месте регистрации, величины тока источника. Ил. 12, библ. 12 (на английском языке; рефераты на английском, русском и литовском яз.).

İ. Tarımer, C. Ocak. Vėjo generatorių pagamintų iš tos pačios geometrijos nuolatinių magnetų, rotoriaus vidaus ir išorės našumo palyginimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 4(92). – P. 65–70.

Aprašomos kompiuterinės programos elektrinio potencialo pasiskirstymui skaičiuoti. Gautos kreivių šeimos, kurios parodo priklausomybę standartizuotoje eksperimentinėje erdvėje. Nustatytos elektrinių konstantų kitimo priklausomybės nuo anizotropijos, atstumo tarp elektrinių potencialių bei šaltinio srovės dydžio. Il. 12, bibl. 12 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).