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Influența generatoarelelor sincrone cu magneți permanenți în industria energiei regenerabile

The influence of permanent magnet synchronous generators in the renewable energy industry

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Rezumat: *Generatoarele sincrone cu magneți permanenți sunt esențiale în buna funcționare a lanțului de conversie a energiei regenerabile – eoliene, de aceea sunt subliniate tipurile de geometrii constructive ale rotoarelor acestora. Lucrarea de față este un studiu bibliografic care vine în sprijinul producătorilor de top ai centralelor eoliene, pentru a ușura munca acestora de proiectare. Un rol important al GSMP este dat de magneți permanenți din pământuri rare care asigură o cantitate ridicată de energie magnetică necesară funcționari excelente a GSMP, ceea ce ii recomandă producătorilor de centrale eoliene.*

Cuvinte cheie: GSMP, magneti permanenti din pamanturi rare, conversie energetică.

Abstract: *Synchronous generators with permanent magnets are essential in the good functioning of the renewable energy - wind energy conversion chain that is why the types of constructive geometries of their rotors are highlighted. The present work is a bibliographic study that supports the top manufacturers of wind power plants, in order to facilitate their design work. An important role of the SGPM is given by permanent magnets from rare earths that provide a high amount of magnetic energy required for excellent functions of the SGPM, which is recommended for wind power plant manufacturers.*

Keywords: SGPM, rare earth permanent magnets, energy conversion.

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1) Introduction:

The first commercial appearance of the synchronous generator can be dated to August 24, 1891, with the demonstration that was carried out at an international electrical exhibition Lauffen in Frankfurt, this demonstration was so convincing regarding the feasibility of transmitting a.c. power, over long distances, that the city of Frankfurt adopted it for their first power plant, commissioned in 1894 [1]. Since then and until now, synchronous generators have changed many constructive geometries until they have the constructive forms we know today. In the last decade, permanent magnet synchronous generators have become increasingly prevalent in industrial applications: GSMPs are widely used in: renewable energy systems - especially in new generations of wind power plants, servo - industrial applications due to their high performance characteristics, space, automobiles, electronics, exploitation and research equipment [2].

2) Structural elements. The principle of operation

The synchronous electric generator belongs to the family of electric rotary machines. The electric generator, polyphase alternating current, usually three-phase, of each rotor tends to align with the rotating field produced by the stator, their rotor has an angular speed equal to the synchronism speed Ω (the angular speed of the rotating magnetic field). The magnetization of the rotor is produced by the permanent magnets in the rotor. This type of generator is called a synchronous generator (SGPM) and is shown in figure 1. Or simply put, it is a synchronous machine where the classic excitation winding is replaced by a permanent magnet, thus becoming electric machines without a brush-ring system [3].

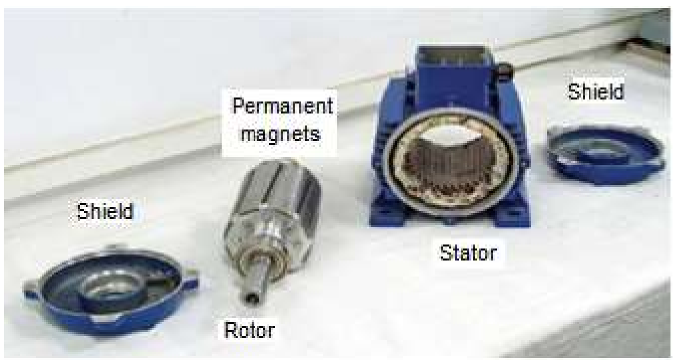

Fig. 1 The component elements of a SGPM [4]

The rotor presents a great constructive diversity, from which the variants can be distinguished:

- according to the construction method we have:

a) **The rotor with apparent poles** has the magnetic circuit made of sheet metal or solid steel with the coils of the excitation rotor winding in series and arranged on these poles. This construction is simpler and cheaper, but presents reduced mechanical safety at high speeds.

b) **The rotor with submerged or smooth poles** has a cylindrical magnetic circuit. It is executed as a package of sheets or solid steel with high mechanical resistance. The rotor winding, called the excitation, made up of series coils, is placed in slots made on the generators on the outside of the rotor. Slots are not evenly distributed on the rotor circumference, each pole corresponds to a polar "tooth" (the space between two slots) called "wide tooth", shown in figure 2.

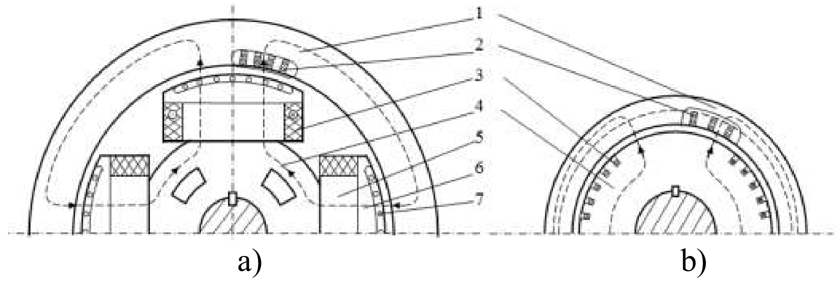

Fig. 2 Basic constructive elements of synchronous generators: a) with apparent poles; b) with submerged poles. 1-stator yoke, 2-stator winding (induced), 3-rotor winding (inductor), 4-rotor yoke, 5-rotor pole, 6-pole piece, 7-damping winding [5].

The rotor can be made with permanent magnets in which case there are solutions:
c) **Radial flow rotor** are the most conventional rotors for SGPM as can be seen in figure 3. We obtain a higher power due to the increase in machine length and a flexibility for high scaling. It is mainly used in: wind systems, traction, ship propulsion, robotics [6].

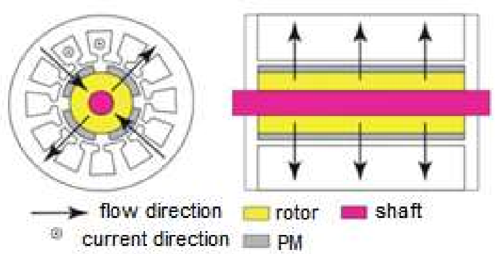

Fig. 3 Cross-sectional view in the radial direction and in the axial direction, respectively, of a typical SGPM radial flow [6]

d) **In axial flow machines**, the length of the machine is much reduced compared to radial flow machines, shown in figure 4. Their main advantage is high torque density, so they are recommended for applications with size restrictions, especially on axial direction [6]. One of the disadvantages of axial flow machines is that they are not balanced in the single rotor and stator edition. Usually, for better performance, the rotor is sandwiched between two stators or vice versa.

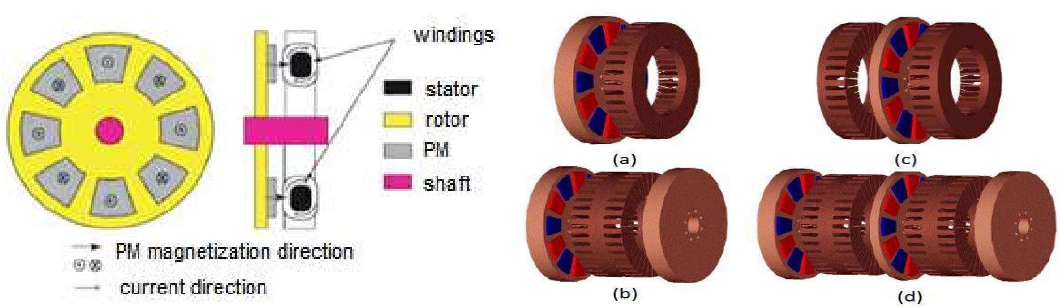

Fig. 4 Cross-sectional view in the radial direction and in the axial direction, respectively of a typical SGPM axial flow [6, 7].

e) **In cross-flow machines**, the plane of the flow path is perpendicular to the direction of rotor movement. The use of cross-flow machines can be proposed in applications with a high level of torque density. An attractive property of transverse flux machines is that the current loading and magnetic loading can be adjusted independently. Figure 5 shows a fraction of a typical SGMP crossflow.

A disadvantage of transverse SGMP is high leakage flux leading to poor power factor. Another disadvantage is that in turning the SGMP transversely, the mechanical construction is weak due to the large number of parts. They are used in: wind systems, free piston generators for hybrid vehicles, the ship's propulsion and wind system, applications with high torque density [6].

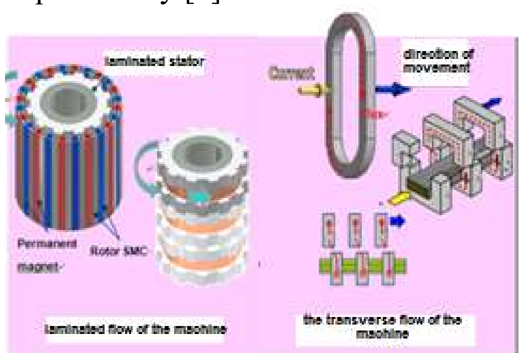

Fig.5. Representation of transversal flows [6]

f) The rotor surrounds the stator in **external rotor** machines. In these machines, the magnets are usually located on the inner circumference of the rotor. Consequently, for the same outer diameter of the machine, in the outer rotor machine the rotor has a larger radius compared to the stator and it can be equipped with a larger number of poles for the same pitch. Another advantage is that the magnets are well supported despite the centrifugal force. In addition, better cooling of the magnets is provided. Outboard rotor machines are common for small HAWT turbines, where sometimes the hub carrying the blades is directly attached to the rotor.

g) However, **inner rotor** machines are a more common solution on the market today. In small machines the main contributors to losses are copper losses and therefore the stator winding has the largest temperature rise in the active material of the machine. Figure 6 shows a SGPM inner rotor and a SGPM outer rotor [6].

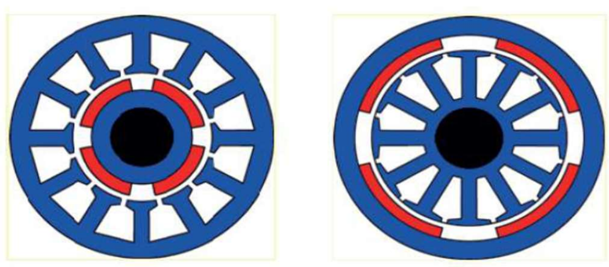

Fig.6. SGPM inner rotor (left) and SGPM outer rotor (right) [6].

From the point of view of the configuration of the permanent magnets, they can be mounted:

h) Surface mounted magnets

A common topology is where the magnets are mounted on the surface of the rotor, sometimes referred to as the **outer magnet**. Magnets are glued and/or "bandaged" to the inner surface of the rotor to resist the centrifugal force, as can be seen in figure 7. Usually, the magnets are oriented or magnetized in the radial direction and less often in the circumferential direction. The direction and quadrature of the reactances are almost equal. The construction of the rotor core in the SGPM is the easiest of the PM configurations due to the simple geometry of the rotor. Here the PMs are radially magnetized.

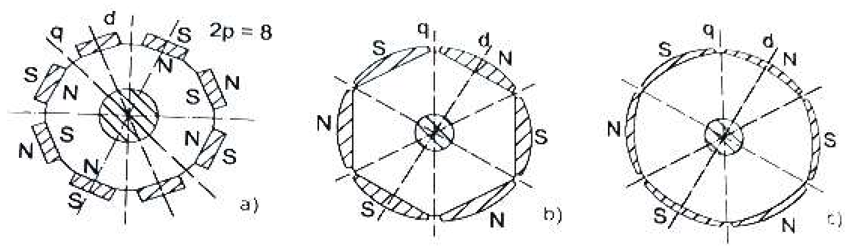

Fig. 7 Features SGPM rotor surface mounted magnets [7]:
a) uniform thickness surface magnet
b) type magnet "bread leaf"
c) deconcentrated magnets

By placing them outside the rotor directly in the air-gap, there is a corresponding reduction of the mass and therefore of the moment of inertia [7].

i) Inserted magnets

In machines with **inserted magnets**, the rotor core of the machine is modified with iron interpoles, represented in figure 8. Iron interpoles are prominent of the rotor core wherever magnets are not present on the surface. Interpoles cause silence and inductances give different straight and quadrature directions. In these machines, part of the torque is reluctance torque and the torque density is higher compared to SGPM. The magnets are radially magnetized. Flux leakage is higher compared to SGPM, resulting in lower power factor. Therefore, in direct drive application, inverter usage is less as compared to geared applications. This topology is not common in gearless wind systems [6].

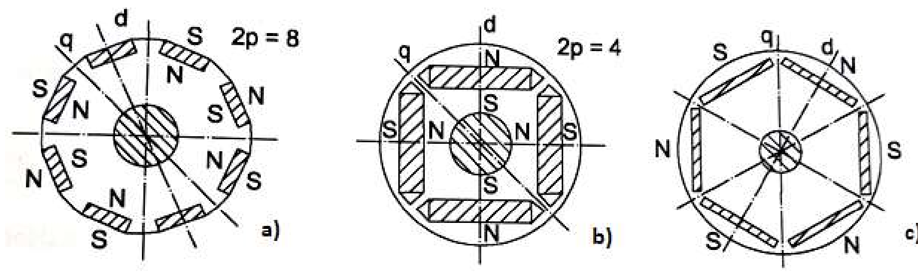

Fig.8 Features built-in magnets for SGPM rotor [7]:
a) medallion type magnets; b), c) internal magnets with a single layer.

j) **Disc type magnets**

MP from rare earths characterized by high coercive magnetic field values are used. The rotor has the shape of a disc. Permanent magnets are axially magnetized and are shown in figure 9. They are mainly used in wind power plants [8].

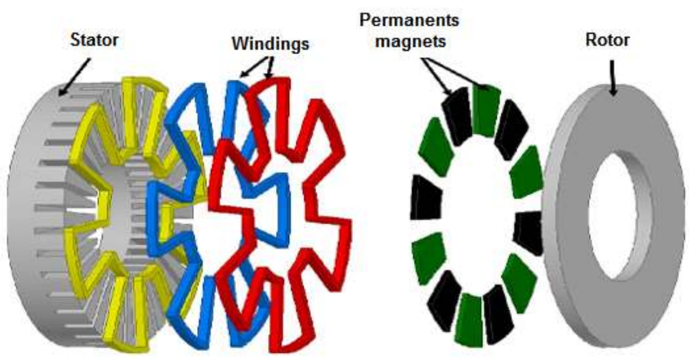

Fig. 9 Represents disc type magnets [9]

Another classification of SGPM is made according to the type of winding:
Windings can be divided into overlapping and non-overlapping categories. Non-overlapping windings can only be wound in concentrated mode. The overlap term is usually omitted. For example "overlapping winding" is almost always referred to as distributed winding. In this text, on the other hand, "concentrated winding" means "concentrated winding that does not overlap with two layers", as in figure 10 [6].

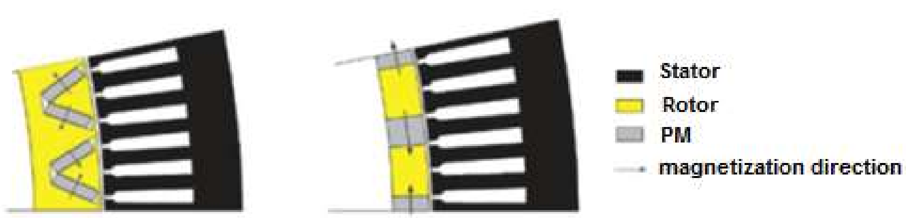

Fig.10 Cross section of a pair of poles of a V-shaped buried magnet design (left) and a tangentially buried magnet design (right) [6]

3) Permanent magnets used for SGPM

The use of permanent magnets with high stored energy density as motor excitation sources leads to high performance SGPM s in terms of high power density, net superior efficiency and reliability, and high speed [10].
In the following we present comparatively the four classes of magnets used in the construction of generators [11,12]:

Classes of magnets *Tabel 1*

AlNiCo	FERRITE	SmCo	NdFeB
They can be isotropic and anisotropic	Breakable	They are high energy PMs	They are the strongest on the market
It is obtained by casting and sintering	It is obtained by sintering	It is obtained by sintering	It is obtained by sintering
Low coercive field (160[kA/m])	High coercive field (265[kA/m])	Very high coercive field (700[kA/m])	Highest coercive field (1000[kA/m])
High remanent induction (1.35[T])	Low remanent induction (0.39[T])	Medium remanent induction (1.05[T])	High remanent induction (1.35[T])
Low magnetic energy	Low magnetic energy	High maximun magnetic energy	High maximum magnetic energy
Good corrosion resistance	Good corrosion resistance	High corrosion resistance	Fragile
High termic resistence	High termic resistence	Stabile termic resistence	Moderate termic resistence
-	Maximum work temperature 400^0C	-	Low work temperature 150^0C

Data are compiled from technical sheets of different PM manufacturers (for the year 2019), for temperatures between 20 - 30◦C. Hci is the intrinsic coercivity of the MP, for alnico MP the normal coercivity is given (since the data sheets do not give Hci). No *CBmin* MP is given for alnico because that material class is typically used on a minor degaussing loop and *Cbmin* MP therefore depends on which minor loop is chosen. When µrec is not given, it is estimated by µrec = B^2r/(4μ0|BH|max), i.e. assuming the maximum energy occurs in the linear part of the magnetization curve, the estimated µrec are marked with a "*". Worldwide it is noted that the demand for permanent magnets is increasing, especially for those made of neodymium [13].

Properties of MP materials available on the market [13] *Tabel 2*

Magnet type	Br [T]	Hci [kA/m]	|BH|max [kJ/m3]	Mrec [-]	CBminMP [-]
Alnico	0.55–1.37	38–151	10.7–83.6	1.3–6.2	-
Hard ferrite	0.20–0.46	140–405	6.4–41.8	1.05–1.2	−0.4–0.4
Nd-Fe-B	1.08–1.49	876–2710	220–430	1.0–1.1 *	−2.3–0.2
Sm-Co	0.87–1.19	1350–2400	143–251	1.0–1.1 *	−2.7−0.62

Figure 3.1 shows the market demand for permanent magnets from rare earths with 59%, followed closely by those from ferrites with 31%.

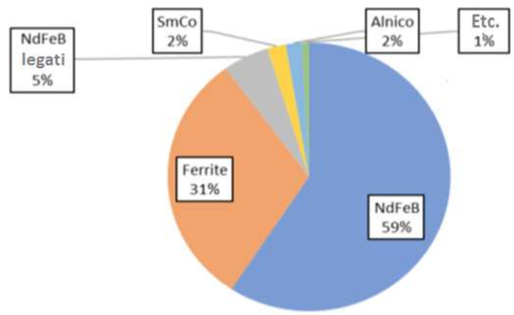

Fig.3.1 Current share of MP demand worldwide [14]

The estimate of the market of permanent magnets relative to the price per kilogram is presented in table 3. Permanent magnets from rare earths - NdFeB have the highest price [15].

It represents the price/kg value of PM [15] *Tabel 3*

MATERIAL [-]	COST [$]/PERFORMANTS [-]	MASS[tone]
NdFeB	11,200	160,000
Ferrite	5,800	830,000
SmCo	400	4,200
AlNiCo	350	6,300

For wind power plants, development is currently in the direction of permanent magnet generators. These advantages have led to the current situation where synchronous generators produce over 90% of the electricity in Romania, but also in the world.
The advantages of opting for such a SGPM: they have the highest efficiency (over 90%), they are the only ones that provide both active and reactive energy, they allow the frequency and voltage to be kept constant, low operating noise, reliability, high efficiency.
Disadvantages of SGPM: increased cost price, safety, demagnetization of magnets, ability to operate at high speed.

4) Mathematic Model of the Synchronous Generator

Mathematical modeling of SGPM is an essential condition to be able to obtain generator control algorithms, as well as dynamic characteristics for wind energy conversion systems [16]. For the mathematical model of the SGPM in dq0 or the orthogonal model represented in figure 4, the rotating frame of reference will also be extended to the SGPM torque analysis. The tension function of the SGPM in reference to the dq axes of the frame can be expressed as follows [17, 18].

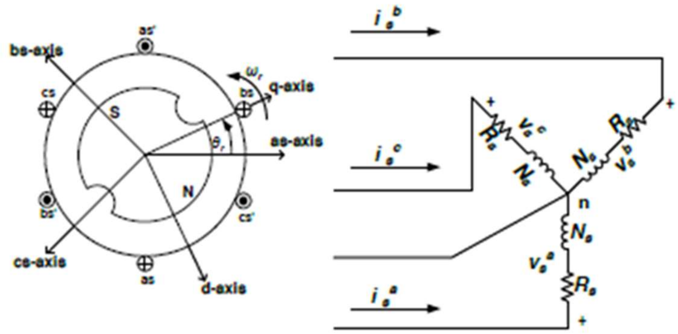

Fig. 4 Orthogonal model [19]

$$U_d = R_a i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (1)$$

$$U_q = R_a i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \varphi \ (2)$$

$$\omega = p\Omega \ (3)$$

Where:

Vd, Vq, id, iq – dq0 components of stator voltage and current;
Ra – resistence of stator winding;
Ld, Lq – stator winding inductance;
φ – permanent magnetic flux;
p – pole pairs number;
Ω – magnetic flux;
ω = generator electrical angular speed;
The equation of electromagnetic torque has this expresion:

$$T_{em} = \frac{3}{2}\, p \left(L_d - L_q\right) i_d i_q + \varphi i_q) \ \ (4)$$

The voltage equations of the stator circuit are given by (7), where x ∈ {a, b, c}.

$$v_s^x = R_s i_s^x + \frac{d}{dt}\, \lambda_s^x \ \ (5)$$

The SGPM has sooth poles (Ld = Lq = Ls), replacing the formula of voltage in the current one [18]:

$$\frac{dt_d}{dt} = -\frac{R_a}{L_s}\, i_d + \omega i_q + \frac{1}{L_s}\, U_d \ (6)$$

$$\frac{dt_q}{dt} = -\frac{R_a}{L_s}\, i_q - \omega\left(i_d + \frac{1}{L_s}\varphi\right) + \frac{1}{L_s} U_q \ (7)$$

The generator was modeled considering the scheme shown in the figure below 3. The voltage function of the SGPM in the *dq* - axes reference frame can be expressed as follows [13] and [14].

5. Conclusions:

The permanent magnet synchronous generator is one of the most attractive generators for wind power plants. This type of generator can work for any size wind farm from kW (or even several hundreds of watts) to many MW.

By choosing to use SGPM we have a number of advantages:

1. High efficiency: SGPM are the highest efficiency class of electric machines. This is due to the existence in their structure of permanent magnets as a source of excitation and which do not require energy consumption from outside the machine. The absence of the mechanical switch and the ring-brush system reduces mechanical friction, implicitly mechanical losses, which adds an extra to the efficiency.

2. Compaction: The relatively recent appearance of high energy density permanent magnets (rare earth magnets) allow high flux densities to be achieved in SGPM. That leads to obtaining high torque density, so implicitly, it reduces the dimensions and weight of the machine.

3. Simplicity in control: SGPM can be controlled very simply, invoking strategies and methods very well developed at the moment.

4. Simplicity in cooling: since there is no electric current circulation in the rotor, it does not heat up, so it does not need cooling. The stator of the machine is the one through which the electric current passes, and its need for cooling is satisfied at the level of the outer periphery of the machine casing.

5. Simple maintenance, pronounced longevity and high reliability: The absence of brushes and mechanical switch suppresses the need for periodic maintenance and the risk of failure of these components.

6. Very low noise emissions: Not being a mechanical switch but an electronic one, the machine is very quiet, and if the electronic control converter is operated at high frequencies, the noise produced by the switch goes beyond the perceptible zone of the human ear.

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