COMPARATIVE ANALYSIS OF PERMANENT MAGNET MATERIALS FOR WIND TURBINE DRIVEN PERMANENT MAGNET GENERATOR

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Abstract: *The use of alternate energy resources for electrical power generation has attained a rapid development in the past few decades. In particular, the power generation utilizing wind energy, has achieved a significant growth in countries all over the world. Since, the wind energy conversion system (WECS) is demanded to be more cost competitive, the comparisons of different wind generator systems become necessary. In this paper, a comparison among permanent magnet generators of different topologies is provided in order to choose an appropriate generator for direct drive applications. The direct drive permanent magnet generators are more superior in terms of energy yield, reliability and maintenance. The properties of permanent magnet and the selection of permanent magnet materials play a very important role in the design of permanent magnet generators. This paper also analyzes the different types of permanent magnet materials based on their magnetic, thermal and B-H characteristics. The proposed PMG topology with different types of magnetic materials placed in the rotor is to be modeled using MATLAB/SIMULINK and the generated voltage, voltage reduction, total harmonic distortion and the load current are to be analyzed for fixed wind velocity and different loading conditions.*

Key Words: *B-H characteristics, permanent magnet generators, permanent magnet materials, WECS, wind turbine.*

1. Introduction

Wind power is emerging as one of the fastest growing sustainable energy resources and technology in the world. With the advantage of clean, inexhaustible, cost effective and eco-friendly, the use of WECS is increased abundantly. A WECS has become a reliable and competitive means for electric power generation through which the energy available in the wind is captured and converted in to electrical energy. Induction generators are widely used in WECS due to its advantages of reduced unit cost and size, low maintenance and better transient performance [1]. Even though the induction generator is robust and inexpensive, permanent magnet generators are preferred over induction generator due to its improved efficiency, direct drive operation and no need of excitation. In the fixed speed power generation scheme, the wind speed fluctuations are directly translated to electromechanical torque variations which lead to the high mechanical and fatigue stress on the system. Whereas the variable speed power generation scheme enables a larger amount of energy capture from the wind [2].

The normal speed of wind turbine is 40 to 120 rpm. But the wind turbine generator rotates at a speed of 1000 to 1500 rpm [3]. Since the turbine speed is lower than the generator speed, a gearbox is utilized between the wind turbine and generator. However, the gearbox used in conventional wind energy systems subjects to vibration, generates noise, increases losses and requires frequent maintenance. To overcome these disadvantages and increase reliability, a gearless wind energy conversion system for direct driven generators is introduced, where the generator is coupled to the rotor of a wind turbine directly [4]. The most common permanent magnet materials available are NdFeB, SmCo, Alnico, Ceramic and Flexible magnets. In this paper the proposed topology of PMG is analyzed with various types of permanent magnet materials under different load conditions.

2. Principle and rotor Construction

The PMG is used for many years in wind turbine applications. The stator of the PMG is similar to that of the alternator, whereas the new component is the rotor, which in contrast to the conventional rotors lies on permanent magnets, as the source of excitation rather than electric charge in windings. The advantages of PMG over electrically excited machines are high efficiency and energy yield, highly compact and reliable, easy maintenance and it eliminates field copper loss by improving their thermal characteristic. The PMG allows a very good flexibility in their geometry, so it paves way for various topologies.

2.1 Radial Flux PMG

In RFPMG, the flux distribution is in radial direction. The wind generator system operates at good performance over wide range of wind speeds, when it is utilized in direct drive wind turbines. In this type of PMG the length of the machine and air gap diameter can be chosen independently [2]. If necessary, the RFPMG can be made with a small diameter by using a long machine. The magnets can be placed in many ways on the rotor. Based on the methods of mounting the magnets in the rotor, it is of several types. Regardless of the manner of mounting the basic principle of operation is the same.

2.1.1 Surface Mounted RFPMG

Fig. 1 shows the surface mounted rotor configuration of RFPMG. The surface mounted RFPMG with radial orientation has high power density intended generally for low speed applications. In this topology, the magnets are mounted on the surface of the outer periphery of rotor. The advantages of this configuration are easy manufacturing of the machine with high number of poles by gluing permanent magnets on the rotor surface, higher remanent flux density and less weight. But it has the disadvantages of lower structural integrity, lower mechanical robustness and not preferred for high speed applications [5].

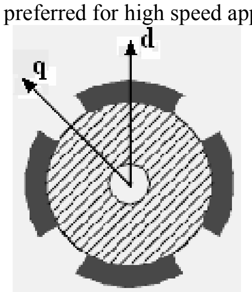


Fig. 1. Surface mounted rotor of RFPMG

2.1.2 Surface Inset RFPMG

In this configuration, the magnets are placed in the grooves of the inner periphery of the rotor. Fig. 2 shows the surface inset rotor configuration of RFPMG. It has the advantages of more mechanical robustness as compared to surface mounted PMG, easy to construct, and best suited for high speed applications. It combines the benefits of both the surface and interior magnet arrangements. The only one disadvantage is that it is very complex to manufacture.

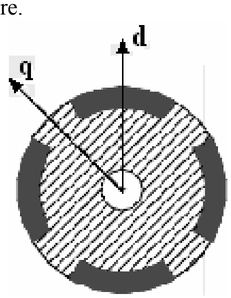


Fig. 2. Surface inset rotor of RFPMG

2.1.3 Interior RFPMG and Interior RFPMG with Circumferential Orientation

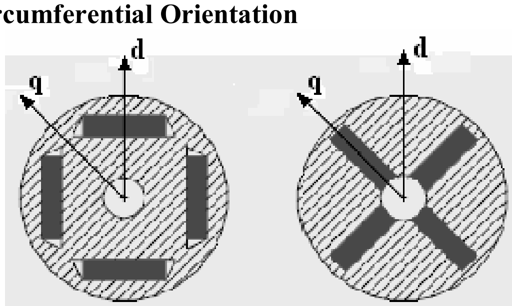


Fig. 3. Interior RFPMG and with circumferential orientation

Fig. 3 shows the rotor configurations of interior RFPMG and interior RFPMG with circumferential orientation. In these configurations, the magnets are placed in the middle of the rotor laminations in radial and circumferential orientation respectively. It is mechanically robust and suited for high speed applications. But the manufacturing of this arrangement is more complex than the surface mounted and surface inset rotors.

2.2 Axial Flux PMG

The AFPMG is a generator producing magnetic flux in the axial direction that is parallel to the rotational shaft instead of the radial direction. Comparing with RFPMG the advantages of AFPMG are simple winding, low cogging torque and noise (in slot less machine), short axial length and higher torque / volume ratio. It includes the disadvantages of low torque / mass ratio, large outer diameter, large amount of permanent magnet and structural instability (in slot less machine), difficult to maintain air gap in large diameter (in slotted machine) and difficult in production of stator core (in slotted machine). Two sided AFPMG is superior to one side AFPMG, however, one sided constructions use less copper and have a lower conduction loss.

2.2.1 Slotless Single Stator Double Rotor AFPMG

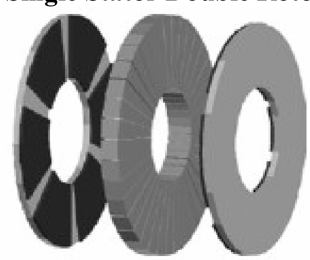


Fig. 4. Slotless single stator double rotor PMG

Fig. 4 shows the configuration of slotless single stator double rotor PMG. The slotless single stator double rotor is a typical structure of slotless AFPMG, which is often referred to as torus machine [6]. The two rotor discs are made up of mild steel and have surface mounted permanent magnet to produce an axially directed magnetic field in the machine air gaps. The machine stator comprises a slotless toroidally wound strip iron core that carries a three phase winding in a toroidal fashion by means of concentrated coils. It does not require any stator back iron since the main flux travels axially. As the large turbines have low speed, the designed rated speeds decrease with an increase in power rating. The torque densities for direct drive machines are much better than that of high speed machines with gearbox.

2.2.2 Double Stator Slotted AFPMG

Fig. 5. Axial flux PMG with double stator

Fig. 5 shows the configuration of axial flux PMG with double stator. The shape of the stator as well as the rotor resembles a pancake and these machines are commonly referred to as pancake machines. The machine consists of two external stators and one inner rotor. The permanent magnets are axially magnetized and are surface mounted or inset into a cut window in the rotor disc. In all axial flux machines, the rotor rotates relative to the stator with the flux crossing the air gap in the axial direction. The stator iron core is laminated in the radial direction and resembles concentric rings that have a constant slot width and tapered teeth.

2.2.3 Double Rotor Slotted AFPMG

Fig. 6 shows the single stator and double rotor AFPMG.This configuration is similar to that of the double stator slotted AFPMG, except that there is one stator and two rotors. The stator is located in the middle of the two rotors and slotted on both side. An iron flux path is needed on the rotor back of yoke, but the stator back yoke can be eliminated and saved.

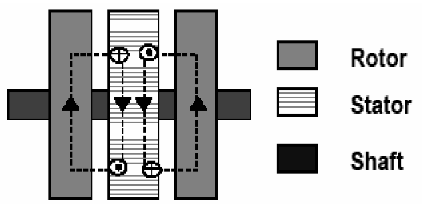


Fig. 6. Single stator and Double rotor AFPMG

2.3 Transversal Flux PMG

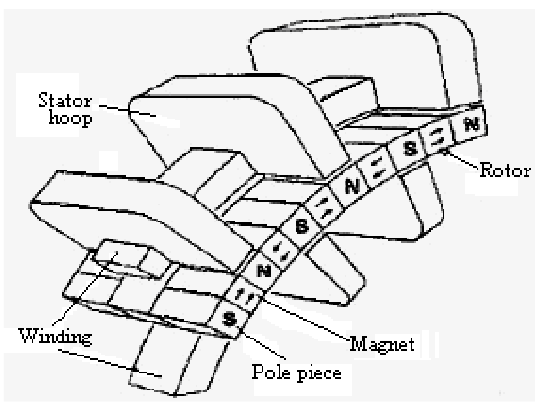


Fig. 7. Transversal flux PMG

The transversal flux PMG is rather different from the other machine types, wherein the path of the magnetic flux is perpendicular to the direction of the rotor rotation. Fig. 7 shows the typical structure of transversal flux PMG. The major difference between radial or axial flux PMG and transverse flux PMG is that the transversal flux concept allows an increase in the space for windings, without decreasing the available space for the main flux that results in very low copper loss. Also, it can be made with a very small pole pitch which makes it capable of producing a higher force density in the air gap than the other machine types. However the force density of TFPMG with large air gap may be a little high or even low depending on the outside diameter. Unfortunately, the electromagnetic structure is more complicated than for conventional generator types and so it is more expensive to manufacture. The TFPMG has a very high force per weight ratio and low power factor which leads to an increase in the necessary rating of the power electronic converter. There is some different rotor structures for this topology, such as the rotor with single sided or double sided flux concentration and with single sided surface magnets. TFPMG seems to be suitable for direct drive applications because of the high specific torque, although special methods of manufacturing and assembly are required.

2.4 Comparison of Different Rotor Topologies

The type of permanent magnet generators that are analyzed in this paper are radial flux PMG, axial flux PMG and transverse flux PMG. The comparison between RFPMG and AFPMG topologies on different criteria is shown in Table 1. The transverse flux PMG has the strength of considerably low copper loss and high specific torque than AFPMG and RFPMG. But it has the drawbacks of structural complexity and low power factor. The TFPMG is probably better than the radial flux PMG but it is not included in the comparison since it does not seem to have gained a foothold in wind power generation.

Table 1
Comparison of RFPMG AND AFPMG

S.No	CHARACTERISTICS	RADIAL	AXIAL
1.	Construction	Mechanically robust and structurally stable	Structurally instable
2.	Heat removal	Poor removal of heat through air gap	Good ventilation and cooling of stator winding
3.	Active weight and axial length	Much bigger	Small
4.	Rotor diameter	Very less with limited number of poles	Large with more number of poles
5.	Applications	Mostly used for high speed applications	Most suited for low speed direct drive applications
6.	Size	Comparatively larger	Highly compact
7.	Reduction of active material and machine cost	Hard to reduce the active material and machine cost	Saving of active material and reduction of machine cost is possible

Table 2
Advantages and Disadvantages of Different Magnets

S.NO.	PERMANENT MAGNET MATERIALS	ADVANTAGES	DISADVANTAGES
1.	Neodymium-Iron-Boron	-High remanence -Highest energy product -Good coercivity -Compact -Low energy cost -Linear II quadrant curve	-Performance varies/Temp -Susceptible to corrosion -Difficult to magnetize -Low service temperature -May require Zinc or Nickel coating
2.	Samarium Cobalt	-High energy product -High coercivity -Higher corrosion and oxidation resistance -High service temperature -Very good thermal stability -Linear II quadrant curve -Compact	-Brittle -High cost -Difficult to magnetize
3.	Alnico	-Higher thermal stability -High flux density -High service temperature -Low tooling cost -Complex shapes -Easy to magnetize - Non-linear II quadrant curve	-Very low coercivity -Hard and brittle -Cost variability -Required thickness
4.	Ceramic	-High coercivity -Low cost -High corrosion resistance -Easy to magnetize -Linear II quadrant curve	-Low remanence -Brittle -Limited shapes -Low energy product -Performance varies/Temp -high tooling cost
5.	Flexible	-High flexibility -Easy to magnetize -Easily shaped -Requires little machining	-Low energy product -Low service temperature -Performance varies/Temp

3. Theoretical Analysis of Different Types of Magnetic Materials

A permanent or hard magnetic material retains magnetism or remanence even in the absence of an applied magnetic field and exhibits a large intrinsic coercivity i.e., the field required to demagnetize the material. The permanent magnet family consists of non-rare earth magnets and rare-earth magnets. The non-rare earth magnets include Alnico (Aluminum-Nickel-Cobalt) magnets and Ceramic (Strontium and Barium Ferrite) magnets. A special form of Ceramic magnet is "Flexible" material, made by bonding Ceramic powder in a flexible binder. The rare-earth magnets include SmCo (Samarium and Barium Ferrite) magnets and NdFeB (Neodymium-Iron-Boron) magnets. Two major families of rare earth permanent magnets, Smco magnets and NdFeB magnets, have been widely used in a variety of applications. Both the magnets NdFeB and SmCo have the main advantage of high magnetic material properties at small sizes in comparison with traditional ferrites, Alnico and other materials [7] [8]. The desirable qualities of permanent magnet materials are high coercivity, high saturation magnetization, high remanence, high energy product and nearly linear second quadrant B-H characteristics. The advantage and disadvantages of these magnets [9] are explained in Table 2.

4. Selected Permanent Magnet Material and PMG Topology

The NdFeB magnet is chosen to be the best when compared to SmCo and Alnico magnets. Even though the SmCo magnet consists of higher magnetic properties like that of NdFeB it is very expensive. Among the second quadrant B-H curve of all the magnets Alnico has the highest flux density but it is non-linear. However, NdFeB magnets are linear and it exhibits the highest properties of all magnetic materials at room temperature. B-H characteristics of permanent magnet materials are shown in Fig. 8. The surface mounted AFPMG may be a better choice for low speed direct drive wind turbines. Among various types of topologies in AFPMG, for low-speed applications the most commonly studied is Torus machine. It is a slotless, toroidal stator, double sided, axial-flux, disc type, permanent magnet brushless machine. The highest efficiency exists in the double rotor axial flux machine, as the iron loss in this configuration is the least. The advantages of this machine are very light, highly compact and high power to weight ratio. The salient features of the Torus machine are summarized as follows: 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 at high electric loading. Vibration and high frequency rotor losses associated with stator slot opening are also eliminated [10].

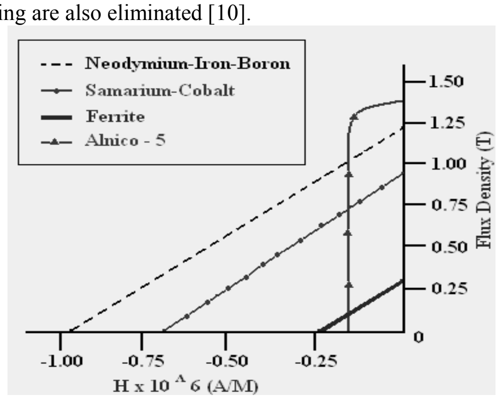


Fig. 8. B-H Characteristics of Permanent Magnets

4.1 Mathematical Equation for Wind Turbine Model

Wind turbines can be classified into vertical axis type and horizontal axis type. Most modern wind turbines use a horizontal axis configuration due to the advantages of low cost, high efficiency and ease in design for high power ratings. The output power of the wind turbine is given as (1),

$$P = \frac{1}{2}\pi\rho R^2 V^3 C_p \tag{1}$$

Where P is the mechanical output power of wind turbine (W), ρ is the air density in (K_g / m^3), R is the radius of the turbine (m), V is the wind speed (m/s) and C_p is the power coefficient of the turbine which in turn is a function of tip speed ratio λ [10] and blade pitch angle β (deg). Tip speed ratio is the ratio of blade tip speed to wind speed. C_p is expressed as a function of the tip speed ratio λ [8] given by (2),

$$\lambda = \frac{R\omega_t}{V} \tag{2}$$

It is important to note that the aerodynamic efficiency is maximum at the optimum tip speed ratio. The torque value obtained by dividing the turbine power by turbine speed is given as (3),

$$T_t(V, \omega_t) = \frac{1}{2}\pi\rho R^3 C_t(\lambda) V^2 \tag{3}$$

Where C_t (λ) is the torque co-efficient of the turbine, given by (4),

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \tag{4}$$

The power co-efficient C_p [8] is given by (5),

$$C_p(\lambda) = \left(\frac{116}{\lambda 1} - (0.4 * \beta) - 5\right) 0.5 e^{\frac{-165}{\lambda 1}} \tag{5}$$

Where

$$\lambda_1 = \frac{1}{\left(\frac{1}{(\lambda + 0.089\beta)} - \frac{0.035}{\beta^3 + 1}\right)} \tag{6}$$

4.2 Modeling of Proposed DDPMG Topology

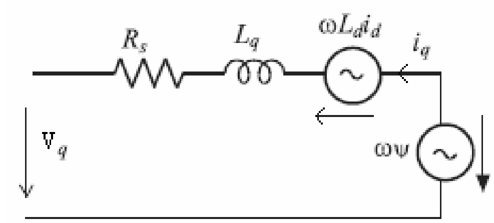


Fig. 9. Quadrature axis model of PMG

A specific model of the machine is required to determine the steady state and transient behavior of the PMG. The equivalent circuit of q-axis model of PMG is shown in Figure 9. The model of PMG can be obtained by means of two phase machines in direct and quadrature axes. The d-axis is a rotor magnetic axis and the axis that leads the d-axis by 90° is called q-axis [5]. The equivalent circuit for a d-axis model of PMG with the rotor reference frame is shown in Fig. 10.

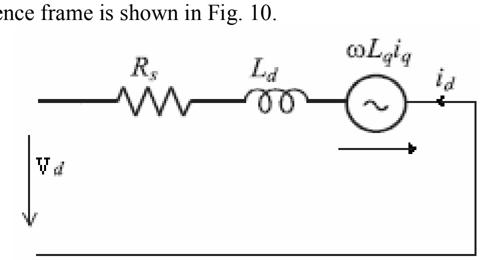


Fig. 10. Direct axis model of PMG

The convention terminal voltage equation of the PMG driven by the wind turbine obtained from the above dq model may be expressed in the matrix form as,

$$[V_{abc}] = -[R_{abc}][i_{abc}] + \rho[\psi_{abc}] \tag{7}$$

The complete model of the generator is derived in dq-coordinates. The voltage equations for d and q axes [1] are given by,

$$V_d = -R_s i_d - L_d \frac{d}{dt} i_d + \omega_r L_q i_q \tag{8}$$

$$V_q = -R_s i_q - L_q \frac{d}{dt} i_q - \omega_r L_d i_d + \omega_r \psi_m \tag{9}$$

As the position of the magnets in the rotor determines, independently of stator voltages and currents, the instantaneous induced emfs and subsequently the stator currents and torque of the machine, the rotor reference frame is preferred. When rotor reference frames are considered, it means the equivalent q and d axis stator variables are transformed to the reference frames that are revolving at rotor speed.

The electromagnetic torque in the rotor is given by,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[(L_d - L_q) i_q i_d - \psi_m i_q\right] \tag{10}$$

The input torque with respect to the torque developed in the wind turbine and the rotor angular velocity of the generator ω_r is related as,

$$T_i = J\left(\frac{2}{P}\right)\rho\omega_r - T_e \tag{11}$$

Assume that the air gap is uniform and the stator inductances of q and d axes windings are equal to L_s. The output voltages of PMG in rotor reference frame is $V_q = V_s$, $V_d = 0$. Under this assumption by substituting the above values, the voltage equation in q-axis and electro magnetic torque may be expressed as,

$$V_s = -(R_s + \rho L_s)i_q + \omega_r \psi_m \quad (12)$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[-\psi_m i_q\right] \quad (13)$$

5. Results and Discussion

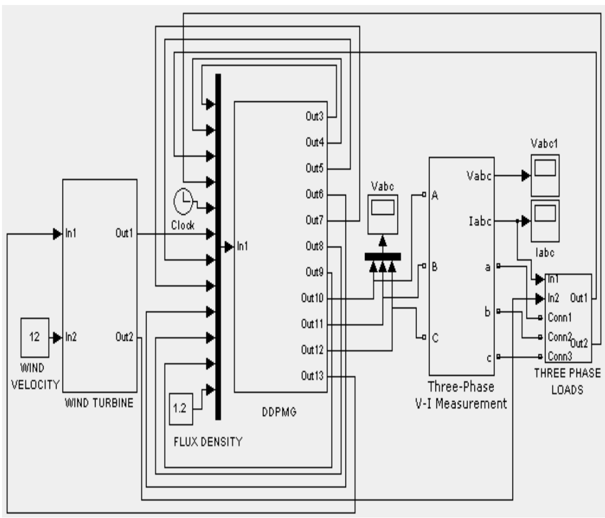


Fig. 11. Matlab/Simulink Model of PMG Driven by Wind Turbine

The equations discussed above have been modeled in the Matlab/Simulink. In order to simplify the implementation, the main computation part has been written in a function format. The simulated model of the wind turbine driven PMG with three phase loads is shown in Fig. 11. The rotor of the PMG consists of the permanent magnets. The characteristics and the flux distribution of permanent magnet decide the output voltage of the PMG. The various types of magnetic materials are analyzed on the basis of generated voltage, voltage drop, THD and load current for fixed wind velocity of 12m/s. The results of the comparison are discussed in the following sections. The types of magnetic materials, along with its grades and values of flux density taken for analysis are shown Table 3.

Table 3
Permanent Magnet Materials

S.NO	PERMANENT MAGNETIC MATERIAL	GRADE	REMANENT FLUX DENSITY IN TESLA
1.	Flexible	1	0.16
2.	Ceramic	8	0.39
3.	SmCo	26	1.05
4.	NdFeB	N35H	1.2
5.	Alnico	5	1.25

5.1 Output Voltage and THD for Different Magnetic Material

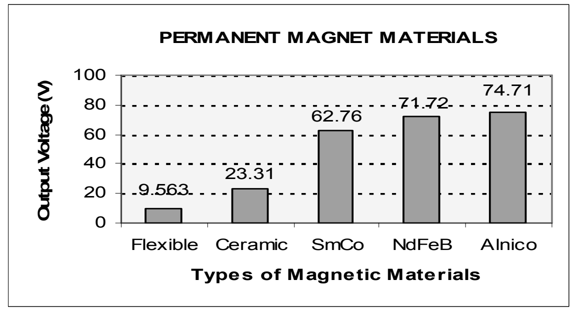


Fig. 12. PMG output voltages for different PMM

Fig. 12 shows the types of permanent magnet materials available and their corresponding output voltage when used in PMG under no load. If NdFeB magnet is used in the rotor, the stator produces the voltage of 71.72V and Alnico produces 74.71 V. But, NdFeB magnets are preferred as the Alnico magnets are high temperature sensitive and have less coercivity.

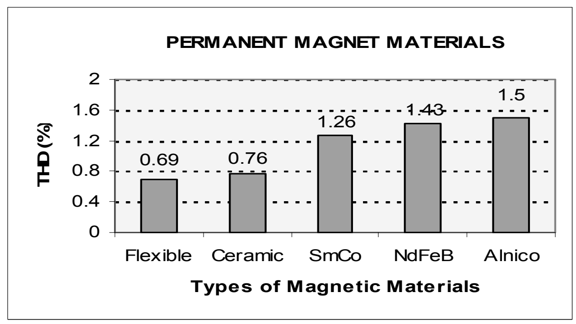


Fig. 13. THD for different PMM with load

Fig. 13 shows THD for different permanent magnet material under certain load condition. The THD of NdFeB and Alnico are higher than the THD of other permanent magnet materials comparatively. As the remanent flux density of the magnet increases the output voltage and also the THD is increased. But the THD of NdFeB is less when compared to Alnico.

5.2 Terminal Voltage Vs Load Power

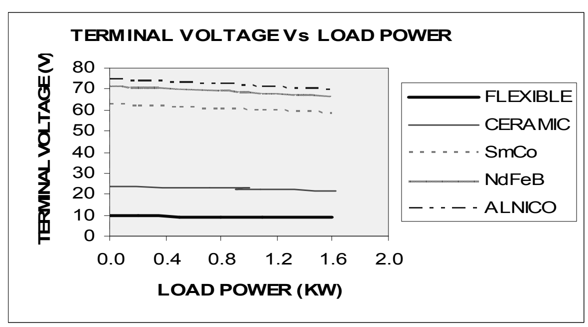


Fig. 14. Terminal voltage Vs load power

Fig. 14 shows variation of terminal voltage with respect to the load power. The no load voltage of Alnico is higher than SmCo and NdFeB, whereas the ceramic and flexible magnets has very less voltage. The change in terminal voltage from no load to full load is 8.5% for Alnico but for NdFeB it is 7.97% only.

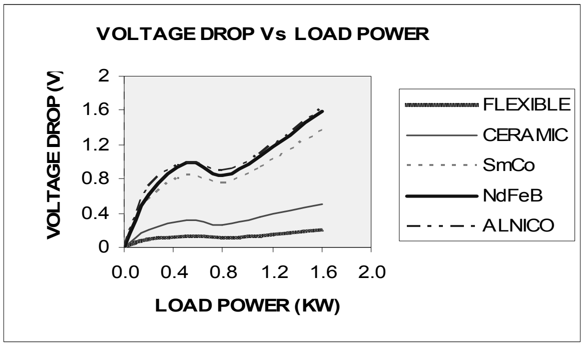


Fig. 15. Voltage drop Vs load power

Fig. 15 shows the drop in voltage due to the variation of load power for different magnetic materials. With the increase in the load the drop in the terminal voltage also increases. The drop in voltage for ceramic and flexible magnets are very less when compared to NdFeB magnets. For Alnico, SmCo and NdFeB magnets the drop in voltage is increased as the load power is increased. Since, SmCo is costlier than NdFeB and Alnico, NdFeB is preferred to be better.

5.3 THD Vs Load Power

Fig. 16 shows the variation of THD for different permanent magnet material under varying load conditions. If the load power of the PMG is increased, the load current also increased and thus results in more harmonic distortion. The variation in THD is linearized after certain loading conditions. THD for ceramic and flexible magnets are very less compared to other types whereas for NdFeB magnet it lies between Alnico and SmCo.

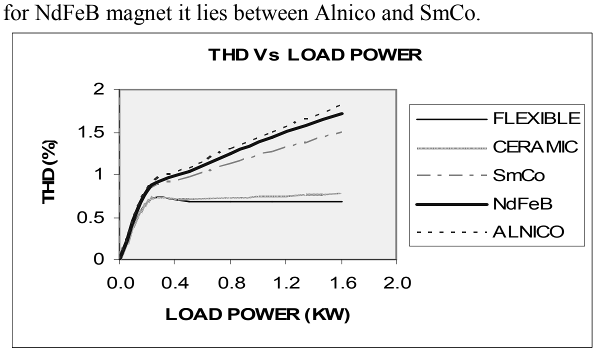
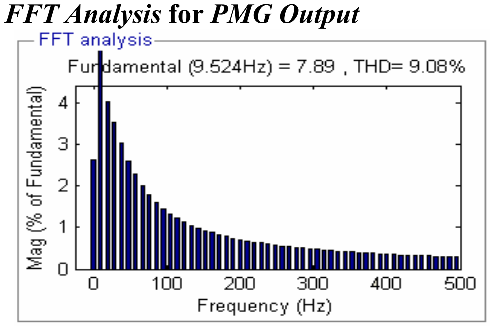
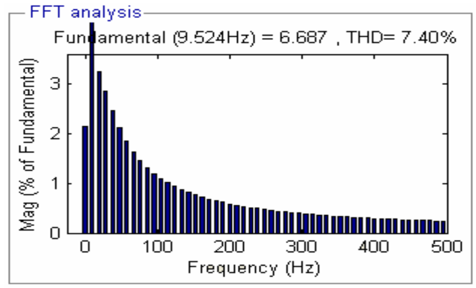


Fig. 16. Total harmonic distortion Vs load power

5.4 *FFT Analysis* for *PMG Output*



(a)



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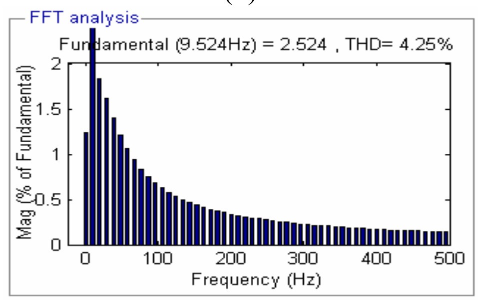

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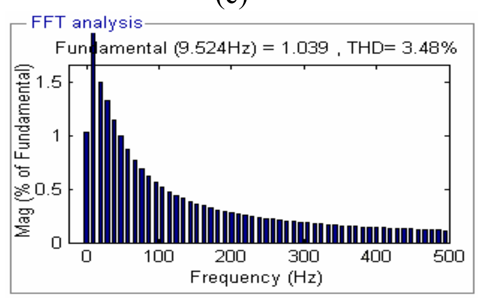
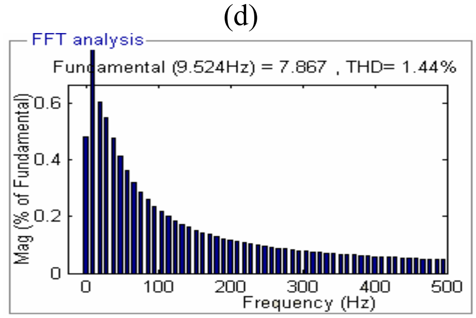


(d)



(e)

Fig. 17. FFT analysis for PMG output with different permanent magnets (a) Alnico; (b) SmCo; (c) Ceramic; (d) Flexible and (e) NdFeB

Fig. 17 shows the FFT analysis for PMG with different types of magnets placed in its rotor. The THD of the PMG output is measured with the help of FFT analysis for a fixed wind velocity of 12 m/s. For Alnico and SmCo magnets the THD is very high with the values of 9.08% and 7.4%. Moreover, the THD of Ceramic and Flexible magnets are feasible about 4.25% and 3.48% but the output voltage is very less when compared to NdFeB magnets. In spite of the different types of magnets the best THD is obtained from the NdFeB magnet with the value of 1.44%.

5.4 Output Voltage and Load Current Waveforms for Proposed PMG

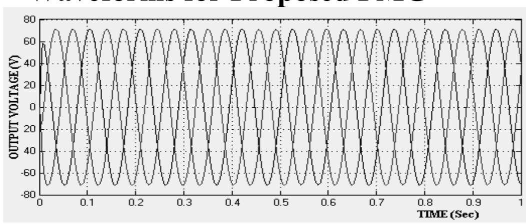


Fig. 18. PMG output voltage for NdFeB magnet

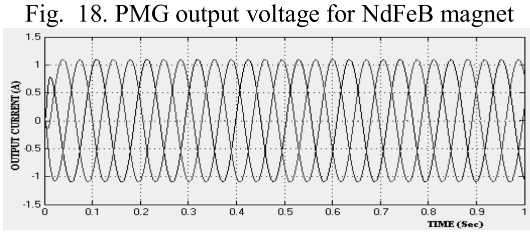


Fig. 19. PMG load current for NdFeB magnet

Fig. 18 shows the output voltage of PMG having NdFeB magnets. Similarly, the PMG model is analyzed with different values of flux densities. The output voltage of NdFeB magnet is 68.18 V for fixed wind velocity of 12 m/s. Figure 19 shows the load current of PMG having NdFeB magnets in its rotor.

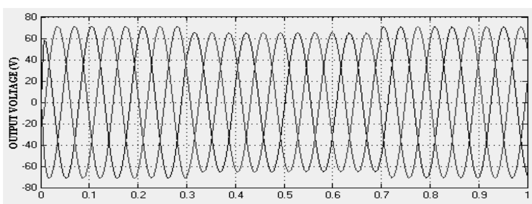


Fig. 20. PMG output voltage for NdFeB with varying loads

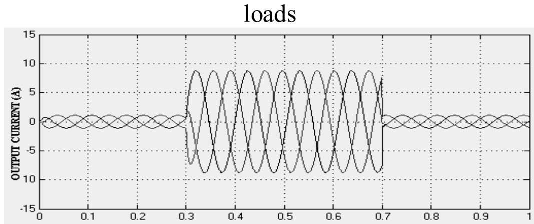


Fig. 21. PMG load current for NdFeB with varying loads

Fig. 20 and Fig. 21 shows the output voltage and output current waveforms of PMG having NdFeB magnets with continuously varying load conditions. The output voltage of PMG with NdFeB magnet is reduced and its load current is increased, when there is increase in the load dynamically.

6. Appendix

Specifications

PMG: Rs=0.34Ω, Ls=0.65 mH, ψ_m = 1.2 T, P=18.

7. Conclusion

With the improved performance and low cost of PMG in recent years, the variable speed direct drive PMG becomes more attractive. The paper provides a comparison on different topologies of PMG for low speed direct drive applications with their advantages and disadvantages. For most of the comparisons, the low speed constructions are superior, since the multipole PMG are preferred in low speed gearless wind systems. The Torus construction is simple and is more suitable for low power rating wind generators. There are different types of permanent magnet materials available to be used as in the rotor of PMG. The proposed DDPMG for variable speed wind energy conversion system has been analyzed with different types of modern permanent magnet materials based on their characteristics. Among all the permanent magnet materials, NdFeB magnet is observed to be better since it yields high energy density with less weight, high coercivity and moderate temperature sensitive. Simulation study was carried out on proposed WECS with different types of permanent magnet materials in MATLAB/SIMULINK.

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