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The Impact of the Selection of Permanent Magnets on the Design of Permanent Magnet Machines – a Case Study: Permanent Magnet Synchronous Machine Design with High Efficiency

***Abstract**. Considering that the natural sources of the earth are limited, it is necessary to produce economical electrical machines with a high efficiency through better design and a proper selection of materials. At present, magnets have a high energy product (BHmax) with suitable magnetic and physical properties for applications in electrical machines. This paper considers how an electrical engineer could take modern Permanent Magnets (PMs) into account when designing a PM machine. Also in this study, the magnetic and mechanical properties of synchronous PM machines are analysed via the Maxwell program based on finite element analysis. Furthermore, the simulation results of the designed PM synchronous motors with different magnet material types on their rotors are compared against each other according to their efficiency, torque, speed and output power. As the last step, the design was optimized to achieve maximum efficiency. Furthermore, this paper shows the price guidepost of modern PMs, which indicates that there will be a large demand for magnets unless alternative technologies prevail.*

***Streszczenie.** W artykule przedstawiono symulacyjne porównanie działania maszyn synchronicznych z magnesami trwałymi, w zależności od materiału, z którego wykonano te magnesy. Wzięto pod uwagę sprawność, moment mechaniczny, prędkość i moc. Analizę własności magnetycznych i mechanicznych przeprowadzono z wykorzystaniem programu Maxwell, bazującego na analizie metodą elementów skończonych. Dodatkowo, dokonano optymalizacji modelu pod względem maksymalnej sprawności. (**Dobór rodzaju magnesów do maszyny synchronicznej z magnesami trwałymi dla uzyskania wysokiej sprawności**).*

Keywords: Permanent Magnets, Design of PMSM, Electrical Machines, FEM, Improvement of PMSM Design.
Słowa kluczowe: magnesy trwałe, projektowanie PMSM, maszyny elektryczne, FEM.

Introduction

PMs are necessary components in many fields of technology because of their ability to provide a magnetic flux without windings, and they have applications in a wide range of devices [1] such as electro-mechanical machines and devices, automation applications, mechanical force and torque applications, office equipment, computer peripherals, microwave devices, electron ion beam control sensors, acoustic and electric signal transducers, medical electronics and bioengineering, transportation and advertising.

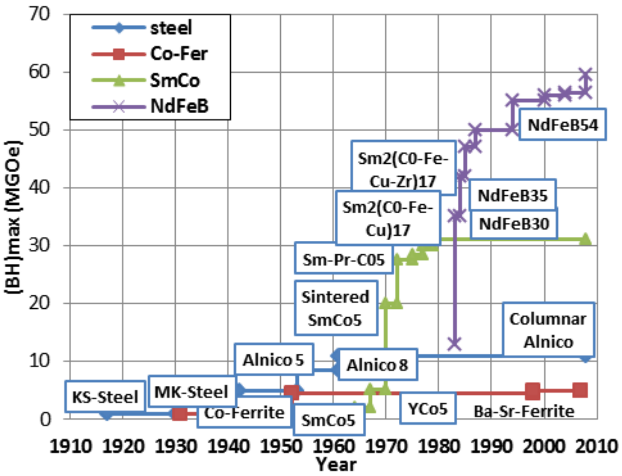

Fig. 1. Development of PMs.

The development of hard magnetic materials has been very rapid, with the advent of rare-earth PMs in the last few decades. Fig. 1 shows the important changes in PMs in the last century [2]. The improvement in PM materials over the past 90 years can be tracked by the BHmax value in the graph.

The use of magnets in electrical machines has increased due to developments in magnet features and the decrease in magnet prices. In the recent years, there have been many studies on the development of the design and operating characteristics of electrical machines with PMs [1]. Such trends and examples were discussed by Karl J. Strnat [3]. Design aspects of PM machines using NdBFe magnets were presented [4]. P. Pillay and R. Krishnan made a comparison of PMSM and BDCM types, obtaining application characteristics of these two magnets [5]. The theory and design of fractional-slot concentrated-winding synchronous PM machines together with their attributes such as high-power density, flux-weakening capability, comparison of single- versus double-layer windings, fault-tolerance rotor losses and parasitic effects as well as a comparison of their interior structure versus surface PM machines and various other electric machines were obtained by EL-Refaie [6].

China produces 97% of the world's rare earth elements, a key component in a large assortment of advanced military and civilian technologies. Increasing global demand and export quota reductions by the Chinese over the past six years have led to international concerns about future supply shortages [7]. Furthermore, wind power usage is increasing rapidly and the newest generators use PMs, specifically NdFeB types [8], as these magnets are vital for reducing the size and improving the performance of magnetic circuits. The PM market includes data that is readily available as well as data which is difficult to obtain or not credible for magnetic materials. According to some future sale estimates, NdFeB alone could account for sales over $17 billion by 2020 – that is, assuming adequate supplies of the raw materials [9]. Therefore, in the design of electrical machines, selection of appropriate materials and the proper design of the machine with all its components, including magnets, are crucial. Although sales of Ferrite magnets may seem high, their usage in the electrical machines with large power densities is not preferred because of Ferrite magnets' small BH_{max} value (41.4kJ/m^3).

In this study, the price guidepost of modern PMs are provided, magnetic and mechanical properties of synchronous PM motors with different magnet material types on their rotors are investigated and their simulation results are compared with each other according to their efficiency, torque, speed and power. The optimal efficiency was chosen as design criteria in the design process.

Characteristics of PM Materials

The magnets' characteristics must be known to decide which magnet is the most suitable for different applications. Requirements demanded by applications are flux density, BH_{max}, resistance to demagnetization, a good demagnetization curve, recoil permeability, corrosion resistance, electrical resistivity, a low magnetizing field requirement, a usable temperature range, acceptable magnetization change with temperature, physical strength, availability in particular size and shapes and manufacturability. Characteristics of PM materials can be classified generally under three groups as magnetic, temperature and manufacturing characteristics. These can be detailed as follows:

Magnetic Properties:

The basis of magnetic properties is the BH curve or hysteresis loop, which characterizes each magnet material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field. The demagnetization curve, which is in the second quadrant of the BH curve, describes the conditions under which PMs are used in practice. This curve provides specific information about how a given material performs under a variety of magnetic loading and temperature conditions. The curve is representative of the specific material used to make the magnet, and is independent of the geometry the magnet is made into.

Temperature Properties:

The major limitation in the application of magnets is the limited temperature tolerance. For PMs the BH loop changes shape with temperature. With an increase in temperature, all PM's lose remanence.

For maximum power density the product of the electric and magnetic loadings of the motor must be as high as possible. The electric loading is limited by thermal factors and the demagnetizing effect on the magnet. A high electric loading necessitates a greater magnet length in the direction of magnetization to prevent demagnetization. The greatest risk of demagnetization is at low temperatures when the remanent flux density is high and coercivity is low; in a motor, these result in the highest short-circuit current when the magnet is least able to resist the demagnetizing ampere-turns. It also necessitates a high coercivity, which may lead to more expensive grades of material (such as 2-17 cobalt-samarium), especially if high temperatures will be encountered.

Manufacture of PMs:

Another important characteristic of the magnets is manufacturability. PMs are manufactured by one of the following methods:

- Sintering (Rare Earths and Alnicos),
- Pressure Bonding or Injection Molding (Rare Earths),
- Casting (Alnicos),
- Extruding (Bonded NdFeB),
- Calendering (NdFeB)

A structural comparison of PMs is given in Table 1 which is an own elaboration based on [10-14]. The sintering process involves compacting fine powders under high pressure in an aligning magnetic field; the sintering is then fused into a solid shape [10]. After sintering, the magnet shape is rough, and will need to be machined to achieve close tolerances. Bonded magnets with complex geometries can be produced using multi-component injection molding techniques. A broad selection of polymer binders and polymer additives provide flexibility for production and satisfy the requirements of various applications including use in electric machines.

Table 1. Structural comparison of the PMs

Method	*Properties*
Sintering	*+ Maximum energy product for a given magnet size & weight *– Limited to simple geometries – Brittle *➢ Maximum Output
Injection Molding	+ Complex geometries + Relatively tough + Lower assembly costs + Allows high volume manufacturing – Lower BHmax ➢ Shaping flexibility
Pressure Bonding	+ Greater volumetric loading of magnetic phase – Complex magnetizing patterns – Brittle – Tight geometric tolerances – Limited to simple geometries ➢ Low cost manufacturing
Casting	+ Allows relatively complex shapes + Higher BHmax + Extremely hard and brittle – Difficult to machine – Lower mechanical resistance ➢ Shaping flexibility
Calendering & Extruding	+ Complex geometries + Easy to tool and machine – Lower BHmax ➢ Shaping flexibility

*+ Positive *– Negative *➢ Keyword

PM Materials Used in Motors

PMs are used in many different industrial products and for many different functions. As shown in Fig. 2, the worldwide use of PMs can be divided into seven main areas.

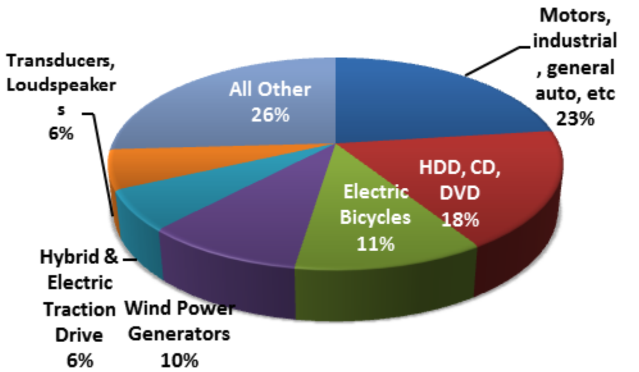

Fig 2. World output for Rare-earth PMs by applications.

Some fast growing applications are HDD, CD, DVD applications, Hybrid & Electric Traction Drives and wind power generators. One of the main uses for rare earth magnets, primarily NdFeB, is in electro mechanic devices such as hard disk drives, CD's and DVD's where the magnet is used both for driving the spindle motor and for positioning the read/write head. Hybrid automobiles and solely electric vehicles are becoming increasingly more common in the US and Europe.

Compared to their uses in the market, electrical machines have important application areas as seen in Fig. 2. PMs can be designed to be on the stator or the rotor. The magnets can be mounted on the rotor surface or embedded in the rotor. Opting for interior construction simplifies the assembly and relieves the problem of retaining the magnets against centrifugal force. It also permits the use of rectangular instead of arc-shaped magnets, and usually provides an appreciable reluctance torque which leads to a wide speed range at constant power. Use of PMs in the construction of electrical machines leads to the following benefits [10];

1. No electrical energy is absorbed by the field excitation system and thus there are no excitation losses which creates a substantial increase in efficiency,
2. Higher torque and/or output power per volume compared to electromagnetic excitation,
3. Better dynamic performance than motors with electromagnetic excitation,
4. Simplification of construction and maintenance,
5. Reduction of prices for some types of machines.

Replacing the field winding and pole structure with PMs usually permits a considerable reduction in the stator or rotor diameter, caused by the efficient use of radial space by the magnet and the elimination of field losses. In the meanwhile, field control is sacrificed by the elimination of brushes, slip rings, and field copper losses. Armature reaction is usually reduced and commutation is improved, owing to the low permeability of the magnet. The loss of field control is not as important as it would be in a larger drive since it can be overcome by the controller and in small drives the need for field weakening is already less common. Excitation combined with power electronics makes PM motors attractive for achieving constant torque and power characteristics.

Still, the cost of the magnet may be a limiting factor. The air-gap flux-density of A.C. motors is limited by the saturation of the stator teeth. Excessive saturation absorbs too much excitation MMF (requiring a disproportionate increase in magnet volume) or causes excessive heating due to core losses. The magnetic loading, or air-gap flux, is directly proportional to the remanent flux density of the magnet, and is nearly proportional to its pole face area. A high power density therefore requires the largest possible magnet volume (length times pole area). These motors have the disadvantage of high cost compared to conventional motors since it will be necessary to include power electronics. For economic reasons, the PM material in most small motors is sintered ferrite, although bonded rare earth PMs are of increasing importance. When the smallest possible weight and volume are desired, as in aerospace applications, dense SmCo and NdFeB can be chosen.

Alnicos (Al, Ni, CO, Fe), Rare-earth materials, i.e., SmCo and NdFeB are two classes of PMs currently used in electric motors. Basic characteristics of these PMs are given in Table 2. Alnico magnets, with the oldest PM material still in use, comprise a composite of aluminium, nickel and cobalt with small amounts of other elements added to enhance the properties of the magnet. Alnico can produce a strong magnetic flux in a closed magnetic circuit but has relatively small resistance against demagnetization, that is, relatively little coercity.

Compared to some other magnet materials Alnico magnets have good temperature stability, are less affected by temperature changes and have a very high Curie point.

Table 2. Basic characteristics of PMs

	Br (T)	Hc (kA/m)	BH_{max} (kJ/m^3)	Max. Oper. Tem. (°C)	Relative Cost by weight	Density (g/cm^3)	Relative permability (μ/μ_0)	Electrical Resisitivity ($\mu\Omega$·cm)	Cost($/)	Cost ($/kg)
Alnico5	1,25	50,93	43,8		15		2,2			
Alnico8	0,83	131,3		540		7,3	2	45 - 75	$ 12.08	% 23,379
Alnico9	0,7	151,2	39,8		10		1,5			
SmCo24	1	708,2	191	350	115	8,3	1,05	80 - 90	$ 51.67	% 100
SmCo28	1,07	819,67	222,8	380	130					
NdFeB30	1,1	843,54	238,7			7,42	1,09			
NdFeB35	1,23	899,25	278,5	300	70	7,4		120 - 160	$ 41.59	% 80,491
NdFeB54	1,5	1050	437,7			7,5	1,05			

Samarium cobalt is a type of rare earth magnet material that is highly resistant to oxidation, has higher magnetic strength, high remanence, high instrict coercivity and high corrosion resistance. Additionally, it shows very low variation of field strength with differing temperatures, has better temperature resistance than Alnico material, a very high Curie point and high corrosion resistance.

Another important type of magnet is Neodymium Iron Boron (NdFeB). NdFeB with BHmax increased to up to 437,7kJ/m^3 (for NdFeB54), is the latest and most powerful type in another family of rare earth magnetic materials, which is used in large machine applications. This material has similar properties as Samarium Cobalt except that it is more easily oxidized and generally doesn't have the same temperature resistance. They offer the highest possible remanence and depending grade. NdFeB magnets are highly corrosive and brittle, except in some molded and sheet forms. The material has also been improved, with lower chemical reactivity, improved consistency, and high recommended temperatures for long-term use. Surface treatments including gold, nickel, zinc and tin plating and epoxy resin coating have been developed that allow them to be used in most applications. The trend to polymer-bond magnets is increasing with the availability of anisotropic powders [13, 14]. For many applications, these favorable features have made NdFeB the first choice of magnet, resulting in its widespread use [15].

Compared to other PMs, NdFeB magnets are more sensitive to temperature and special care must be taken in their design for working temperatures above 100 °C. For very high temperature applications Alnico or rare-earth cobalt magnets must be used. A samarium-cobalt magnet tends to break down magnetically at 700-800°C, the Curie temperature of most samarium-cobalt magnets, after which the material's performance will be significantly degraded. It can be recommended to consider SmCo magnets for high temperature applications of low to moderate tonnage requirements.

Compared to SmCo, NdFeB magnets have a magnetic energy product of up to a magnitude larger, high remanence and high intrinsic coercivity. These attributes are important in PM machines [16]. The focus on devices with low weight and small size has driven usage of rare earth magnets so that NdFeB magnets now represent over half of all magnet sales on a dollar basis.

Analysis of PM Machines Using FEM

In this study, 0.55kW, 220V and 4 poles PM Synchronous Machines (PMSM) are designed. Eight different PMs, whose characteristics are given in Table 2, are used in the motor's rotor. Therefore, eight unique motor simulations are performed. The effect of material properties and the costs of operating the machine were investigated in the case of using different type materials in the rotor magnets of PM motor.

The analyses were performed for eight different machines with different magnet materials and dimensions. A magnetic examination of the designed PMSMs, according to an iron sheet package structure with the same magnet dimensions used in the designed motors, was performed. From this electromagnetic analysis, the actual potential magnetic flux intensity of the motors were obtained.
Detailed knowledge of the field distribution in the air gap of a PM motor is of great importance for the accurate prediction of torque and efficiency characteristics. In this study, the magnetic examination of the designed PMSM according to an iron sheet package structure was performed using the Maxwell 2D program. From this electromagnetic analysis, the actual potential magnetic flux intensity of the motor was obtained. The design criteria is chosen as maximum efficiency for each machine taking the magnet size, material selection and machine size into account. The number of slots, stator and inner-outer diameters, the number of contactors per slot and the dimensions of the magnets of the machines designed to produce the same output power were improved by aiming for the output of the highest power output machine's design with maximum efficiency.

The analysis is conducted according to data given in Table 3 by changing only the types and geometries of PMs. After that, the design was optimized using the data given in Table 3 to achieve the maximum efficiency.

Table 3. General data for the designed motors

	STATOR DATA				ROTOR DATA			
Magnet Type	No. of Slots	Outer Diameter (mm)	Inner Diameter (mm)	Conductor per Slot	Outer Diameter (mm)	Inner Diameter (mm)	Width of Magnet (mm)	Thickness of Magnet (mm)
Alnico5				41			69.136	8
Alnico8	36	165	115	45	114	35	59.974	11
Alnico9				44			68.814	8
SmCo24	24	130	85	54	84	30	48.4	7
SmCo28		125	80	53	79	28	45.44	
NdFeB30				55			41.62	7
NdFeB35	24	120	75		74	26	42.5	5
NdFeB54				50			40.28	4

Results & Discussion

In the magnetic analysis, the no-load operation flux density of the designed motors was found as given in Table 4. The flux line distribution of the machine designed with NdFeB54 is given in Fig. 3 passes over stator and rotor and through the air gap. So, the orderly layout of the flux lines proves that the design is acceptable. When the results tables, figures and saturation points of the PMs are considered, all designed machines are observed to be running stably without reaching saturation.

Table4. Magnetic data: Flux densities (T)

Magnet Type	Stator-Teeth	Stator-Yoke	Rotor-Yoke	Air-Gap	PM
Alnico5	1.378	1.638	0.66	0.527	0.587
Alnico8	1.24	1.344	0.60	0.474	0.555
Alnico9	1.3	1.54	0.624	0.497	0.55
SmCo24	1.538	2.083	1.07	0.745	0.857
SmCo28	1.72	2.08	1.22	0.79	0.913
NdFeB30	1.9	1.988	1.05	0.818	0.95
NdFeB35	1.99	2.04	1.1	0.854	0.957
NdFeB54	2.127	2.02	1.037	0.915	1

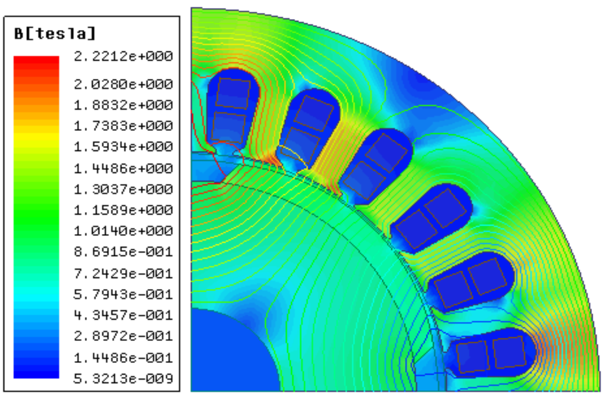

Fig. 3. Magnetic Field Density waveform of NdFeB54.

After the required simulations, the analysis results given in Table 5 were obtained. It can be seen that to enable the Alnico family -whose efficiency is far less than the others'- to run efficiently at the determined output power, a higher ampere turn value was required. To obtain that value, the size of the machine, the number of slots and the dimensions of the magnets were increased. In the SmCo family, only the magnet and the dimensions of the machines needed to be increased. As for the NdFeB family whose efficiency is much higher than the others, no significant changes needed to be made as shown. In the machine design with NdFeB54 PMs, taking the height of the stator flux density into account, more efficient machines with different characteristics can be designed by reducing the sizes of the PMs or changing the number and type of the winding. In the same way, efficiencies as high as that of the machine designed with NdFeB54 PM Material can be achieved by improving the design criteria, to reach the max efficiencies.

The primary determinants of magnet cost are the torque per unit volume of the motor, operating temperature range, and the severity of the magnet's operational duty. As seen in Table 5, the motor designed with NdFeB54 PM has the highest efficiency and highest magnetic flux density on the rotor and stator core; also shown in Fig. 3. This pinpoints the accuracy of the analysis that PMSM designed to have the same output power have a close output momentum with each other in the analysis. Prices for magnets were taken as price per kg in order to compare the economic point of different PMs.

The machine parameters, namely the electromagnetic torque and load angle are very important in the analysis of electrical machines. Using torque angle, also known as load angle, some important operation characteristics of the machines can be examined. And proper selection of the required machine can be achieved using these characteristics which are given from Fig. 4 to Fig. 7.

Table 5. Analysis results

Magnet Type	Efficiency (%)	Air-Gap Flux Density (T)	Rated Torque (Nm)	Rated Speed (rpm)	Total Weight (kg)	Magnet Weight (kg)	Total PM Cost ($)
Alnico5	92	0.528	3.7	Synchronous Speed (1500)	10	1.077	13
Alnico8	91.43	0.474	3.5		9.95	1.3	16
Alnico9	92.013	0.462	3.5		10.12	1.072	13
SmCo24	91.9	0.745	3.51		6.34	0.76	39,5
SmCo28	91.98	0.78	3.5		5.81	0.714	37
NdFeB30	91.91	0.82	3.5		5.47	0.59	25
NdFeB35	92.01	0.85	3.45		5.4	0.416	17,5
NdFeB54	92.37	0.915	3.37		5.27	0.314	13

The torque angle vs. output power characteristics of the designed machines are obtained as shown in Fig. 4. As seen in Fig. 4, machines designed with the Alnico family are more capable of loading than the others. The machine designed with NdFeB54 has the highest output value (2.2kW) at the torque angle of approximately 110°. Depending upon the application, selecting the motor designed with NdFeB family PM will be more appropriate if the output power is the most important parameter. Output power range of NdFeB and SmCo families PMs are also higher compared to Alnico PMs. Therefore, they can be easily adapted to very high output power variations.

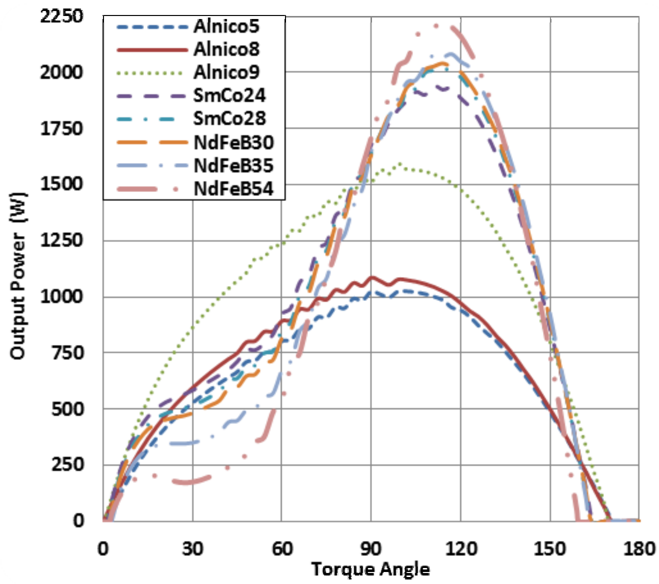

Fig. 4. Torque angle vs output power

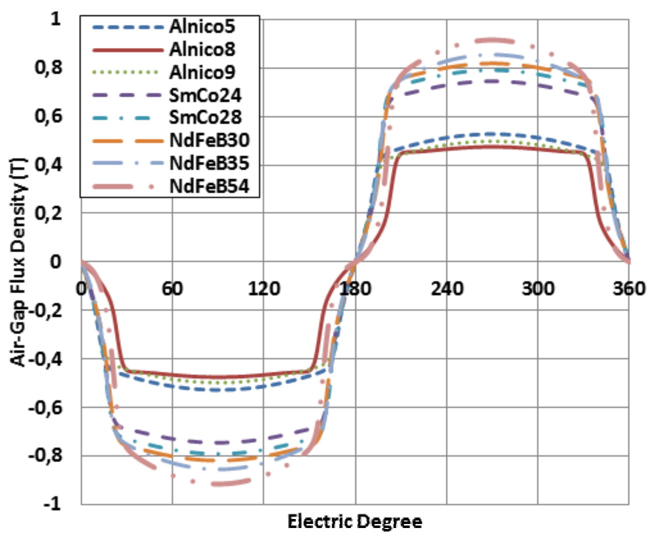

Fig. 5. Electric degree vs. Air-gap flux density

Air-gap Flux densities of the designed machines, which determine the degree of harmonics, are given in Fig. 5. As seen in Fig. 5 the air-gap flux density of the machine designed with NdFeB54 is the highest because of its highest BHmax. Air-gap flux densities, which are obtained after the shaping of pole (magnet) heads, show that the tension inducted from the stator slots has become more proper (sinusoidal).

The analysis shows differences in the efficiencies of the machines, as shown in Fig. 6, even though all eight different machines work with the same output power and synchronous speed. In addition, in the machine design with NdFeB54 PMs, when we consider the height of the stator flux density, more efficient machines with different characteristics can be designed by reducing the sizes of the PMs or changing the number and type of the winding. In the same way, efficiencies as high as that of the machine designed with NdFeB54 PM material can be achieved by improving the design criteria, to reach the efficiencies given in Table 5. As shown in Fig. 6, all efficiencies of the machines were arranged to be equal to each other to ensure that the tables in which the results of the analyses appear and the graphics provided at the end of the results of the analyses are coherent.

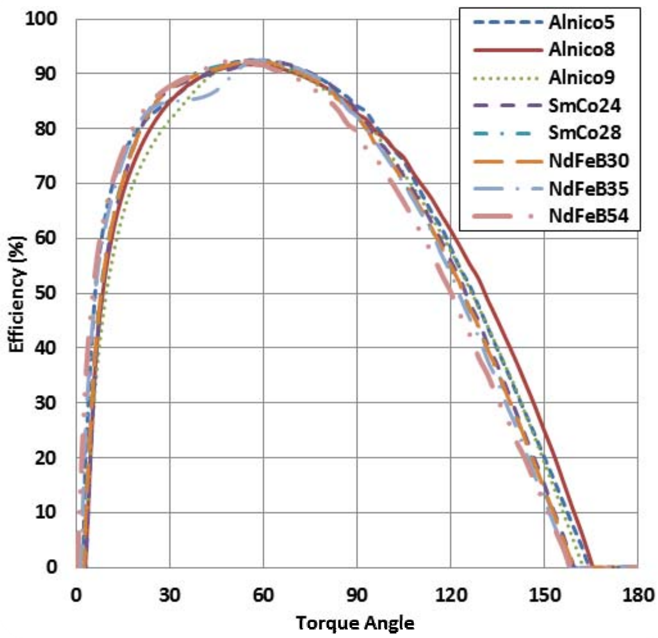

Fig. 6. Torque angle vs efficiency

Fig. 7 indicates the load angle vs. input current. As can be seen from the figure, the Anlico PM family has the lowest loading capacity while the NdFeB PM family has the highest. Choosing the motor designed with the NdFeB family will be more appropriate if the loading capacity of the motor is of the highest importance.

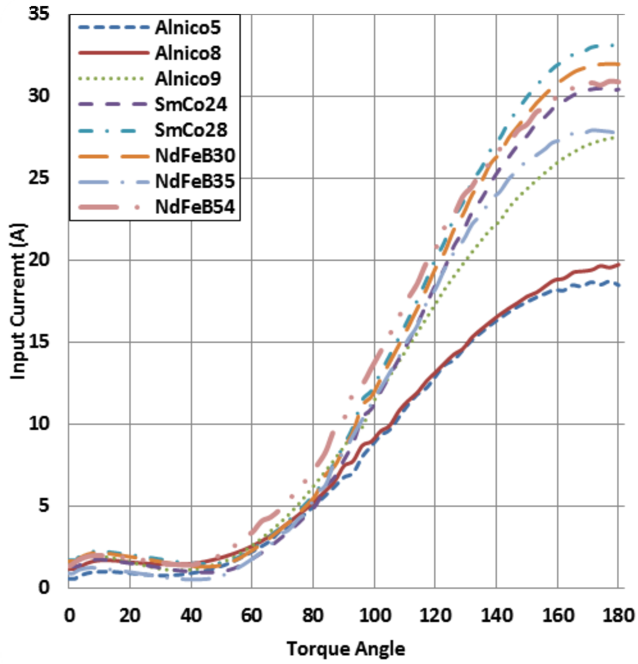

Fig. 7. Torque angle vs input current.

Conclusion

In this study, the possibility of using different PM materials in the rotors of PMSM's is investigated. A general and magnetic analysis of designed PMSMs with power of 0.55kW and a speed of 1500rpm is made changing only the PMs by using Maxwell program, and the results of the analysis were compared in terms of topology, size, magnetic field, air-gap flux, voltage, torque, speed, losses, weight, and efficiency. Furthermore, a price guidepost for modern PMs was shown.

After the analyses, it is realized that the efficiency of the machine is dependant on the type of the PM. The highest efficiency was achieved when the machine was designed with NdFeB54 PM, which is produced with the latest improvements in materials technology. Furthermore, the machine designed with NdFeB54 PM is more advantageous than others when price, volume and characteristics obtained from the analysis are investigated. Therefore, machine designers should consider using the very best sintered NdFeB magnets, keeping their high-remanence and high-intrinsic coercivity in mind.

When the flux distribution and magnetic field strengths are modeled properly, it is possible to design smaller and more economical machines. Wherever small size and low weight are needed, rare earth magnets are a necessity.

Modern magnet materials are available in many different alloys, each designed for a different objective. The ultimate objective is to choose the most economical magnet to reliably reach the design goals. To design a machine with optimum efficiency, correct selection of the magnet material, size, and shape is very important.

New applications and design concepts are evolving, and electrical machines and other devices are becoming further miniaturized as a result of the broader use of magnets. The demand for magnets will remain high unless alternative technologies and materials prevail.

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