Development of Non-rare-earth Magnetic Gears for Electric Vehicles

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Abstract
This paper presents the development of non-rare-earth magnetic gears for electric vehicles. Firstly, the magnetic gears which adopt either non-rare-earth or rare-earth permanent magnets (PMs) are discussed. Then, by using the finite element analysis, the electromagnetic performance of these magnetic gears are evaluated and quantitatively compared based on the same structure. Also, the natural magnetic characteristics of the non-rare-earth and rare-earth PMs are compared. Finally, a comparison of the cost-effectiveness among different types of PMs is carried out. The results indicate that the non-rare-earth PM material is preferred to the rare-earth PM material for application to magnetic gears.

Keywords
electric vehicle, magnetic gear, non-rare-earth element, permanent magnet, rare-earth element, cost-effectiveness comparison

1. INTRODUCTION

Mechanical gears and gearboxes play vital important roles in electric vehicles (EVs). With the help of the mechanical gears and gearboxes, torque and speed can be amplified for various practical applications, such as amplifying the speed (reducing the torque) and amplifying the torque (reducing the speed) to satisfy different driving requirements and road conditions. However, they suffer from some inherent drawbacks, such as the wear-and-tear, contact friction, annoying noise and regular maintenance [Chau et al., 2008].

Obviously the advent of the magnetic gear attributes to the application of permanent magnet (PM) materials which can produce a persistent flux and magnetic force and realize contactless torque transmission. It is well known that these characteristics made the replacement of mechanical gears by magnetic gears possible. Magnetic gears offers the merits of physical isolation, silent operation, maintenance free and inherent overload protection [Chau et al., 2007; Jian and Chau, 2009; Liu et al., 2009; Li et al., 2011].

The first PM material applying to the magnetic gear is non-rare-earth ferrite which can only transmit low torque [Huang et al., 2008]. Ferrite has the advantages of low price, easy manufacture and high coercivity, whereas low remnant flux density is its obvious demerit. Before the invention of rare-earth PMs, aluminium-nickel-cobalt (Alnico) which takes the definite merits of high remnant flux density and abundant elements is also used to develop magnetic gears. After the advent of high-energy rare-earth PM materials such as the neodymium-iron-born (NdFeB) PM and samarium-cobalt (SmCo) PM, they become the PM materials widely adopted for magnetic gears [Atallah and Howe, 2001].

Recently there is an increasing concern on the price and supply of rare-earth elements. Although the rare-earth magnetic gears have better performance, their fluctuant and expensive price and finite reserves will increase the cost of EVs manufacture, hindering further application in EVs.

This paper presents the development of magnetic gears, with emphasis on the comparison between the non-rare-earth and rare-earth magnetic gears. In Section 2 a comprehensive review of magnetic gears will be conducted. In Section 3, based on the same structure, the magnetic gears installed with Alnico, NdFeB and SmCo PM materials will be analyzed and compared. Section 4 will discuss the application of magnetic gears for EVs. At last, a conclusion will be drawn in Section 5.

2. REVIEW OF MAGNETIC GEARS

The basic concept of the magnetic gear can be tracked down to the beginning of the 20th century when a US patent described a device consisting of two rotational shafts with salient electromagnets on their rims [Neuland, 1916]. However, it attracted no attention at that time for its low efficiency and complicated structure. In 1941, Faus proposed another magnetic gear topology similar to the traditional mechanical spur gear.

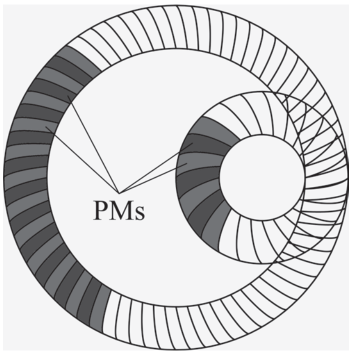

Fig. 1 Involute SmCo magnetic gear

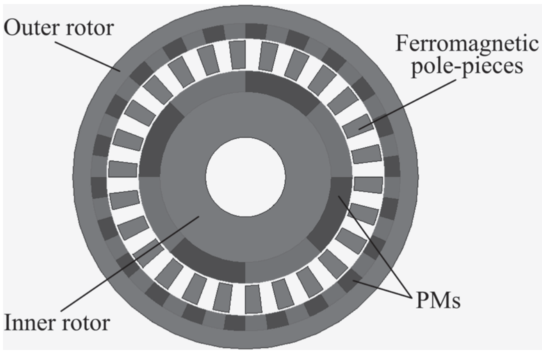

Fig. 3 Coaxial magnetic gear

But it also suffers from the low-energy of ferrite used [Faus, 1941]. Until the emergence of high-energy rare-earth PMs, magnetic gears aroused great interests from researchers. In 1987, Tsurumoto and Kikuchi proposed a new transmission type using an involute SmCo magnetic gear which was shown in Figure 1 [Tsurumoto, and Kikuchi, 1987]. In 1993 and 1994, the magnetic worm gear and magnetic skew gear was also developed, respectively [Kikuchi and Tsurumoto, 1993; Kikuchi and Tsurumoto, 1994]. However, both of them have the demerits of complexity and poor torque density.

In order to avoid the complicated structure of magnetic worm and skew gears, Ikuta proposed the simple parallel-axis magnetic gears which include two basic topologies: radial coupling and axial coupling as shown in Figure 2 [Ikuta et al., 1991]. Although the topology of parallel-axis magnetic gears is very simple, they have not been widely used for industrial application because of their very low torque density.

In 2001, Howe and Atallah proposed an innovative coaxial magnetic gear with high torque density [Atallah and Howe, 2001]. As shown in Figure 3, the ferromagnetic pole-poles which are sandwiched between the outer rotor and the inner rotor take the charge of modulating the magnetic fields both in inner airgap and outer airgap. The key characteristic of this configuration is that all PMs are involved in the torque transmission at the same time, hence obtaining a high torque density with 50-150 kNm/m^3 [Atallah et al., 2004].

Incorporating the concept of the Halbach PM array and the concept of the magnetic gear, Jian and Chau proposed an improved coaxial Halbach magnetic gear as shown in Figure 4 [Jian et al., 2009; Jian and Chau, 2010]. Another configuration in which the PMs in the inner rotor are tangentially magnetized was proposed by Rasmussen et al. [Rasmussen et al., 2005]. As shown in Figure 5, this structure has the advantages of flux concentration and high mechanical reliability.

For the further improvement of mechanical integrity and the saving of PMs, Liu et al. proposed a new concentric magnetic gear topology as shown in Figure 6 [Liu et al., 2009]. The key is to bury all PMs with the

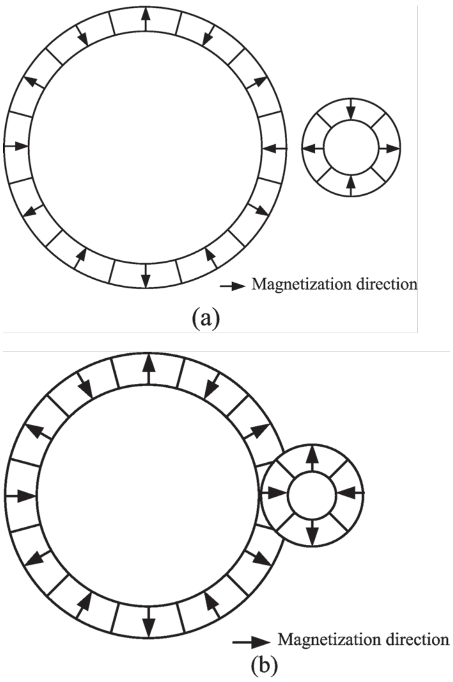

Fig. 2 Parallel-axis magnetic gear: (a) radial-coupling; (b) axial-coupling

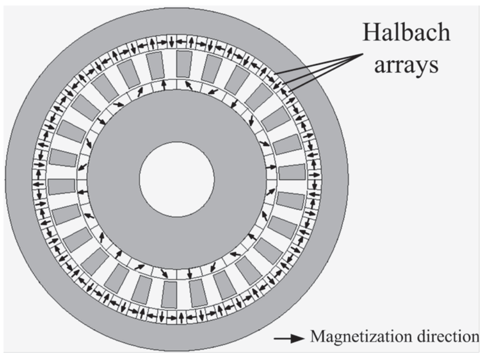

Fig. 4 Halbach magnetic gear

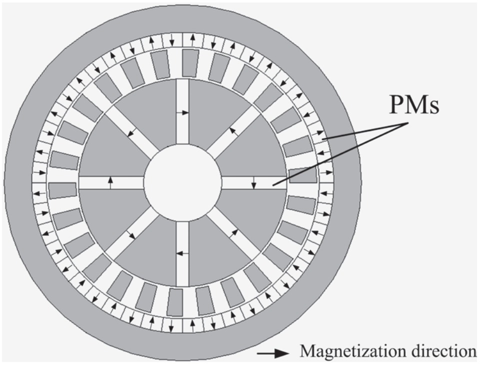

Fig. 5 Magnetic gear with inner tangentially magnetized PMs

same polarity into the iron yoke of the outer rotor so that the salient teeth of the iron yoke serve as the PMs with the reverse polarity, hence further improving the mechanical reliability and also reducing the required PM material.

Because of the high performance of rare-earth PMs such as the SmCo and NdFeB, they are widely adopted for the manufacture of magnetic gears regardless of their very expensive price and low reserves.

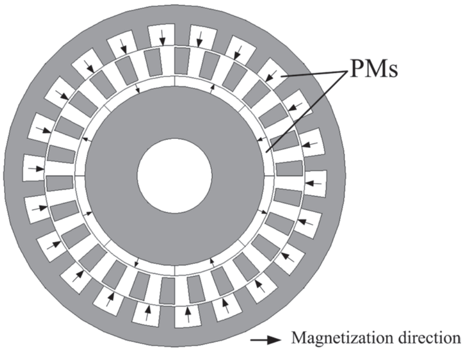

Fig. 6 Magnetic gear with same polarity outer PMs

3. NON-RARE-EARTH AND RARE-EARTH MAGNETIC GEARS

3.1 Performance comparison

Although the operating principle, analytical modelling and numerical field analysis of magnetic gears have been well presented, a performance comparison of magnetic gears using different types of PMs is absent in literature. For a fair comparison, the three magnetic gears, which are installed with the Alnico, NdFeB and SmCo, adopt the same topology based on the following criteria:

- same outside diameter, shaft diameter and axial length;
- same stationary ring;
- same gear ratio;
- same ferromagnetic materials used;
- same volume of PMs used.

Figure 7 and Figure 8 show the 2-D and 3-D configurations of the coaxial magnetic gear for comparison. The corresponding parameters are listed in Table 1.

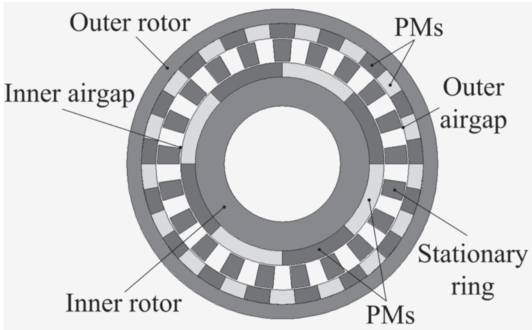

Fig. 7 2-D structure of magnetic gear

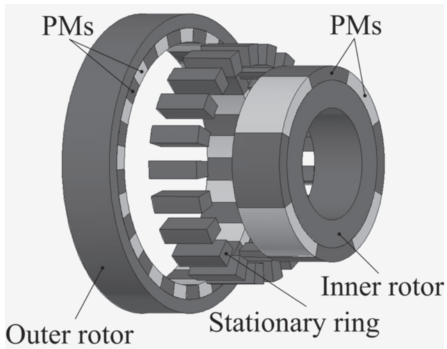

Fig. 8 3-D structure of magnetic gear

Table 1 Key data of magnetic gear

Number of pole-pairs on inner rotor	4
Number of pole-pairs on outer rotor	17
Number of stationary rings	21
Inside radius of inner rotor yoke [mm]	40
Outside radius of inner rotor yoke [mm]	60
Thickness of PMs on inner rotor [mm]	10
Length of inner airgap [mm]	1.0
Thickness of stationary ring [mm]	15
Length of outer airgap [mm]	1.0
Thickness of PMs on outer rotor [mm]	10
Inside radius of outer rotor yoke [mm]	97
Outside radius of outer rotor yoke [mm]	107
Axial length [mm]	40

By using finite element method (FEM), the electromagnetic performance of these three magnetic gears are evaluated and quantitatively compared. Firstly,

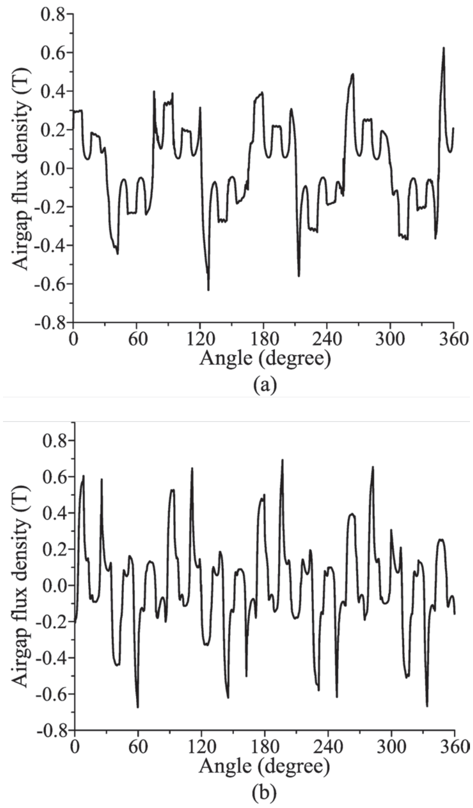

Fig. 9 Airgap flux density waveforms of magnetic gear installed with Alnico: (a) inner rotor; (b) outer rotor

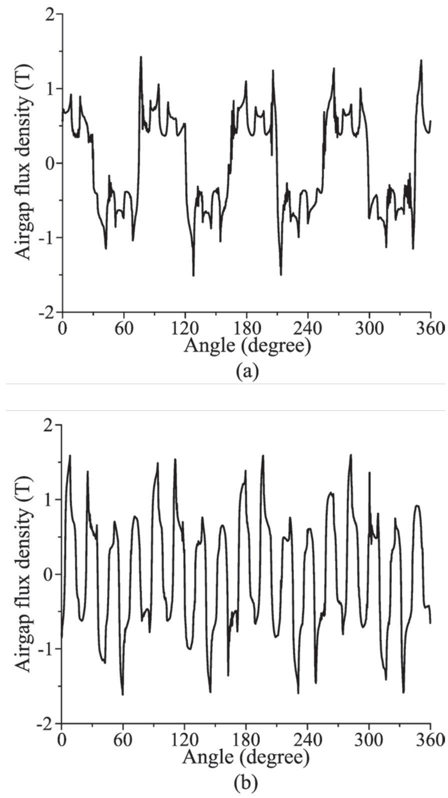

Fig. 11 Airgap flux density waveforms of magnetic gear installed with NdFeB: (a) inner rotor; (b) outer rotor

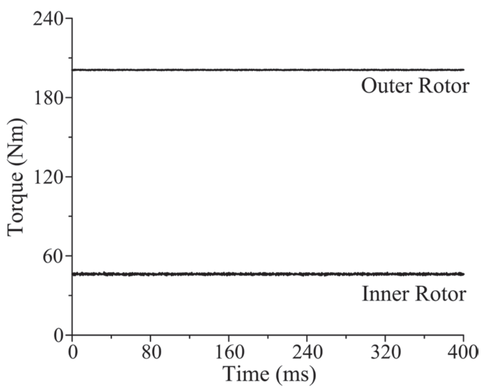

Fig. 10 Torque waveforms of magnetic gear installed with Alnico

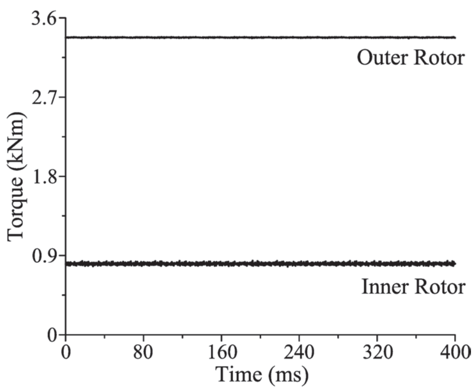

Fig. 12 Torque waveforms of magnetic gear installed with NdFeB

the airgap flux density and torque waveforms of the magnetic gear installed with the Alnico are simulated as depicted in Figure 9 and Figure 10, respectively. Secondly, similar waveforms of the magnetic gear installed with the NdFeB are obtained as shown Figure 11 and Figure 12. Thirdly, similar waveforms of the magnetic gear installed with the SmCo are shown in Figure 13 and Figure 14.

From these figures, it is obvious that the rare-earth magnetic gears based on the NdFeB and SmCo PMs have better performance than the Alnico non-rare-earth magnetic gear. The steady torques developed at the inner rotor and outer rotor of the Alnico magnetic gear are about 47 Nm and 200 Nm respectively, which are 16 times lower than the torques transmitted by the NdFeB magnetic gear which exhibits about 795 Nm and 3376 Nm, respectively. Meanwhile, the SmCo magnetic gear has nearly the same performance as the NdFeB magnetic gear. The corresponding performance comparison is shown in Table 2.

3.2 Magnet material comparison

The airgap flux density difference between the non-rare-earth and rare-earth elements mainly attribute the

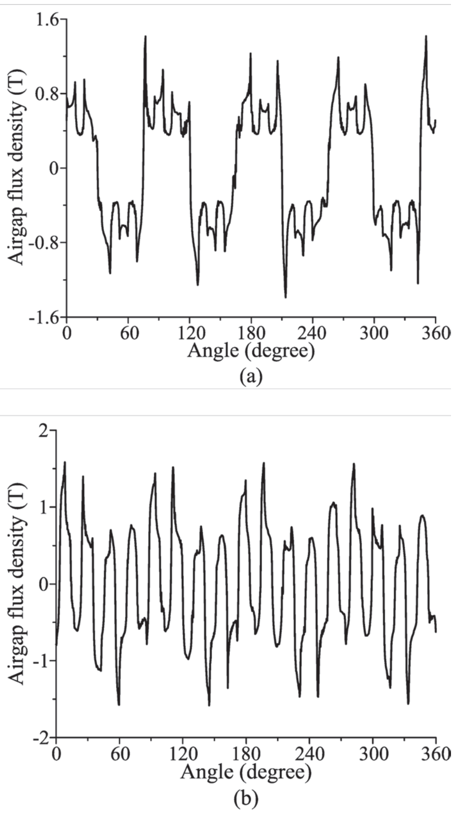

Fig. 13 Airgap flux density waveforms of magnetic gear installed with SmCo: (a) inner rotor (b) outer rotor

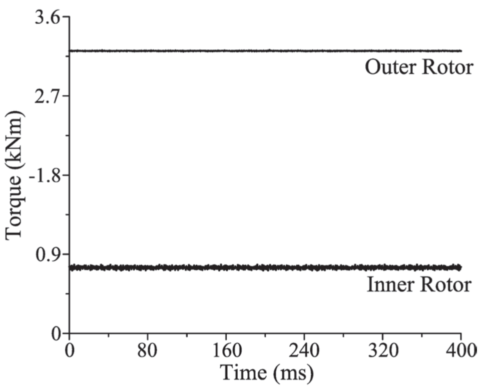

Fig. 14 Torque waveforms of magnetic gear installed with SmCo

Table 2 Performance comparison

	Alnico	NdFeB	SmCo
Inner rotor torque [Nm]	47	795	755
Outer rotor torque [Nm]	200	3376	3210

quality of the PM materials adopted. Rare-earth PMs, which are made from alloys of rare-earth element, produce significantly stronger magnetic field than other types of PMs. The NdFeB and SmCo are two common types of rare-earth PMs which are extensively adopted in industrial applications.

The SmCo, which is the first member of rare-earth PMs, consists of Sm, Co and other elements such as Fe and Cu. Although it has advantage of good temperature stability and high resistance to demagnetization, it is less used than the NdFeB because of its extremely high price and relatively weaker magnetic field strength.

The NdFeB, which is the most successful invention in the rare-earth PMs, is the strongest and most affordable rare-earth PM. It is an alloy of Nd, Fe, B and other elements such as Re, Al and Cu.

Although the rare-earth PMs have very impressive performance in many applications, their high price and low reserves on earth determine that rare-earth PMs will exhaust in the future. The non-rare-earth Alnico PM, which consists of Al, Ni, Co and other elements such as Cu, Ti and Fe, is a potential candidate to compete with the rare-earth PMs. The prominent advantage of Alnico is its very low temperature coefficient and very high remnant flux density Br. Although the low coercivity Hc of Alnico makes it vulnerable to demagnetization, this shortcoming can be solved or even positively utilized [Yu et al., 2008]. Table 3 gives a quantitative comparison of magnetic properties among these three PMs.

Table 3 Magnet material comparison

	Alnico	NdFeB	SmCo
Br [T]	1.4	1.4	1.1
Hc [kA/m]	275	2000	2000
BH(max) [kJ/m^3]	88	440	200

3.3 Cost-effectiveness comparison

In order to conduct a fair cost comparison, the raw material prices of these three PM materials are considered, while neglecting the product prices which are governed by many factors such as the supply and demand, marketing strategy and trade policy. It is obvious that the raw material prices of these three PMs can be calculated according to their compositions. As China is one of the major producers of PMs, the prices of the those elements are based on the Chinese material market in April 2012 as listed in Table 4.

Consequently, the cost of three magnetic gears with different types of PMs can be easily calculated. The inner-rotor torque is taken as the key indicator reflect the cost-effectiveness. Table 5 summarizes their densities, volumes, compositions and torques, hence calculating the cost-effectiveness in terms of cost per torque.

Table 4 Price of main elements

Element	Price (USD/kg)	Element	Price (USD/kg)
Al	2.363	Sm	236.265
Fe	0.126	Nd	252.016
Cu	8.506	B	3.938
Re	2362.651	Ni	18.901
Co	35.125		

As shown in Table 5, the key in comparison is that all three magnetic gears adopt the same volume of PMs ($394cm^3$). Although the AlNiCo PM type has the lowest torque output, the AlNiCo PM type has the lowest price in generating the unit torque, which is only 0.3779 USD/Nm. It means that it is only 84.826 % of the NdFeB PM type (0.4455 USD/Nm) and 81.234 % of SmCo PM type (0.4652 USD/Nm). In addition, the magnetic gears do not involve any armature current, eliminating the possible of accidental demagnetize. Thus the AlNiCo type is the best choice of replacement of the rare-earth magnets.

4. APPLICATION OF MAGNETIC GEARS

Since magnetic gears have many advantages over mechanical gears, they can be widely applied to EVs. First of all, the concept of coaxial magnetic gear can be extended to the concept of magnetic gearbox. A magnetic planetary gearbox has been investigated and analyzed recently [Huang, et al., 2008], revealing that it offers high torque density and can realize the task of power splitting.

In addition, the magnetic-geared machines, incorporating the magnetic gear and the PM machine, offer the merit of low-speed high-torque motion for direct-drive as well as the feature of high-frequency design to achieve high power density, which are highly desirable for EVs [Li et al., 2013].

Also the concept of magnetic gear can be applied to the free-piston generator for range-extended EVs [Li and Chau, 2010]. By integrating a linear magnetic gear into a linear PM machine, a linear magnetic-geared generator is formed which can offer high efficiency and high power density for electricity generation. The low-speed mover of the proposed machine is directly coupled with the pistons of the internal combustion engine and reciprocates with the pistons.

5. CONCLUSION

In this paper, the development of rare-earth and non-rare-earth magnetic gears have been reviewed and discussed, with emphasis on performance, magnet material and cost-effectiveness comparisons. Three magnetic gears individually installed with the Alnico, NdFeB, SmCo are analyzed. Among the three different types of PMs, the NdFeB offers the highest steady torque over the others. Although the Alnico type possesses the lowest torque output, it offers the lowest price per unit torque developed. The application of the magnetic gear has also been discussed. The concept of the magnetic gear can be extended or incorporated to other high performance devices such as rotational or linear PM machines to form a new breed of electric machines for EV applications. Due to the abundant reserves and low raw material cost of Alnico as well as the high cost-effectiveness and free from armature field of the Alnico magnetic gear, the non-rare-earth magnetic gears are preferred to the rare-earth magnetic gears for EV applications.

ACKNOWLEDGEMENTS

This work was supported and funded by the grant (Project Code: HKU710612E) from Hong Kong Research Grants Council, Hong Kong Special Administrative, China.

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Table 5 Cost-effectiveness comparison

	Alnico	NdFeB	SmCo
Density [g/cm^3]	6.7	7.5	8.4
Volume [cm^3]	394	394	394
Composition	Al 8-12 % Ni 15-26 % Co 5-24 % Fe, Cu (balance)	Nd 29-32.5% Fe 63.9-68.6 % B 1.1-1.2 % Re 0.6-1.2 %	Sm 35 % Co 60 % Fe, Cu (balance)
Inner-rotor torque [Nm]	47	795	755
Cost-effectiveness [USD/Nm]	0.3779	0.4455	0.4652

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(Received November 30, 2012; accepted December 10, 2012)