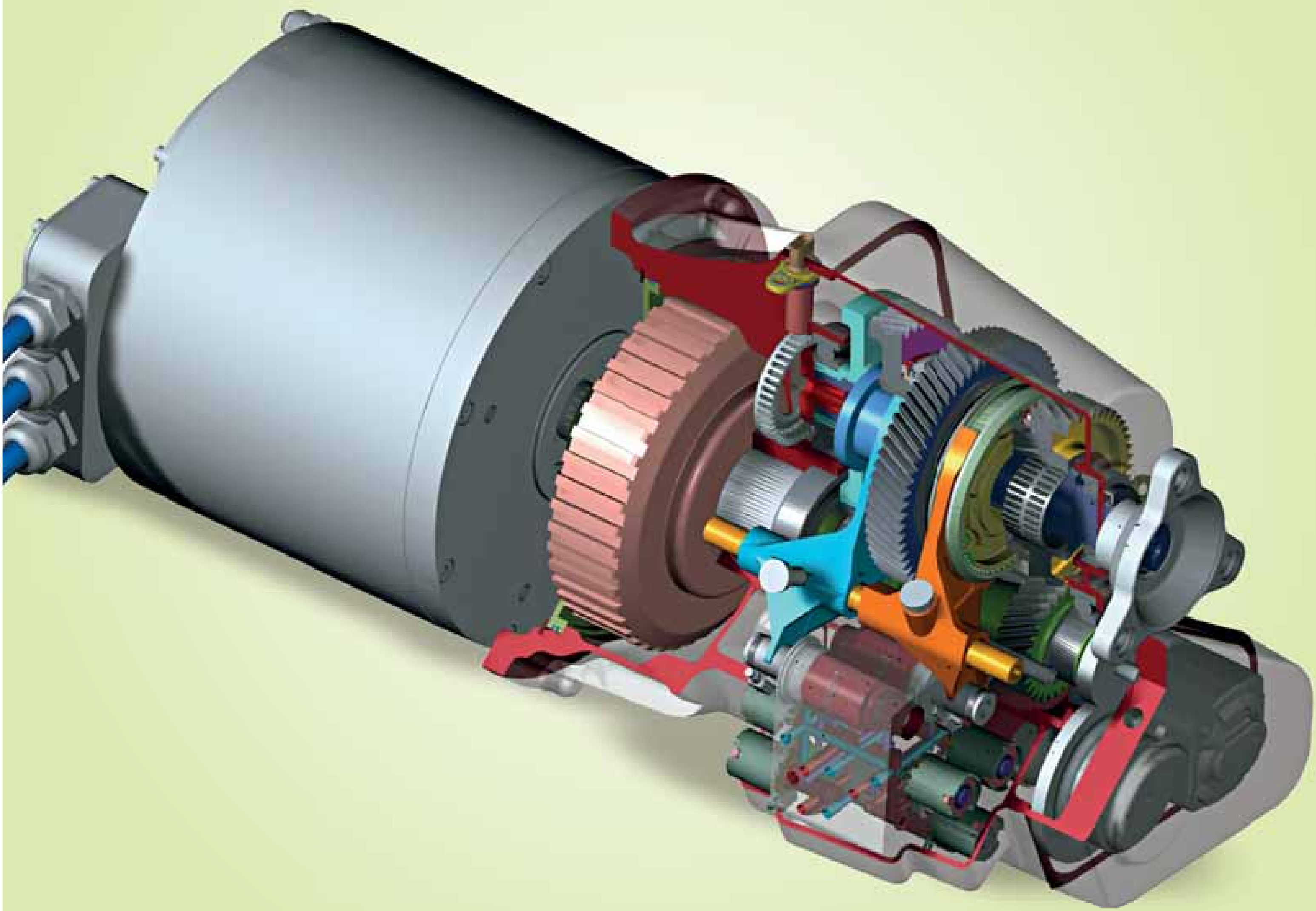
EVOLUTION OF TRANSMISSION FOR EVs, HEVs; POTENTIAL FOR MAGNETIC TRANSMISSION



AUTHORS

ARGHYA SARDAR
is Scientist E & Head, Transportation Division at TIFAC, Department of Science & Technology, Government of India

SURESH BABU MUTTANA
is Scientist C at TIFAC, Department of Science & Technology, Government of India

INTRODUCTION

Transmission plays an important role in enhancing the fuel efficiency of vehicles. In a conventional IC engine vehicle, the efficiency of engine is dependent on the speed and torque values, with the most efficient region being within a particular speed-torque range. Since there are wide variations in speed and torque demands in the real world driving conditions, transmissions having suitable gear mechanisms are used to ensure that the engine operates close to its optimum operating range.

Electric motors have a comparatively flatter efficiency curve and this fact plays a major role in the improved efficiency of electric and hybrid electric vehicles. However, size of the motor is dependent on the maximum torque, and to ensure that the size of the motor remains within desired limit, use of some gear mechanisms is necessary for electric and hybrid electric vehicles too. Mechanical gears are associated with wear and tear, contact friction, noise, and regular maintenance.

In this context, the concept of magnetic gear is relevant. A magnetic gear uses permanent magnets to transmit torque between an input and output shaft without mechanical contact. Although the basic concepts date back to the early 20th century, there has been any significant advancement in the research of magnetic gears only after advancements of permanent magnet (PM) materials, which can produce a persistent flux and magnetic force and realise contact-less torque transmission. This article discusses trends in electric vehicle transmissions alongside trends in magnetic gear technology and attempts to assess the possibility of their convergence.

MAGNETIC GEAR

The concept of magnetic gear was first found in a patent on magnetic gear by Armstrong in 1901. Another patent by Faus in 1941 improved upon it. The magnetic gear topology proposed by him was quite similar to mechanical spur gear. Martin in 1968 contributed a significant improvement with the use of steel pole pieces. But thorough studies on magnetic gears have been undertaken more in the last decade, ❶. A major barrier for the commercial applications of magnetic gears was that the ceramic magnets used could only sus-

YEAR	AUTHORS	FEATURE
1901	Armstrong	Magnetic Spur Gear. Used magnetised coils
1916	Neuland	Magnetic planetary gear. Used magnetised coils. Variable gear ratios
1941	Faus	Magnetic spur gears
1967	Reese	Input rotor with mounted permanent magnet Outer rotor - iron or steel Magnetic planetary gear 50:1 gear ratio
1968	Martin	Magnetic planetary gear & parallel shaft variations
1972	Laing	Magnetic planetary gear variations
1974	Hetzel	Magnet spur gear
1991	Mabe	Magnetic planetary gear
1993	Kikuchi & Tsurumoto	Magnetic worm gear variations
1996	Yao et al	Magnetic bevel gear variations
1997	Ackerman & Honds	Magnetic planetary gears – problem with short circuiting
1999	Ackerman	Improved magnetic planetary gear variation Steel on the outside

❶ List of important patents on magnetic gear; Source: [2]

tain small torque transmission.

In the 1980s, after invention of neodymium iron boron magnets, research on magnetic gears received renewed focus. However, initial topologies were still only replacement of slots and teeth of iron core in mechanical gear by north and south poles of permanent magnets. New operational principle employing the harmonic magnetic flux has also been developed. As a result, a high torque density can be achieved. Hence, high performance magnetic gears can be marketed for industrial and commercial applications. In a milestone paper in 2001, Dr Atallah and his colleagues at Sheffield University established the theory of magnetic gearing (MG) [1].

There are two major categories of MGs – Converted MGs and Field-modulated MGs [3].

Converted MGs: The literature reveals that various types of converted MGs such as multi-element, involute, worm and skew gear types were developed during 1980s, however, all these MGs, in addition to their complexity, have a poor torque density of less than 2 kNm/m3. This is mainly due to the bulky package and low utilisation of PMs. Later, parallel-axis MGs, which include two different magnetic coupling types – radial and axial coupling were proposed. In addition, magnetic coupling characteristics of a perpendicular-axis MG were also studied. Although the configuration of parallel-axis or perpendicular-axis MGs is very simple, their torque density is so low that they could not be widely used. Further it was reported that the study on Magnetic Planetary Gear (MPG) has some encouraging results. MPG has the characteristics of the three transmission modes, a high-speed ratio, and a high torque density. The number of magnetic planet gears is the key to improve the MPG transmitted torque. It was reported that the MPG with six magnetic planet gears exhibits nearly 100 kNm/m3.

Field-modulated MGs: In 2001, Dr Atallah and Howe proposed coaxial magnetic gear (CMG), which is completely different from the converted MGs. It employs PMs on both the outer and inner rotors, and has ferromagnetic pole-pieces between the two rotors. Its operation relies on the use of the ferromagnetic pole-pieces to modulate the magnetic fields produced by each of the PM rotors. Due to contribution to all PMs to the torque transmission, it exhibits a high torque density, namely 50-159 kNm/m3.

Between the two families of MGs, the field-modulated CMGs have better utilisation of PM material and hence higher torque density, as well as their capability of integration into the PM brushless machines to form MGPM machines.

A derivative of Zytek's production 70kW 300Nm E-Drive can be installed in the transmission tunnel with just three additional connections

The Ricardo 'Kinergy' high-speed, hermetically-sealed flywheel energy storage system incorporating an innovative and patented magnetic gearing and coupling mechanism

POTENTIAL ADVANTAGES OF MAGNETIC GEAR

In magnetic gears, there is no mechanical contact between the moving parts; hence there is no wear and lubrication is not required. The operation is silent and maintenance free with very low acoustic noise and vibration.

Magnetic gears have higher efficiency than conventional gears. Torque densities comparable with mechanical gears can be achieved with an efficiency > 99 % at full load. Part load efficiency of magnetic gear can also be higher than that of mechanical gears. Magnetic gears have an inherent protection mechanism against overload torques. If an overload torque is applied, magnetic gears harmlessly slip, safely re-engage when fault torque is removed. Mechanical gear may break down when overloaded.

For higher power ratings a magnetic gear will be smaller, lighter and lower cost than a mechanical gear. In case of mechanical gears, only two to three teeth are engaged in a single stage. In magnetic gear, it is possible to use the full perimeter of the gear to generate torque. Thus, superior torque density can be obtained. For this same reason, high gear ratio magnetic gears can be constructed without the use of multiple stages. Another advantage is inherent anti-jamming.

ELECTRIC AND HYBRID VEHICLE DRIVE SYSTEM

One of the great advantages of the electric motor is its torque characteristic, which provides maximum torque from zero up to low speeds, and then it is governed by the maximum power available as motor speed increase. Electric motors have a wider power range than an internal combustion engine. This has two significant advantages over the typical torque-speed properties of the competing IC engine:

I. It is fundamentally a more desirable characteristic spread of torque over the speed range in contrast to the peak levels of an IC engine,

II. It reduces the need for complex transmission system with wide gearing range.

Early generation electric railway locomotives used gearless drive systems between the electric motors and the driving wheels. For electric drive vehicles, the major driving factor for the use of reduction gear is the size of the motor. Reduction gearing between the electric motor and the driving wheels was introduced to enable the use of smaller, lighter and less costly electric motors. Some form of deep reduction gearing has been used in electric trolley buses.

With the advent of AC motors and controllers in the electric vehicle applications, there has been much simplification in the transmission uses. DC motors needed a transmission to allow reverse driving. But for AC motors, the controller can just command the motor to turn the other way around. Their torque curve is flatter, but their efficiency curve is far from flat. There would be a lot to gain from a choice of gears.

However, there are some problems associated with reducers in many of the commercial one-motor-type electric vehicles. They lack speed shifting functionality, and their maximum torque and maximum rotational speed are determined by a trade-off between the acceleration performance and the maximum speed required with the reduction ratio of the reducer. Setting the reduction ratio at a higher value is effective for reducing motor weight, but it is necessary to increase the maximum rotational speed of the drive motor. This results in greater power loss in the reducer, leading to decreased transmission efficiency. Since size increases with torque, the size of the motor becomes large, when the reduction ratio is set to a lower value, while increasing the maximum motor torque. On the other hand, setting the reduction ratio at a higher value, while increasing maximum rotation speed of the motor, would increase the power loss of the reducer, thereby reducing the efficiency.

Toyota's Hybrid Synergy Drive

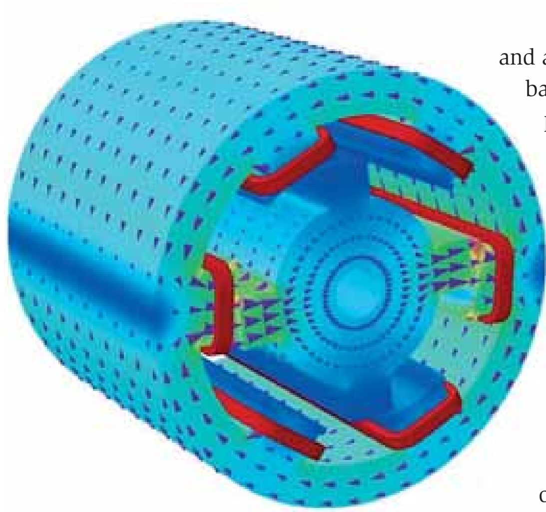
This has led to the consideration of using two-speed transmissions. Switching appropriately between the high reduction ratio gear and the low reduction ratio gear, will enable limiting maximum torque of the drive motor without increasing the maximum motor rotational speed.

Morgan is building an electric Aero Supersport with the help of Zytek, featuring a modified five-speed manual transmission. Furtive eGT, an innovative four-speed transmission designed from scratch to work with an electric motor is being developed by Exagon Motors. Fisker Automotive has also decided to look into the transmissions as a way to dramatically improve performance on EVs. Antonov is developing a three-speed transmission with gearbox specifically designed for EVs. UK transmission engineering and control specialist Vocis has developed electric vehicle-specific, two-speed transmission during the Low Carbon Vehicle Event 2011 at Rockingham Motor Speedway over in the UK.

The powertrain of power-split HEVs is also termed as electronic-continuously variable transmission (E-CVT) system, which was firstly adopted by Toyota Prius in 1997. Then several derivatives such as the GM-Allison compound E-CVT, the Timken compound split E-CVT and the Renault compound split E-CVT were introduced. The Toyota Hybrid Synergy Drive (HSD) has two motors, and depending on the situation, uses only the electric motor, or the driving power both from the electric motor and the engine in order to achieve higher efficiency level. When necessary, the system is also able to drive the wheels while simultaneously generating electricity using a generator. The power-split device consists of a planetary gear box with three inputs/outputs – the internal combustion engine, and the two PMSM machines.

In case of HEVs, the concept of Electrical Variable Transmission (EVT) has been introduced. The EVT is an electromechanical converter with two mechanical ports (to the engine and to the differential) and one electrical port connected to the battery. The system replaces the clutch, gearbox, starter and generator by only one electromechanical system. Various machine types can be used for EVTs, but PM-EVT is becoming most attractive.


Ricardo-designed range extended EV APU



Opera's electromagnetic simulation capabilities for switched reluctance motors

MAGNETIC GEARS FOR XEVs

There are several early phase developments indicating efforts towards use of magnetic gear in xEV applications. Coaxial magnetic gear (CMG) and magnetic planetary gear are the two main design options being pursued.

Efforts have been made [4] for integration of coaxial magnetic gear into PM brushless in-wheel motor to simultaneously meet the low speed requirement for direct driving and the high speed requirement for motor design. Such a motor includes four parts – the stator, the outer rotor, the stationary ring and the gear outer rotor. To address the issue of complex installation and size, a different topology has been proposed [5] employing a stationary armature to replace the inner high speed rotor of the magnetic gear.

Works have also been done on novel powertrain for power-split HEVs incorporating the CMG [6]. The system integrates two PM magnetic gears together with the CMG with the one-side-in and one-side-out mechanical structure. By designing the modulating ring of the CMG to be rotatable, this integrated machine can achieve both power splitting and mixing, and therefore, can seamlessly match the vehicle road load to the engine optimal operating region.

Replacement of the mechanical planetary gear used in the power-split device of the Toyota Hybrid Synergy Drive with magnetic planetary gear has been studied [7]. The magnetic gear has an inner rotor and an outer rotor. Each rotor has a back iron and different number of permanent magnet poles. There are pole pieces in soft magnetic composite material between these two rotors. The inner rotor, SMC pole pieces and the outer rotor play the roles of the sun, the planet carrier and the ring gear respectively. It is shown that the torque density of the planetary magnetic gear can be more than two times the one of the mechanical planetary gear for the same gear ratio, and external outer diameter. Zhu, *et al* [8] also incorporated the concept of magnetic planetary gear into a permanent magnet brushless machine to realise the required speed and torque as well as manage the power split function.

Magnomatics, spun-out from the University of Sheffield, claims gear ratios from 1.01:1 to 1000:1 are possible and torque densities comparable with mechanical gears can be achieved with an efficiency of 99 % or better at full load and much higher efficiencies in part-load conditions than mechanical gears can achieve.

In the low-ratio magnetic gear, a series of steel pole pieces modulate the fields produced by two permanent magnet rotors with different numbers of magnetic poles. The magnet arrays rotate at different speeds. The gear ratio is determined by the ratio of magnets in each array. The transfer of motion between input and output shafts is achieved passively using powerful permanent magnets and an intermediate modulating element. Torque densities comparable with mechanical gears can be realised because of the high degree of magnetic coupling between the rotors. Gear ratios of 50:1 down to 1.01:1 with almost zero torque ripples are readily achievable. Interestingly, low-ratio magnetic gears can be realised in a conventional radial field or in an axial arrangement when a thin 'pancake' design is required.

Magnomatics high-ratio magnetic gears use a rotating diverging air gap to modulate the fields produced by the permanent magnet arrays on the input and output rotors. As with the low-ratio gears, a high degree of coupling between the rotors allows for a very high torque density to be achieved. Ratios of up to 1000:1 can be achieved in a single co-axial stage.

Magnomatics' low-ratio magnetic gear forms an integral component within the company's new type of permanent magnet machine, the pseudo direct drive (PDD) that offers a far higher torque density than conventional motor-gearbox combinations.

The PDD technology invented by Magnomatics uses the low ratio magnetic gear. This technology combines the high torque density of the magnetic gear and the functionality and performance of a brushless permanent magnet machine to offer high torque output for direct drive applications. This technology is aimed at

	Alnico	NdFeB	SmCo
Remnant Flux Density B_r [T]	1.4	1.4	1.1
Coercivity H_c [kA/m]	275	2000	2000
BH(max) [kJ/m³]	88	440	200
Density [g/cm³]	6.7	7.5	8.4
Volume (cm³)	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

2 Magnet material comparison; Source [9]

HEV traction drives, and is suitable for series hybrid and/or parallel hybrid topologies.

CONCERNS OVER MAGNETS

The first PM material applied to the magnetic gear is non-rare-earth ferrite, which can only transmit low torque. Low remnant flux density is obvious demerit of ferrite permanent magnets. However, ferrite has advantages of low price, easy manufacture and high coactivity. Aluminium-nickel-cobalt (Alnico), which takes the definite merits of high remnant flux density and abundant elements, has also been used to develop magnetic gears. After the advent of the high-energy rare-earth PM materials, such as the neodymium-iron-boron (NdFeB) and samarium-cobalt (SmCo), they become PM materials widely adopted for magnetic gears. Rare-earth PMs, which are made from alloys of rare-earth element, produce significantly stronger magnetic field than other types of PMs.

Recently, there is an increasing concern on the price and supply of rare-earth elements. China is one of the major producers of PMs. The prices of the elements are based on the Chinese material market. 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. However, these will increase the cost of EV manufacturing, hindering further applications in EVs.

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. Although the low coercivity of Alnico makes it vulnerable to demagnetisation, this shortcoming can be solved or even positively utilised. 2 gives a quantitative comparison of magnetic properties among these three PMs.

Current magnetic gear designs use large quantities of rare-earth magnet material and unfortunately the high cost of rare-earth material makes the magnetic gear uncompetitive with alternative technology. Motor designs with integrated magnetic gears require fewer magnets as compared to separate magnetic gear; however, still magnet requirement per vehicle will remain a major concern.

CONCLUSION

Magnetic gears have many advantages over mechanical gears. The possibility of integrating it with the electric machine and eliminating conventional mechanical transmission can strengthen the drive towards more compact and lightweight drivetrain for electric and hybrid electric vehicles. Although the first patent related to magnetic gear dates back to 1901, significant research efforts started only after the advent of rare-earth magnets, and then further intensified after Atillah and Howe theoretically demonstrated in their milestone paper in 2001 that it was possible to obtain a torque density of 100 kN/Nm3 with strong NdFeB magnets.

During the last decade, the research on magnetic gears has moved from presenting physical demonstrators, various topologies and analytical calculation methods to various ways of integrating magnetic gear with the motor. Supply constraints and volatile price of rare-earth magnets has also catalysed intensified efforts towards alternatives of rare-earth PMs. But since rare-earth PM-based motors are widely preferred in xEV drivetrains at present, use of magnetic gear integrated with such motors will definitely continue to attract research efforts. It is expected that continued research efforts will result in improvement in utilisation of permanent magnet in such topologies.


Mitsubishi PHEV drivetrain system

REFERENCES

[1] K Atallah and D. Howe; A Novel High-Performance Magnetic Gear; IEEE Transactions on Magnetics, Vol. 37, No. 4, July 2001
[2] Gareth P Hatch; Recent Developments In Permanent Magnet Gear Systems & Machines; Presented at the Magnetics 2010 Conference, Lake Buena Vista, Florida, USA; January 2010
[3] X. Li et al; Comparison of Magnetic-geared Permanent Magnet Machines; Progress In Electromagnetics Research, Vol. 133, 177-198, 2013
[4] Linni Jian; An integrated magnetic-geared permanent magnet in-wheel motor drive for electric vehicles; IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008, Harbin, China
[5] Ying Fan; An improved magnetic-geared permanent magnet in-wheel motor for electric vehicles
[6] Linni Jian et al; A Novel Power-train Using Coaxial Magnetic Gear for Power-split Hybrid Electric Vehicles
[7] L Baghli, E Gouda, S Mezani, A Rezzoug; Hybrid vehicle with a magnetic planetary gear; International Symposium on Environment Friendly Engines in Electrical Applications; 2-4 November 2010, Gharadia, Algeria
[8] Xiaoyong Zhu et al; A new magnetic planetary geared permanent magnet brushless machine for hybrid electric vehicles; IEEE Transactions on Magnetics; Vol 48, No 11, November 2012
[9] Mu Chen et al; Development of Non-rare-earth Magnetic Gears for Electric Vehicles; Journal of Asian Electric Vehicles, Volume 10, Number 2, December 2012

Read this article on
www.autotechreview.com