2010, 12th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2010

High-performance magnetic gears topologies

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Abstract-**Magnetic gears offer significant advantages over traditional mechanical gears, such as the ability to increase as well as decrease the input speed, contactless power transfer, high gear ratios, oil free operation, inherent overload protection, high torque density, potential for high efficiency and little or no maintenance. This paper presents an overview of high-performance magnetic gears.**

I. INTRODUCTION

Changing the speed of a mechanical drive is almost invariably associated with a mechanical gear which involves transmitting a force by direct contact. Mechanical gearboxes are used extensively to match the operating speed of prime-movers to the requirements of their loads, booth for increasing the rotational speed and decreasing the speed, since it is usually more cost and weight effective to employ a high-speed electrical machine together with a gearbox to transform speed and torque. However, although, high system torque densities can then be achieved, gear lubrication and cooling are often required, whilst noise, vibration and reliability can be significant issue.

Magnetic gears offer several potential advantages, such as:

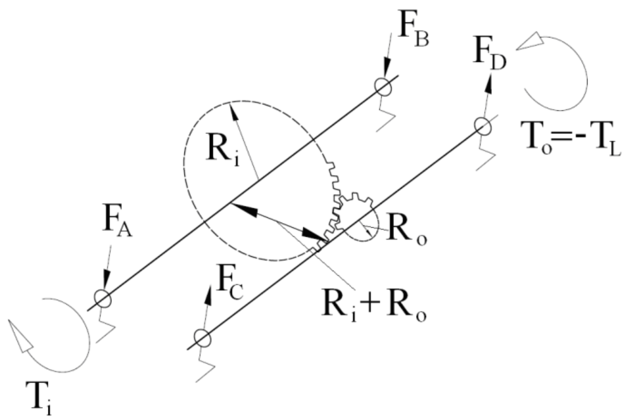
- reduced acoustic noise and vibration
- no mechanical contact losses
- no mechanical fatigue
- reduced maintenance and improve reliability
- precise peak torque transmission capability, and inherent overload protection
- physical isolation between input and output shaft

Despite these advantages, magnetic gears have received little attention from both research institutions and industry, due to the relative complexity of magnetic gears and the shortcomings of earlier permanent magnet (PM).

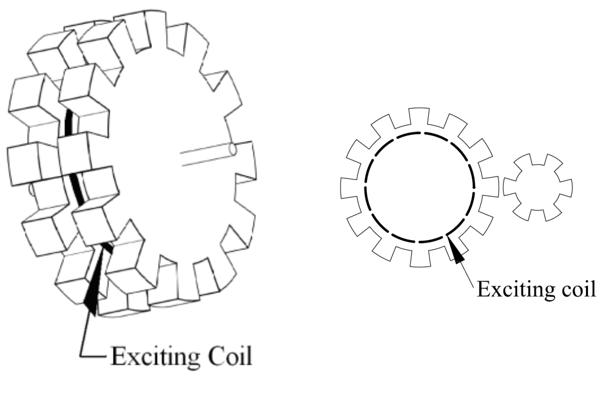
The basic idea of magnetic gearing can be tracked down to the beginning of the 20th century. An interesting example is U.S. Patent Application filled in 1913 [1], it described electromagnetic gears consisting of two rotational shafts with salient steel pole. Two shafts were magnetically connected with stationary electromagnetic poles. Even though the gearing topology in the patent seemed quite effective, apparently nothing was done to utilize the idea in commercial applications, and the topologies in the patent may have been forgotten. In contrast, magnetic gearing has received relatively little attention, probably because of the relative complexity and poor torque density of the magnetic circuits which have proposed [2]-[8].

II. MAGNETIC GEARS

The ability to transmit force without direct contact (e.g. by magnetic means) has been well known and it suggested the possibility of constructing a magnetic gear [5]. It can be assumed that the basic requirements of such a gear are the same as those for a mechanical gear i.e. the provision of an efficient means for coupling two shafts so that the ratio of their speed is fixed at a predetermined value. The magnetic



a



b

Fig. 1 Simple equivalent gear systems
a Mechanical
b Magnetic (showing the excitation method considered for eccentric wheel gears)

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gear presented in [4] has been reported to be disappointing in its performances at speed in terms of efficiency and power/weight ratio. In addition, the low-speed performance described, indicated severe restrictions on its use as a torque-transmitting device. Apart from work relating to this gear, surprisingly little attention appears to have been paid to magnetic gearing, despite the advantages of not transmitting the torque through a mechanical contact. Such a gear would have built-in protection from overload, and could also have been arranged to be free from backslash.

A magnetic gear topology which employed the variable reluctance principle to transmit torque and which had a much improved utilization of the magnetic circuit compared to previous topologies, has been proposed [7]. A true magnetic gear must be capable of transmitting torque at standstill, and the input energy must be transferred to the output shaft by means other than through an electrical winding operating at the input power level. Thus, a double energy conversion is not permitted, and loses in a magnetic gear should consist only of core loss and a small excitation loss if permanent magnets are not used [7]. Neglecting losses, both magnetic and mechanical gears must satisfy the condition that the energy input rate must equal the output rate plus the energy storage rate. In a mechanical gear, energy may be stored in mechanical deflection, whereas, in the magnetic gear, energy may be stored in the magnetic fields, mainly in the airgap if the iron is considered to have high permeability. A successful design requires that oscillations in the stored magnetic energy must be kept to a minimum. This avoids additional excitation loss and possible torque or speed pulsations.

In any gear, the algebraic difference between the input and output torques in any plane must be balanced by a reaction torque to earth at some point in the mechanism. If the input and output shafts are not coaxial, as in the simple gear of Fig. 1a, for example, then the reaction torque can be provided by the forces shown at the shaft support bearings, so that [7]:

$$\begin{aligned}(T_L + T_i) &= (F_A + F_B)(R_i + R_O) \\ &= (F_C + F_D)(R_i + R_O)\end{aligned} \tag{1}$$

On the other hand, if the input and output shafts are arranged to be coaxial, then some alternative path to earth must be provided for the reaction torque. For example, the layshaft bearings transmit the reaction torque to earth in an automobile gearbox. The implication of this latter argument has been crucial in considering any possible design of magnetic gear. The simple arrangement of Fig. 1a has been acceptable mechanically. On the other hand, the magnetic equivalent Fig. 1b would been immediately evoke criticism as to the poor utilization of the magnetic circuit. This, indeed, would been justified, since only one or two of the magnetic teeth contribute significantly to energy transfer at any time. This, of course, result in an extremely poor torque/volume ratio for the magnetic device. The mechanical gear has the same problem, but this is largely irrelevant since the force which can be transmitted across mechanical teeth is many times that for the same-sized magnetic teeth. Any attempt to improve the torque/volume ratio for a magnetic gear towards a value acceptable for electromagnetic devices must apparently be centered upon increasing the ratio of active/total number of magnetic teeth.

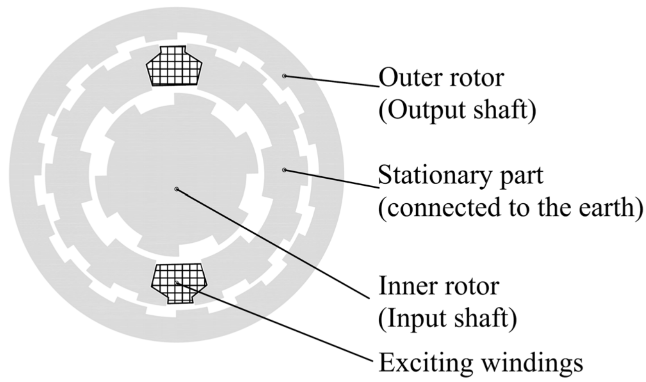

Fig. 2 Details a two pole elements [7]

The problem of producing a magnetic gear may therefore be reduces to that of devising an improved magnetic circuit in which a higher utilization of the airgap surface is achieved. Fig. 2 indicates the first simple step which was taken from Fig. 1b. In Fig. 2, the larger wheel has its teeth on the inner surface. The expected performances of such gear may be investing using conformal transformation [7].

The conclusion was that the magnetic gear must have a small active airgap over the periphery for good transmission. This small airgap implies concentric wheels. Concentric wheels, in turn, call for an additional member to transmit the reaction torque to earth. The important implication of this latter statement was that, in increasing the active members in the gear from two to three, an addition in the magnetic circuit is automatically implied [7].

The fundamental consideration of a new magnetic gear would indicate that the system illustrated in Fig. 2 was possible form of magnetic gear.

Element shown in Fig. 2 consists of:

(a) an inner connected to the input shaft
(b) a stationary member connected to the earth, carrying the exciting winding and consisting of a number of transfer blocks
(c) an outer connected to the output shaft.

This magnetic gear from [7], its torque transmission capability and efficiency were less than 5kN/m^3 and 35%, respectively.

While improving features permanent magnets, magnetic gears increased interest and a patent [9] which represents the "planetary" magnetic gear type with two PM parts, is Ackermann's patent from 1997. The principal mode of operation is alike the previous described high performance magnetic gear. The problem about this gear has been there was a short circuit of the magnetic flux. This problem was however solved by a newer patent from Ackermann [10]. This patent minimizes the short-circuiting of the flux by having the steal part as the outer part. A patent [5], describes the same type of magnetic gear. A variant of the planetary gear with two PM magnets parts is described in the patent [3]. The special about this patent is that it is claimed that this type of construction has a high gear ratio of 1:16. A new magnetic gear topology which combines a highly competitive torque transmission capability and a very high efficiency is described in [11], [12]. It employs rare-earth permanent magnets on both the inner rotor and the outer rotor, and has ferromagnetic pole-pieces between the two rotors. However, unlike the topology shown in Fig. 3, all the permanent magnets contribute to torque transmission. Indeed simulation and experimental shown that such a gear had a transmitted torque density capability which was comparable with that of two- and three-stage helical gearboxes, viz. 50-150 kNm/m^3.

The coupling between magnets is a function of several variables including the number of poles, the material properties, dimensions and separation. Fundamental to the operation of a magnetic gear is the magnetic fields produced by the permanent magnets on either the high- or low-speed rotors modulated by the steel pole pieces, which results in space harmonics having the same number of poles as the related magnet rotor. Fig. 4 illustrates the schematic of a type magnetic gear. It has been showed in [11] that the number of pole pairs in the space harmonic flux density distribution produced by either the high or low speed rotor permanent magnets is given by:

$$\begin{aligned} p_{m,k} &= |mp + kn_s| \\ m &= 1,3,5,...,\infty \\ k &= 0,\pm1,\pm2,\pm3,...,\pm\infty \end{aligned} \quad (2)$$

where p is the number of pole-pairs on the PM rotor and n_s the number of the stationary pole-pieces The gear ratio is then given by[11]:

$$G_r = \frac{n_s - p}{p} \quad (3)$$

when the modulating pole-pieces are held stationary. Keeping the outer rotor stationary may be a preferred operating arrangement since it may simplify the overall mechanical design. The torque will then be transmitted to the pole pieces instead of the outer rotor, the gear ratio then becomes:

$$G_r = \frac{n_s}{p} \quad (4)$$

The major advantage by this principle compared with conventional magnetic gear types is that the content of energy is much higher and herby it is possible to transfer a higher torque.

In [13] a high torque per volume density magnetic gear was described and analyzed with the help of 2-D FEA. The calculations shown that the magnetic gear with a gearing ratio of 5.5 and a stall torque of 27 Nm had a torque per volume density on 92 kNm/m^3. Tests with the gear shown that the

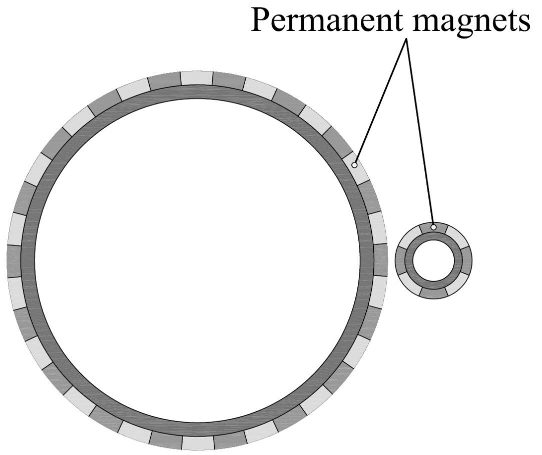

Fig. 3 Schematic of a typical conventional external magnetic gear using permanent magnets

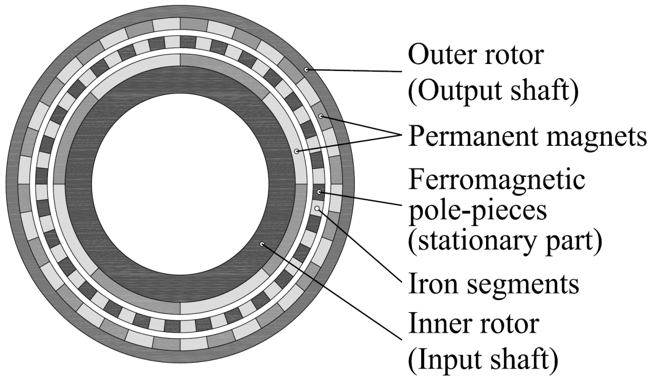

Fig. 4 Proposed magnetic gear topology[11] [12]

stall torque was only 16 Nm. The efficiency was only 81%, and the efficiency expected was 96%. The reductions were caused by large end-effects in the short practical construction.

In [17] a magnetic gear was described and analyzed with 2-D finite element to minimize the cogging torque, and a cogging factor defined in [18] was used for selecting suitable permanent magnets poles and modulator pole-pieces combinations, i.e.:

$$f_c = \frac{2pn_s}{N_c} \quad (5)$$

where N_c is the smallest common multiple between the number of poles on one of the permanent magnet rotors (p) and the number of stator poles-pieces (n_s). The factor gives a good estimate of the severity of the cogging torque. The more cogging torque factor is lower than the more cogging torque

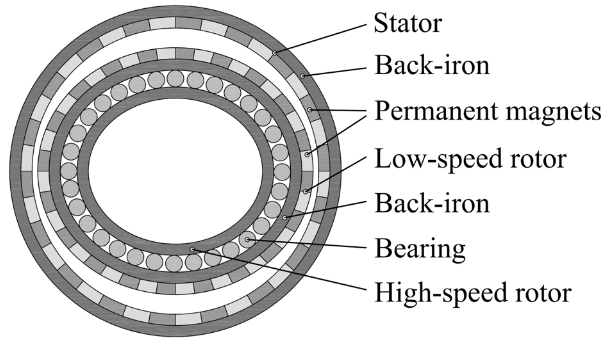

Fig. 5 Proposed magnetic harmonic gear topology [14]

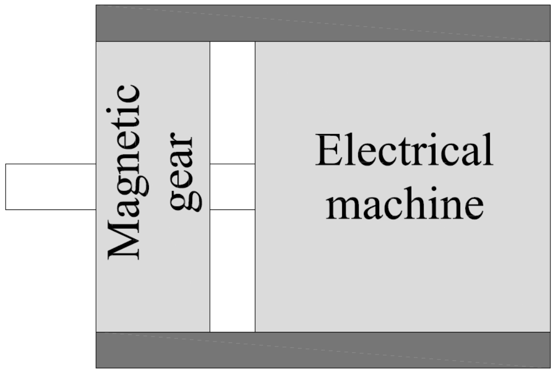

Fig. 6 Mechanically coupled magnetic gear and electrical machine

is lower. From the cogging torque factor it is clear that the larger the smallest common multiple and the lower the number of poles, the smaller the cogging torque factor will be and thus the cogging torque. To keep a reasonable number of total magnets, the number of pole-pairs on the high speed rotor was chosen to be two ($p_h=2$) and to obtain the lowest cogging torque, the cogging torque factor was chosen as $f_c=1$ thus a gear ratio $Gr=10.5$ was chosen [17]. Tests with the magnetic gear shown that the efficiency was above 70% at speed of 1000 rpm.

A novel magnetic harmonic gear was described in [14]. It was shown that the transmitted torque is ripple-free and that the torque density of up to 110 kNm/m^3 can be achieved and gear ratio higher than about 20:1 when rare-earth permanent magnets were used. Fundamental to the operation of the magnetic harmonic gear is the mechanism for producing a time-varying, sinusoidal variation of the airgap length between a set of permanent magnets which are mounted on a flexible low-speed rotor and another set of permanent magnets which are mounted on a rigid outer cylindrical stator. To achieve this, the gear employs an appropriately profiled high-speed rotor, which is equivalent to the wave generator in a mechanical harmonic gear, and which deforms the flexible low-speed rotor using a sliding contact such that the low speed rotor assumes the same profile whilst rotating independently. As a result of the variable airgap length, the magnetic fields which are produced by both sets of permanent magnets are modulated such that asynchronous space harmonics are generated by one set of magnets which have the same number of poles as the other set of permanent magnets, and vice-versa. Fig. 5 illustrates the schematic of proposed magnetic harmonic gear topology. It was shown in [14] that the number of pole pairs in the space harmonic flux density distribution produced by the low speed permanent magnet rotor is given by:

$$\begin{aligned} q_{m,k} &= mp + (-1)^k p_w \\ m &= 1, 3, 5, \ldots, \infty \\ k &= 1, 2 \end{aligned} \tag{6}$$

where p_w is the number of sinusoidal cycles which result in the airgap between the low-speed rotor and the stator and the variable k was introduced to differentiate between the various asynchronous space harmonics which are associated with each harmonic of the magnetic field produced by the permanent magnets. The gear ratio is then given by:

$$G_r = (-1)^{k+1} \frac{p_w}{p} \tag{7}$$

where p is number of pole-pairs of the low-speed rotor, when the static field produced by the stator its velocity is zero. This type of magnetic gear is particularly suited to applications for which a high gear ratio is required.

III. INTEGRATED MAGNETIC GEAR

Recent advances in magnetic gears have led to their torque transmission capability becoming competitive to that of mechanical gears, whilst they offer significant operational advantages [12].

There are various ways in which a magnetic gear may be combined with an electrical machine to realize a high torque density “pseudo” direct-drive. In [15] and [16] a novel method of coupling a magnetic gear and a permanent magnet brushless machine, both mechanically and magnetically, to realize a “pseudo” direct-drive machine was presented. Fig. 6 shows the simple way in which a magnetic gear may be combined with a high speed electrical machine and Fig. 7 shows a schematic of a “pseudo” direct-drive machine which is comprised of 3 main components, viz. an inner high-speed permanent magnet rotor, a low-speed rotor equipped with soft magnetic pole-pieces, and a stator in which each tooth carries a coil and on which magnets are mounted at the inner bore. In the brushless ac mode of operation, the torque which results from interaction of the high-speed rotor and stator windings is similar to that of a conventional surface mounted permanent

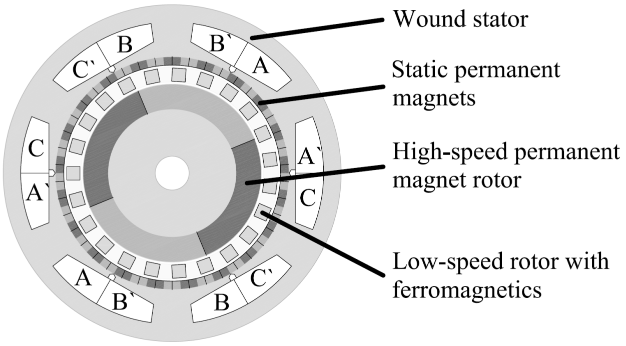

Fig. 7 Schematic of "pseudo" direct-drive machine [15]

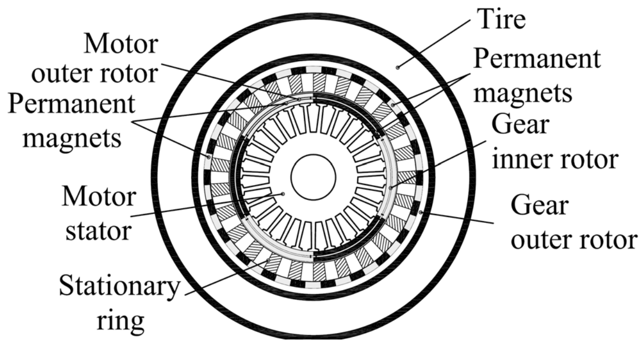

Fig. 8 Configuration of proposed in-wheel motor [19]

magnet brushless machine, and is given by:

$$T_h = k_w \frac{\pi D_s^2 l_a}{2\sqrt{2}} Q_{rms} B_1 \quad (8)$$

where D_s is the stator bore diameter, B_1 is the peak fundamental airgap flux density, l_a is the active length of the machine, Q_{rms} is the rms electrical loading, and k_w is the winding factor. Since the output torque, T_o of the low-speed rotor is given by [15], [16]:

$$T_o = T_i \times G_r \quad (9)$$

where G_r is the gear ratio, then results:

$$T_o = k_w \frac{\pi D_s^2 l_a}{2\sqrt{2}} Q_{rms} B_1 G_r \quad (10)$$

It was shown that a torque density in excess of 60 kNm/m^3 can be achieved from a naturally air cooled machine, at the power factor of 0.9 or higher [16]. It exhibits the highest torque density of any known electrical machine technology, whilst at the same time having a high power factor, and has a enormous application potential. There is also potential to further enhance the performance capabilities of "pseudo" direct-drive machine.

In [19], by adopting coaxial topology significantly improved in [11], thus it can offer very high torque density comparable to mechanical gearboxes, and some distinct advantages, was to integrate a coaxial magnetic-geared into a PM brushless motor so that the low-speed requirement for direct driving and the high speed requirement for motor design can be achieved simultaneously. It can offer the advantages of lightweight, compact size, high efficiency and low-speed high-torque operation. The key was to artfully integrate a coaxial magnetic gear into a permanent-magnet (PM) brushless motor in such a way that they can share a common PM rotor, hence the low-speed requirement for direct driving and the high-speed requirement for compact motor design can be achieved simultaneously and both the static and dynamic characteristics of the proposed motor were studied by time-stepping finite element method. Fig. 8 shows the configuration of the proposed in-wheel motor for EVs, in which an outer-rotor PM brushless motor is artfully integrated into a coaxial magnetic gear to achieve compact construction. It consists of four main parts: the motor stator, the motor outer-rotor which is also the gear inner-rotor, the stationary ring and the gear outer rotor. Three airgaps are formed to separate them from each other. In order to provide magnetic paths while reducing eddy current loss, the stationary ring is built of laminated ferromagnetic materials. Moreover, epoxy is filled in the slots of the stationary ring to enforce the structural strength for high torque transmission. Both the gear inner-rotor and outer-rotor are supported by bearings on the shafts to guarantee free rotations. For direct driving, the tire rim is directly mounted onto the gear outer-rotor. The inner rotor is designed like a cup with permanent magnets mounted on its inside and outside surfaces. In addition, permanent magnets are employed on the inside surface of the gear outer rotor. All the permanent magnets were radially magnetized, and the pole-pair number of the inner rotor and outer rotor were 3 and 22 respectively, while the number of ferromagnetic segments was 25, thus the gear ratio resulted was 22:3.

IV. CONCLUSIONS

Steel mechanical teeth are quite strong and can sustain a much higher stress than that achievable even with the best of magnets. But most single stage mechanical gears have two to three teeth engaged at a time. Magnetic gears are more flexible; good topologies use nearly half of the magnets in the device to generate holding torque. These devices offer the promise of power-to-weight ratios superior to mechanical gears with minimal vibration, no lubrication, and long life. Generally for the magnetic gears is that the torque per volume that counts and that is why the "planetary" gear type will be a possible candidate for future research in magnetic gears. The "pseudo" direct-drive motor [15], [16] overcomes the torque density limitations of conventional direct drive permanent magnet motors, by exploiting a mechanically and magnetically integrated passive magnetic gear, which acts as a speed-reducing, torque-increasing transmission that requires no lubrication. The resulting motor topography offers superior torque density, allowing drastic reductions in motor frame size to be achieved for a given load, while maintaining the practical advantages of a naturally cooled system.

ACKNOWLEDGMENT

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), ID59321 financed from the European Social Fund and by the Romanian Government.

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