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State of the art of Multiport Electrical Machines and Magnetic Gears with respect to Wind Power Generation Application

Claudia V. Pop[1], D. Fodorean[1]

[1] Department of Electrical Engineering
Technical University of Cluj Napoca (Romania)
claudia.pop@mae.utcluj.ro, daniel.fodorean@emd.utcluj.ro

Abstract. This paper presents a state of the art of multiport machines and magnetic gears designed for power generation applications. A multiport machine consists mainly of an electrical machine wo which a magnetic gear is integrated. Thus, one can get a device with more than two shafts, capable to operate at different levels of torque and speed. The main structures found in the literature, their operation, speed increase capability, materials, advantages and disadvantages are depicted in this review-type paper.

Key words. state of the art, multiport machines, magnetic gear, electric power generation

1. Introduction

In the last decades, the main topics which are discussed in the scientific community, as well as in the socio-political realm are with respect to the environment protection, as well as the clean energy and the problem of greenhouse gas decrease [1]-[4]. In such terms, the overall energy production has to be as clean as possible. If a closer look is focused on the different types of energy resources and their impact on environment, we can say that the renewable energies are a good fit. Another renewable energy resources, i.e. the solar and wind sources of energy, have almost no health risk and with almost zero greenhouse gas emission; these categories are the most environmentally friendly and safer.

On the other hand, the global average renewable energy prices are in continuously dropping. This doesn't mean that the production is dropping, on the contrary, based on the evolution of the technology, the cost of production is going down and the market of renewables will rise.

All forms of renewable energy have become more competitive, but the cost of wind and solar generating power have fallen aggressively, comparative with other ones. For example, between 2010 and 2021, the cost of onshore wind power generation dropped with 39% and the offshore wind power generation dropped with 29% till present [2].

Based on these facts, is no wonder that renewable energy is preferred, especially the wind power [3]. The main advantage of the wind power generators is the small surface covered by them. Let's take for example, a wind power plant. The surface used for the turbines is just 2% of the entire surface. The rest of the surface can be used for agriculture or for other purposes. Therefor it's a win-win solution at least for 20-30 years, which represents the lifetime of a wind generator power plant.

There are several types of wind generators with different architecture, volume, and power level, but the main parts are generally the same as principles. Mechanically, the main components of the turbine are the rotor blades, the nacelle, and the tower. Inside the nacelle are placed a set of gears and the generator. These gears have the role of linking the turning blades to the generator and increasing the rotational speed of the shaft. The blades have a relatively slow rotation speed which needs to be increased to convert rotational energy to electrical energy. In this case, the focus is on the gears because they have an important role in the assembly.

Classical geared devices, the mechanical ones, are used in general for applications which need request different level of speed and torque. There are several types of gears like spur gears, worm gears, spiral gears, planetary gears etc. Most of them have been widely used in different industrial applications because they can achieve quite high torque density. [5] Although, despite their good performances, they come with some series of drawbacks like regular maintenance, need of regular lubrication, limited reliability, and noisiness. [6]-[7] To overcome these disadvantages, some solutions were implemented by using different materials. The best solution was to use magnets because they have high energy density. The new architectures with permanent magnets (PM) became promising solutions, having several merits due to the lack of lubrication, reduced maintenance, reduced noise production and isolation between their moving parts. The first patented magnetic gear (MG) dates from 1901 and it was the first idea of gear with magnetic force [8]. Then, in 1941 was used for the first time a magnetic gear with PMs [9]. Later, new magnetic

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materials have been discovered, as one can observe in Fig.1, based on rear earth materials, like Samarium Cobalt (SmCo) or Neodymium Iron Boron (NdFeB). Since the SmCo material was invented, the use of magnetic gears has increased and then, after NdFeB was discovered, the magnetic gears (MG) have reached a lot of attention due to magnetic properties merits. Some of the advantages of MGs has been emphasized for applications where a high speed is demanded. The used of a MG with high transmission ration is possible, without affecting the power density of the electromagnetic drive. This is of huge importance, also for power generation applications [10].

Based on the improvement of the magnetic material, the interest in studying MGs has exponentially increased. As one can observe in Fig. 2, in the last three decades the number of publications on this topic has increased by almost 300 times. Till 2008 it was a relatively a slow increase, but from 2010 the publication number exploded. This fact can be related to the high efficiency obtained by the new studied topologies.

This paper contains not only an overview on the MG and their development, by highlighting their advantages and disadvantage, but also on the so-called multiport machine, which contain an electrical machine with an integrated magnetic gear. The manuscript will have a focused on different structures, with their speed-torque capability, but also the main equations which are defining their use.

2. Magnetic Gears Topologies

The operating principle of MGs is very similar to their mechanical counterparts, the difference consists in replacing the metallic teeth with magnets. The presence of the magnets reduces the metallic physical contact with contactless magnetic interaction.

Based on the working principle, the MG can be divided in two groups. The non-modulated type of gears, first group, are usually based on the magnetic interact between the PMs and just a small percent of PMs is interacting. The other group, the modulated MGs, is using a ring of iron pole pieces, also called flux modulator. Next, these two groups are presented.

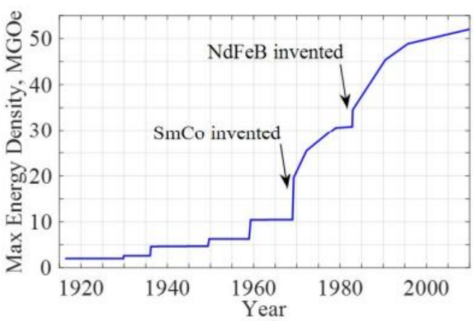

Fig.1. Improvement of the material energy density [11].

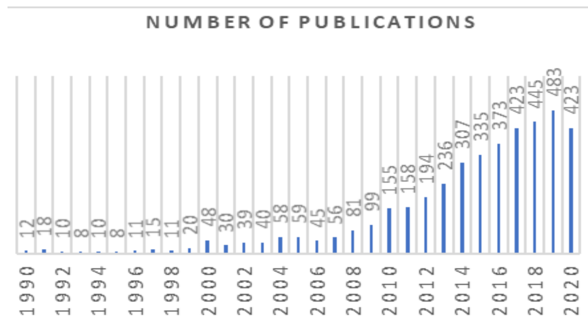

Fig.2. The increasing interest in MGs, based on published IEEE papers.

A. Non-Modulating MG

The conventional non-modulated MGs, known as MG with narrow magnets, prove the basic concepts of magnetic interaction. In general, such architectures consist in two magnetic wheels, with PMs on their surfaces. The operating principle is based on interaction between the PMs from one wheel, interacting with the PMs from the other wheel, creating a driving force which is applied on the driven wheel. In Fig.3. are shown various types of non-modulated gears [12].

There are also some magnetic conventional topologies which can provide high torque, but they have complex structure. For example, the magnetic planetary gear (d), can achieve torque density up to 100 kNm/m^3 while using six planets [13] and almost 50 kNm/m^3, by using three planets. Another example is the harmonic gear topology, shown in (e). Such topology is used for high gear ratio, the main advantage of this MG type. Studied in [14], such topology with relatively high gear ratio can achieve up to 150 kNm/m^3. The significant drawback of both MG topologies presented above is the structural complexity. For the planetary gear, in general there are three planets and one sun and the risk of detachment of PMs is high and if one of the planets is affected, the whole structure is affected. For the harmonic topology, the inner rotor is flexible and there is also a high risk of PMs detachment and the risk of inner rotor breakage.

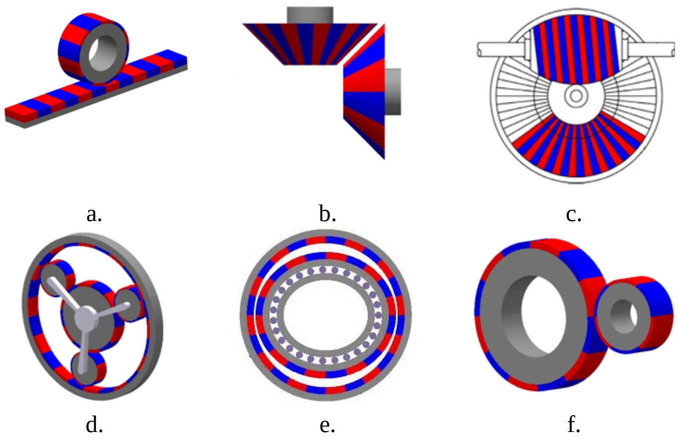

Fig.3. Non-Modulating MG: a) rack & pinion, b) bevel type, c) worm type, d) planetary type, e) harmonic gear, f) spur type.

B. Modulated MGs

The other group of MGs are the so-called modulated MGs or MGs guided by flux. Their most important advantages are their compactness, high torque density and overall high efficiency. Despite the different architecture of these MGs, they are all based on the same working principle. Their assembly has two moving parts and one static part. On the surface of the moving parts the PMs are attached, having a different number of magnetic poles – even the shape of the PMs can be different (surface mounted, of spoke type, halfback array, half inserted or fully inserted, on one layer or different layers). The static part is made of iron pole pairs and is placed between the moving parts. This static part is also called flux modulator, the reason of the MGs group name.

In Fig.4 are shown some of the topologies of modulated MGs with the highest efficiency. First topology (i) presented in Fig.4 is the linear MG type and it was studied by Atallah in [15]. Such application can achieve up to 1.7 MN/m^3 by using strong NdFeB material type. The main drawback of this topology is the sensitivity of the modulator part and especially the axial length of the space between the rings placed between the PMs of the rotors. Such MG type is generally used for marine applications and wave power generations [16]. The second topology from Fig.4 is the axial type of MG and it was studied by Mezani in [17]. For an outer rotor diameter of 200 mm and a gear ratio of 5.75:1 was achieved, as well as a 70 Nm/m^3 torque density. Such architecture is mainly used for applications where an isolation between input and output shafts is needed.

The radial type of MG topology offers the best results in terms of torque density. The main benefits of such architecture are due to the compact structure and the use of all PMs, at once, in the production of the torque. Such topology with high efficiency was studied by Atallah in [18] and it can achieve a torque density up to 150 kNm/m^3. Another topology, the spoke variant (Fig.4.iv) is studied in [19]. Based on bench tests, a torque density of 54 kNm/m^3 was obtained. In general, it is preferred a rotor with surface-mounted PMs, against a spoke topology.

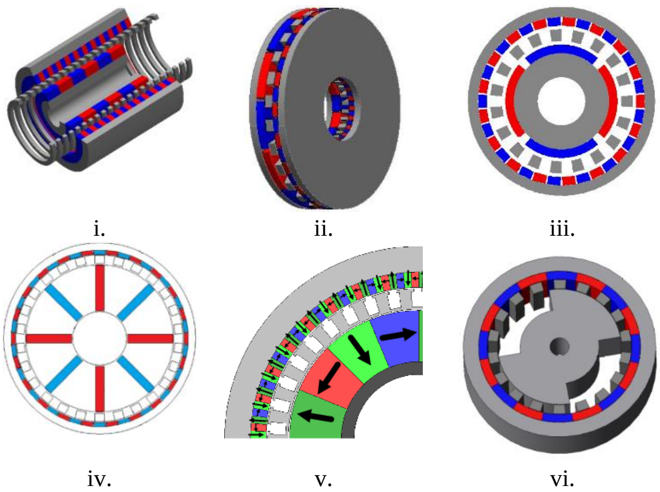

Fig.4. Modulated MG: i. linear, ii. Axial, iii. Concentric, iv. Spoke type, v. Halbach array type, vi. Reluctance type.

There are other architectures of MGs like the one from Fig.4.v, with different PM orientation [20] or reluctance MG, in Fig.4.vi, depicted in [21].

Despite their architecture, all presented MGs can achieve different values of torque density or gear ratio. In Table I is presented a comparison between different MGs configurations and their efficiency in torque transfer.

Table I. - Gear ration and Torque desnity Comparison of MGs

MG type	Gear ratio	Torque density (kNm/m^3)
Bevel gear [22]	3:1	5
Planetary MG [23]	3:1	97.3
Harmonic MG [24]	360:1	75
Axial MG [25]	5.75:1	70
Radial MG [18]	5.75:1	120
Spoke MG [26]	5.5:1	92
Halbach MG [27]	6.67:1	5
Reluctance MG [21]	8:1	29

3. Principle of operating

The working principle of MGs is based on the magnetic interaction between the PMs used. For example, the first group of MGs, the conventional ones, the PMs represents the counterparts of the mechanical teeth. This category has to fulfil some requests about the number of PM pole pairs and the magnetic gear ratio. This means that in case of transition between mechanical to PM gear, the architecture and the gear ratio has to be the same, the difference is the replacement of mechanical teeth with PMs. [28] For the second group, the number of magnetic pole pairs and iron pole pieces can be different, because in this case, there is a new element which makes a significant difference between mechanical and PM gears. Next, the accent will be on the modulated MGs, due to their increased efficiency.

A. Gear ratio

In general, a MG architecture consists in two rotors and a modulation ring, placed between them. The gear ratio is directly related to the number of PM pole pieces and iron pole pieces. Each rotor is covered in PMs pieces and to achieve the highest torque, they must fulfil the next equation: [29]

$$p_{in} + p_{out} = n_s \tag{1}$$

where p_{in} and p_o are the pole pair number of the inner and outer rotor and n_s is the number of iron pole pieces of the modulating ring. The rotors are working at different levels of rotational speed, and they can rotate in the same direction or in opposite direction. The modulating ring is usually static.

The gear ratio of MGs is given by:

$$G_r = -\frac{\omega_{out}}{\omega_{in}} = \frac{p_{in}}{p_{out}} \tag{2}$$

where ω_{out} and ω_{in} are the mechanical speeds of the outer and inner rotor, respectively. These equations are generally available for modulating type MGs.

By using these relationships, it can be obtained single fixed gear ratio. There are solutions to obtain variable gear ratio and one of them is proposed in [30]. The idea is to keep the iron pole pieces fixed and, in this way, the gear ratio has another value. Or one of the rotors are kept fixed and, again, the gear ratio has a different value.

B. Iron pole-pieces design

The flux modulator is the representative piece of the second group of MGs – from here the group has gained its name. The modulating ring is made of non-magnetic material. There are some different architectures of the pole pieces, studied in [31-32]. The geometry of this active part is very important because it's part of torque transmission unit, and it influences the iron losses. As one can observe in Fig. 5, different types of mechanical linkages were proposed. The structure with iron bridges on inner, outer, and middle, respectively, were proposed in order to reduce the losses. The other variant, without bridges is built by attaching metallic parts by some non-metallic parts and fixed them on the top and at the bottom with some fixing rings. Also, in [33] it was studied the effect of the modulator length and it was observed the connection between the increasing torque and the length of the modulator.

C. Cogging torque

A detailed analysis on cogging torque for MGs was elaborated in [34]. In order to reduce the cogging torque, different techniques were analyzed, but the skew technique is preferred [35-36]. Also, in [37] it was introduced a cogging torque factor, k_r, which gives a specific poles-pieces configuration to obtain smooth mechanical characteristics.

$$k_r = \frac{(2 \cdot p_{in} \cdot n_s)}{LCM(2 \cdot p_{in} \cdot n_s)} \tag{3}$$

where LCM represents the least common multiple. It was found out that the smaller factor k_r is, the lower cogging torque is obtained.

D. Rotor's design aspects

By using PMs in the rotor's structure, it can be obtaining a higher efficiency of the unit. But because of the centrifugal forces, especially in case of high-speed

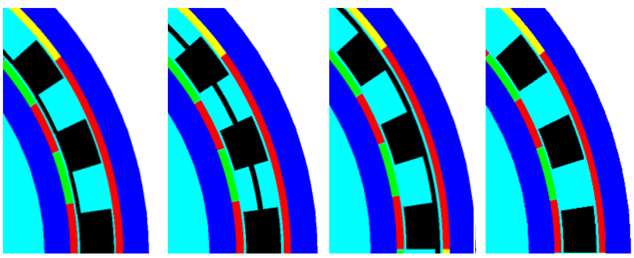

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Fig.5. Iron pole-pieces bridges: a. bottom, b. middle, c. up, d. without bridges.

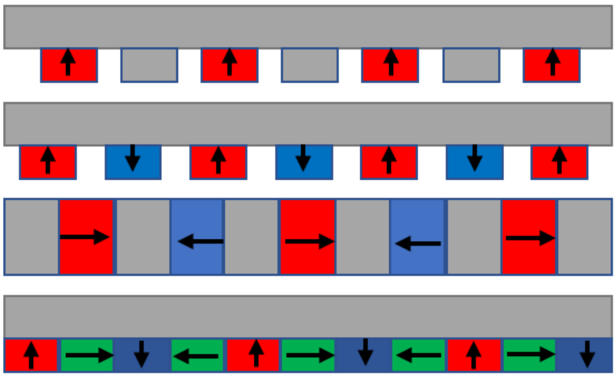

Fig.6. Different arrangements of the PMs and their orientation: leakage pole, surface-mounted, flux concentration, Halbach array.

operation, a special attention has to be paid on the integrity of the PMs. There are several topologies of PMs configurations, shown in Fig.6, each one with their advantages, [38-41]. These configurations of PMs were studied to obtain better performances or less losses [38]. For example, the topology in Fig.6 up, depicted in [40], is introducing salient leakage poles to reduce the quantity of the used PMs, while it can still maintain high torque density. Different topologies with PMs, including interior [42] and spoke-type [43] PMs configurations were also studied to avoid damaging the surface PMs. Unfortunately, both solutions have shown significant torque reduction capability, after their efficiency were compared with topologies with surface-mounted PMs. Also, were studied topologies with different magnetic materials to reduces the costs and make them more affordable, such as ferrite type [44].

4. Magnetically Geared Machines

The efficiency of torque transferring, and the advanced technology of MGs have led to a new direction of applications with MGs, in electrical machines domain. The MG can be integrated with the electrical machine in one unit, reaching an increased torque density. Thus, it can be obtained a higher torque density even if it is using a cascaded configuration, but, in this case, the volume will significantly increase.

First model of such magnetically geared machine was published in 1993 in [45]. Different other topologies were studied since then, each with their own particularities [46-49]. The most simple and robust topology of magnetically geared machine are the ones with outer rotor and inner stator. Such configurations are shown in the Fig.8 [50-54].

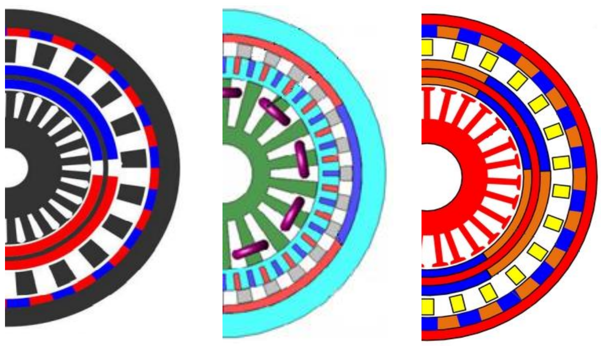

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Fig.7. Electrical machines with integrated magnetic gears.

Such variants are also called multiport machines, offering access at least to two shafts of different torque and speed levels. The outer rotor is coupled to the inner rotor of the MGs, both rotos been equipped with PMs. If the application requires a separation between the electrical machine and MG, this decupling is providing high flux-weakening capabilities [55]. The main advantage of the coupled topology is the higher level of torque density, on one hand. Secondly, it offers to possibility to have access to two different shafts of different levels of torque and speed. This can be critically advantageous for wind power applications, since the wind speed can vary in an important range. Thus, such a solution will offer a speed extension for the wind power generation system. On the other hand, such topology has also a drawback: the complex mechanical structure.

The machine with MG has four concentric components with three airgaps between them. It has two rotos (the outer rotor of MG and the inner rotor of MG coupled with the machine's rotor) rotating at different angular velocities and possible in different directions. The concentric configuration is quite challenging, but despite these difficulties, several configurations and prototypes were investigated in [56-58]. To reduce the complexity, some configurations with outer stator were studied, but these can achieve lower torque density, up to 60 kN/m^3 [45]. In comparison, the inner stator variant can achieve up to 150 kN/m^3, which is a significant result [59-60].

5. Conclusions

Mechanical gears are used in several application in industry domain but their drawbacks, like often maintenance and performance limitation are significant. For example, in wind power industry, gearbox needs on many occasions maintenance interventions, which lead to interruptions in electric power generations. A solution is required to overcome this shortcoming and one possible solution is the used of magnetic gears (MGs). The magnetic configuration has the advantages of lower maintenance, torque transfer without physical contact and it offers the possibility of physically decoupling the input shaft with respect to the output shaft. The industrial interest has increased regarding the use of MGs lately, thus a review on the possible solutions to be used, even the ones with multiport options, has motivated this study. Beside the renewable energy domain, such solutions are useful for the automotive industry.

The current development of MGs has been presented in this paper, with special attention paid to the concentric configurations, but also for variants containing an outer rotor electrical machine with integrated magnetic gear. Till present, there are various applications using MGs because of their advantages, but the subject of losses is still under investigation. A lot of work is still needed for more practical validation in order to widely evaluate the suitability of the MGs or multiport electrical machines and their place in industry. The most important drawbacks of such variants are the complexity and the cost of the PMs, mainly. But the other emphasized advantages make the MG or the multiport machine a desired candidate for electric power generation applications.

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