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Magnetically Geared Induction Machines

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A wound rotor induction machine is artfully coupled to a magnetic gear to achieve a high torque density drive system called MaGIM “Magnetically Geared Induction Machine”. The high-speed rotor of MaGIM is common to both the machine and gear sides. A rotating diode rectifier electrically links the machine’s wound rotor and a dc ‘boost’ winding on the gear side to increase the torque transmission capabilities of the overall system. The first investigations on a 100 kW – 120 rpm MaGIM are promising since a torque increase of about 15% could be obtained by inserting the diode rectifier. For fixed speed applications, this induction-machine-based system can be directly supplied from the mains.

Index Terms— Magnetic gears, Induction machines, Wound rotor

I. INTRODUCTION

IN LOW speed/high torque applications, a compact system is achieved using a mechanical gear to match a high speed/low torque machine to its load. This requires lubrication, cooling and maintenance and results in potential jamming at overload operation. Direct drive solutions are of limited torque density in achieving low speed/high torque output because of limited admissible heating factor.

In the last decade, a new concept of magnetically geared Permanent Magnet (PM) machines has been introduced for a wide variety of applications [1]-[4]. In such a system, the transmitted torque is limited by the magnetic gear transmission capability, based only on the interaction between magnets through field-modulating ferromagnetic pieces.

We aim here to introduce a novel topology using an induction machine/magnetic gear to achieve a high torque/low speed drive system with extended torque transmission capabilities. This concept is called MaGIM which stands for: **M**agnetically **G**eared **I**nduction **M**achine.

II. PRINCIPLE OF OPERATION OF MAGIM

Figure 1 presents a schematic view of the MaGIM device. It is composed of four armatures among which two are stationary and the two others are rotating at different speeds. The principle of operation of MaGIM is described hereafter:

- The most inner armature represents the stator of the induction machine. A p pole-pair, 3-phase winding is located in the slots. When supplied via a balanced 3-phase voltages (or currents), a rotating magnetic field is created in the machine air gap.
- This rotating field induces currents in another p pole-pair, 3-phase winding which faces the stator. This results in an electromagnetic torque production which moves the high-speed rotor at a mechanical speed Ω_h .

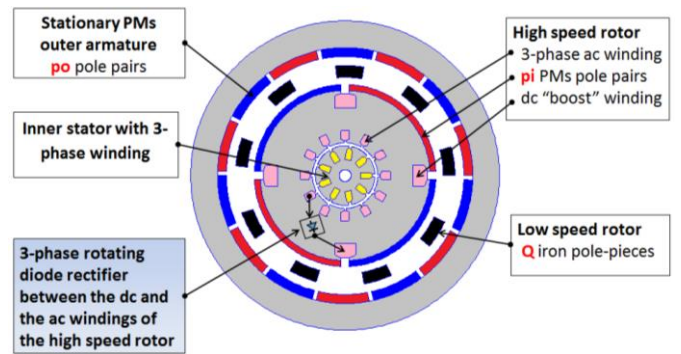


Fig. 1. 2D cross section view of MaGIM

- The magnetic gear is mounted on the external surface of this high speed rotor. The principle of operation of the magnetic gear is based on modulating the magnetic field created by p_i PM pole-pairs by Q ferromagnetic pole pieces. The obtained field interacts with p_o PM pole-pairs of the external armature to transmit torque to the low-speed load. The combination $p_o = Q - p_i$ results in the highest torque transmission capability of the gear. The external armature being held stationary, the torque is transmitted to the low-speed load via the pole-pieces. The resulting gear ratio is then $Gr = Q / p_i$ so the speed of the pole-pieces (low-speed rotor) is $\Omega = \Omega_h / Gr$.

Notice that the overall torque on the high-speed rotor is null as the machine torque cancels the high-speed torque of the gear. In such a system, the transmitted torque is limited by the interaction between magnets via the pole-pieces.

In order to increase the torque transmission capabilities of the system, 3-phase windings on the high-speed rotor are electrically connected to a p_i pole-pairs dc winding (called dc boost winding) via a rotating diode rectifier. This results in an extra torque which allows more operation flexibility compared to magnetically geared PM machines.

The description of the principle of operation of MaGIM presented here doesn't address the full theory behind each component of the studied system. The main objective of this paper is to show the effectiveness of the proposed device in achieving a high torque density drive system with torque boost capability. Nevertheless, relevant works on magnetic gears and

magnetically geared PM machine [1]-[4], [9] as well as on induction machines [5], [8] can help the reader understand this theory.

III. APPLICATION EXAMPLE

A MaGIM rated at 100 kW, $\Omega=115$ -120 rpm, 8000Nm is considered for the simulation studies. It is supplied from the mains at 400 V – 50 Hz, so a constant speed application is considered here.

A. Preliminary design of MaGIM

As it can be seen, the MaGIM design is a complex task. There are many electromagnetic interactions between the different armatures which makes it difficult to have a simple sizing procedure like in conventional electrical machines. For a preliminary design, the machine and the gear sides are considered separately.

Firstly, the machine has been sized using the electrical and magnetic loading concept together with past experience from machine manufacturers [5]-[6]. A large number of physical and geometrical design parameters arises (~20). Constrained multi-objective Genetic Algorithms (GA) optimization has been used to deal with the preliminary design. The computations are carried out thanks to the NSGA2 Matlab implementation of GA [7]. The objective functions are to maximize the efficiency and to minimize the machine active volume. The most important constraints concern the minimal value of the power factor, the limitation of the saturation level and the heating factor. As reported in [8], the heating factor is the product of the electric loading and the current density. It allows a predetermination of the convection coefficient needed for sizing the cooling system. In our study, it has been set to a maximum value of 2000 ($A^2/mm^2.cm$) which results in medium values of the convection coefficient (typically around 100 W/m².K).

Then, the gear design is considered (without the boost winding). An analytical model based on the formal resolution of Maxwell's equations [9] is used. Again, constrained multi-objective Genetic Algorithms optimization was used to deal with the preliminary design. The objectives are the minimization of the PMs weight and the total gear volume (which also corresponds to the total active volume of MaGIM).

Many simulations are needed to achieve a good compromise between the optimal performances of the machine and the gear sides. In the final stage, finite element analyses are carried out to consider the overall system in which we need to accommodate the boost winding. The FE refinement is done manually but it doesn't take a long time since the GA preliminary design already gives a good starting configuration. We have used "MagNet" software from Infolytica to perform the FE computations.

Fig. 2 presents the optimal Pareto fronts obtained for the designed MaGIM. The optimization time is very short for the machine side (~ 2 mn) but much longer for the gear side (~ 2 hours). The optimal parameters for the final design are those given in Table I obtained with 2D finite element computations. The ferromagnetic parts are made from Silicon iron laminations

(grade EN 10106, 0.5 mm thickness). The main performances of the designed MaGIM are given in Table II.

Fig. 3 shows the flux lines and the flux density distribution in the studied device. It can be seen that the flux density norm is limited to 1.4 T in most of the iron parts. Notice that the narrowing of the yoke in the vicinity of the slots for the boost winding could have a negative impact on the performance of MaGIM, so this has to be considered carefully in the design process.

Fig. 4 presents the instantaneous torque at rated speed on the high speed rotor. This torque comes from the machine and the gear sides, which cancel each other. Indeed, the high-speed rotor doesn't drive any load so its total net torque is zero.

TABLE I
Main parameters of the 100 kW MaGIM

| Parameter description | Value |
|---|--------------------------------|
| Machine side | |
| Stator rated voltage, Vs | 400 V (Δ connection) |
| Stator frequency | 50 Hz |
| Pole pairs, p | 3 |
| Number of stator slots, Ns | 72 (10/12 shortening) |
| Number of rotor slots, Nr | 54 (7/9 shortening, Y) |
| Stator outer radius | 201.4 mm |
| Air gap | 0.6 mm |
| Active length | 260 mm |
| Stator slot height | 49 mm |
| Stator tooth width (rectangular) | 8.6 mm |
| Stator back-iron height | 42 mm |
| Rotor slot height | 32 mm |
| Rotor tooth width (rectangular) | 10.9 mm |
| Rotor back-iron height | 50 mm |
| Turns per phase (stator and rotor) | 72 |
| Stator (Rotor) per phase resistance | 85 m Ω (78 m Ω) |
| Stator (Rotor) phase leakage inductance | 3.1 mH (2.9 mH) |
| Magnetizing inductance | 55 mH |
| Gear side | |
| Inner rotor pole-pairs, p_i | 5 |
| Stationary armature pole-pairs, p_o | 36 |
| Number of pole-pieces, Q | 41 |
| Gear ratio, Gr | 8.2 |
| Airgap (inner and outer rotor sides) | 2.5 mm |
| Inner rotor PMs thickness | 7 mm |
| Stationary armature PMs thickness | 5 mm |
| Pole-pieces thickness | 18 mm |
| Remanence of PMs | 1.3 T |
| Inner rotor radius | 307 mm |
| External radius | 350 mm |
| Boost winding slot area | 4.8 cm ² |
| Resistance (per turn) of the boost winding, R_b | 0.2 m Ω |
| Inductance (per turn) of the boost winding, L_b | 60 μ H |

TABLE II
Main performances of the 100 kW MaGIM at rated operation

| Quantity | Value |
|---|------------|
| Stator phase current | 109A (rms) |
| Rotor phase current | 101A (rms) |
| Speed of inner rotor (high speed), Ω_h | 975 rpm |
| Slip, s | 2.5% |
| Speed of outer rotor (low speed), Ω | 119 rpm |
| Torque exerted on outer rotor | 7970 Nm |
| Power factor | 0.83 |
| Efficiency | 0.93 |
| Iron losses | 500 W |
| Mechanical losses (1% of rated power) | 1000 W |

It can be seen that the gear side torque is almost ripple-free (it is also the case for the low-speed rotor) but the machine torque exhibits some ripples which are mainly due to the slotting effects.

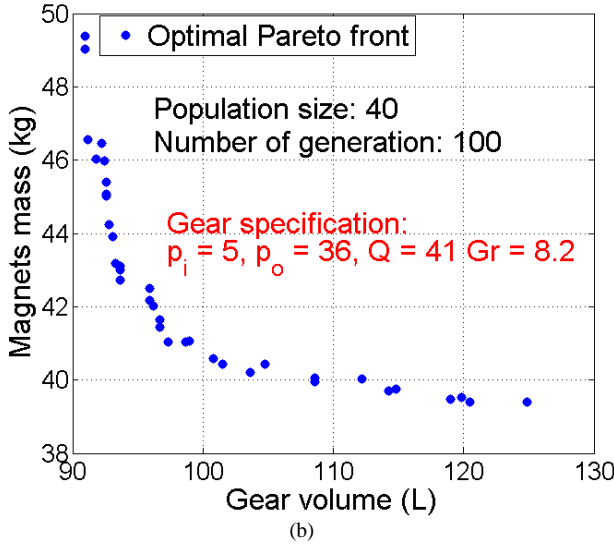
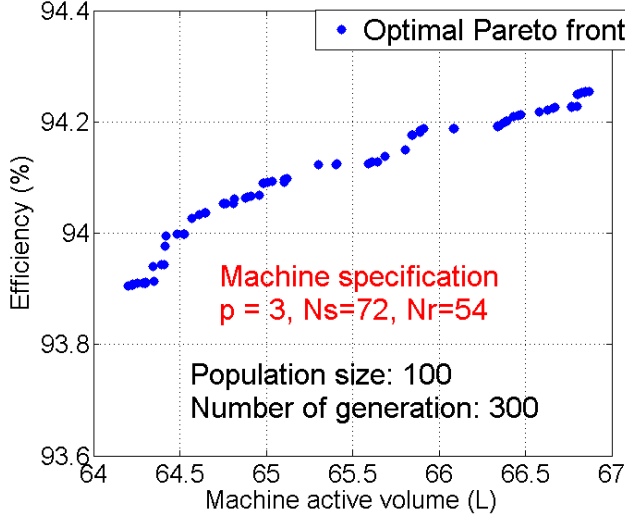


Fig. 2. Optimal Pareto fronts: (a) Efficiency vs. machine active volume, (b) PMs mass vs. gear volume

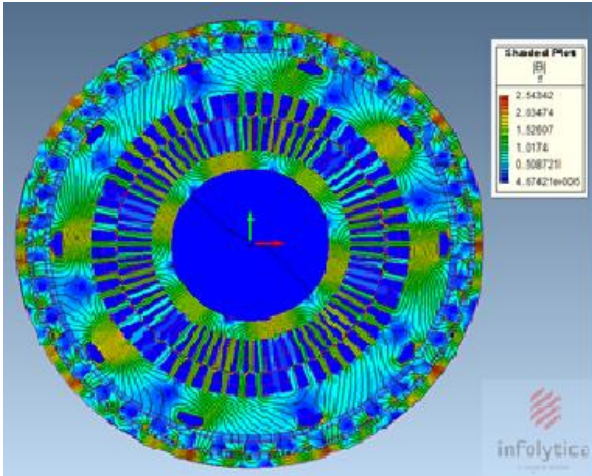


Fig. 3. Flux lines and flux density distribution at rated operation (boost winding is disconnected)

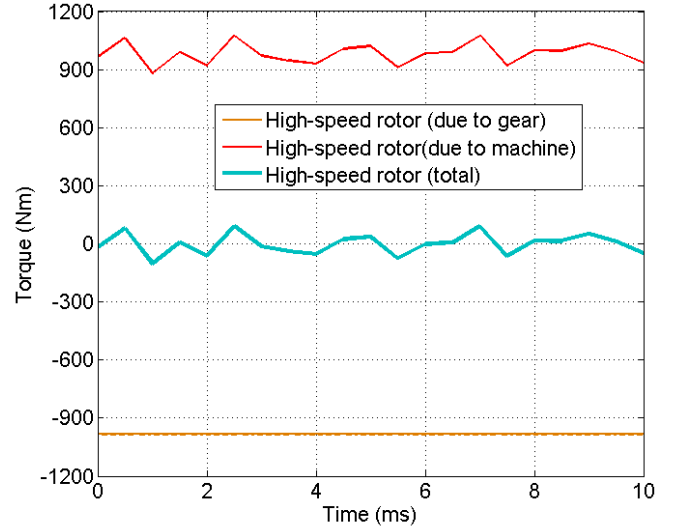


Fig. 4. Torque exerted on the high-speed rotor at rated operation (boost winding is disconnected)

B. Introduction of the boost winding

In order to study MaGIM when the boost winding is connected, a circuit-based model has been developed under Matlab/Simulink - Simscape SimPowerSystems. A dq model is used for the machine. The wound rotor terminals are connected to the ac side of the 3-phase diode rectifier whose dc side is connected to the boost winding (represented by its R , L parameters). Notice that a forward voltage of 0.5 V and an internal resistance of 1 m Ω are assumed for the diodes. The boost winding resistance and inductance are those given in Table I (R_b , L_b) for 1 turn per slot. For N_{dc} turns per slot, the boost winding resistance and inductance become $R_{dc}=N_{dc}^2 \times R_b$ and $L_{dc}=N_{dc}^2 \times L_b$, respectively.

In the simulation studies, the torque developed by the machine is fixed to 970 Nm (rated power at 120 rpm).

Figs. 5 presents the performances of MaGIM for N_{dc} values up to 10.

In order to keep the torque at the desired value, the speed of the high-speed rotor decreases as N_{dc} increases, Fig. 5.a. The machine power also decreases which results in relatively constant current values in the stator and rotor windings. The power factor and the efficiency (the boost winding losses are taken into account) also decrease but remain acceptable compared to the situation when the boost is disconnected (viz. $N_{dc}=0$).

The interest of introducing the boost winding can be observed from Figs. 5. c and d. The dc current in the boost winding (Fig. 5.c) will create an extra torque (obviously, the load angle of the gear will vary with I_{dc} to keep the torque at the desired value). The pull-out torque (computed by FE) referred to the low-speed rotor is shown in Fig.5.d. Compared to the situation where the boost is disconnected ($N_{dc}=0$), a torque increase of about 15% is obtained when $N_{dc}=10$.

This constitutes a major advantage of MaGIM compared to PMs geared machine:

- There is no need to oversize the gear for overload operation
- MaGIM would probably have better transient performances with fast recovery from slipping [10].

IV. CONCLUSION

A new concept of high torque density magnetically geared induction machine has been proposed. A continuous torque density in excess of 70 Nm/L and 78 Nm/L with the boost winding can be achieved.

MaGIM offers several advantages which stem from two features inherent to this concept. The first is that the boost winding results in an additional continuous torque production or a potential possibility of reducing the magnets volume. The second feature relates to transient performances including the probability of having a better recovery from slipping.

Further works are ongoing to consider the boost winding in the optimization procedure of the MaGIM system. Thermal modeling is also to be considered in the design process in order to define the cooling requirements. The behavior of MaGIM within a vector-controlled drive system is also being investigated.

It goes without saying that it is necessary to build a prototype for a full validation of the MaGIM concept.

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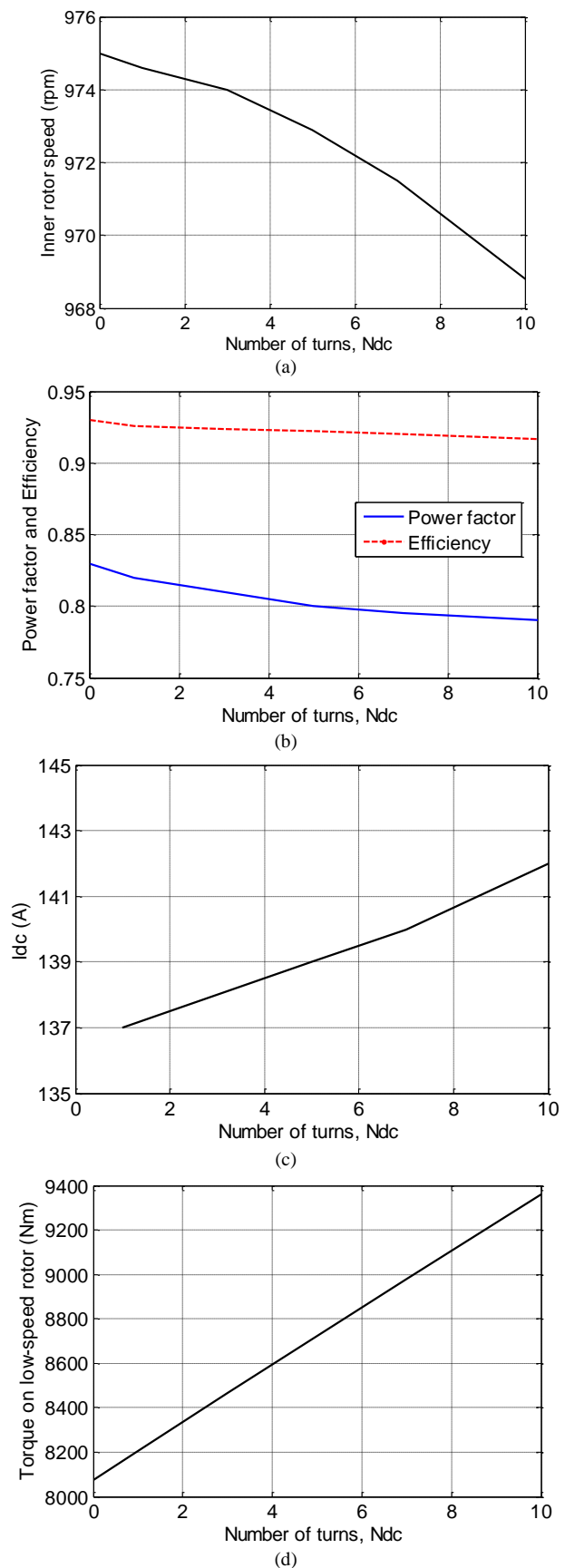


Fig. 5. Influence of N_{dc} on MaGIM performances: (a) Speed of the high-speed rotor (b) Power factor and Efficiency (c) dc current of the boost winding, (d) Pull-out torque on the low-speed rotor