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Comparison Study of Electric Machines for In-Wheel Electric Vehicle Application

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***Abstract*— Electric vehicle motoring is became a famous task due to several problems caused by thermal engine such as pollution and high oil prices. Thus, electric motor is seen as the solver of these problems. So, different research was done about these motors and its applications. Different configurations were proposed in the literature. Each configuration has its own intrinsic features depending on the industrial application. The variety of industrial applications can lead to different choices. Therefore, the choice of a permanent magnet topology must be carefully made. In this paper, a comparison between different machines according to some criteria was done to choose the most suitable for in-wheel motor application.**

***Keywords*— Electric machine, in-wheel motor, efficiency, comparison.**

I. INTRODUCTION

Permanent magnet machines (PMM) are widely used in different industrial applications [1], [2], [3] and [4]. According to the type of application, the PMM has its own configuration and intrinsic characteristics. Therefore, the topology with permanent magnet must be carefully chosen. In this paper, a detailed study of different PMM configurations is presented. Depending on the orientation of the magnetization of the permanent magnets, three types of machinery can be distinguished; the radial flux machine, the axial flux and the transverse flux one. These topologies are illustrated in Fig. 1. Depending on the arrangement of the rotor, two configurations may be encountered; the machine with an internal rotor and the machine with external rotor. Finally, depending on the winding distribution, there are distributed winding and concentrated winding machines. The objective of this study is to present the different machine configurations and to select the most suitable one for the application of in-wheel motor for electric vehicle. The selection criteria which can be adopted are: the simplicity of construction, the cost, the efficiency and the power density.

II. RADIAL FLUX CONFIGURATION

This machine is one of the most classical topology which has a simple construction (Fig. 1). The flux circulates radially through the air gap while the current circulate in the axial direction.

Depending on the rotor configuration, different radial flux PMM can be distinguished [5].

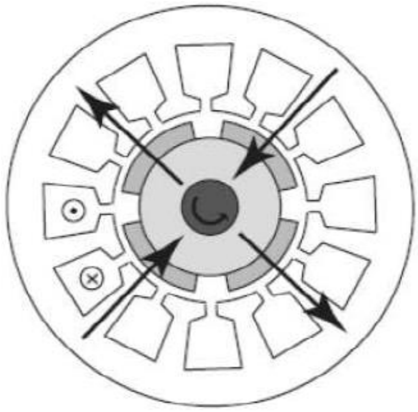

Fig. 1. Radial flux permanent magnet structure

A. Surface mounted permanent magnet with internal rotor

This machine has a simple structure: the magnets are placed, with alternating polarity, in the inner surface of the rotor (Fig. 2a), and it has a reduced cost construction. But because of the location, the magnets are subject to centrifugal forces which may cause their detachment from the rotor [5], so high speed applications become difficult with this machine.

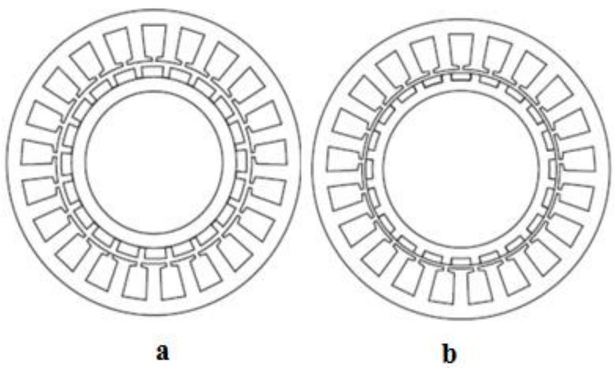

Fig. 2. PMM with surface magnets (a) and inset magnets (b)

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B. Inset permanent magnet machine

It is the same structure as the previous case, except that, the space between magnets is filled with iron (Fig. 2b) [6]. In [7], it was shown that the electromagnetic torque is lower than that produced by a surface permanent magnet. For high speed, this configuration is not adequate because magnet may come off due to the centrifugal forces.

C. Berried permanent magnet machine

In this configuration, the permanent magnets are located inside the rotor. Two structures are presented: the classical one and the one with concentrated flux (Fig. 3). The advantage of the second one is the ability to concentrate the magnet flux in the rotor. This allows a higher induction in the air gap. Because magnets are protected against detachment, this structure is used in high speed applications [8]. But this configuration has high leakage flux between magnets and it is expensive in term of construction.

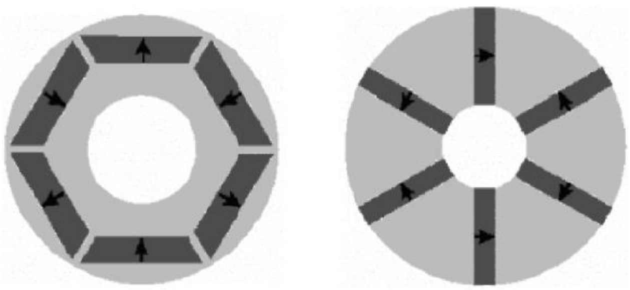

Fig. 3. Burried permanent magnet machine

D. Surface permanent magnet machine with external rotor

For this type of machine, the rotor is mounted outside and the magnets are placed in the internal surface of the rotor as illustrated in Fig. 4. This configuration presents a large rotor diameter allowing a greater number of poles. During rotation, centrifugal forces make the detachment of magnets more difficult. This type of machines can be used for in-wheel motor which makes it more compact.

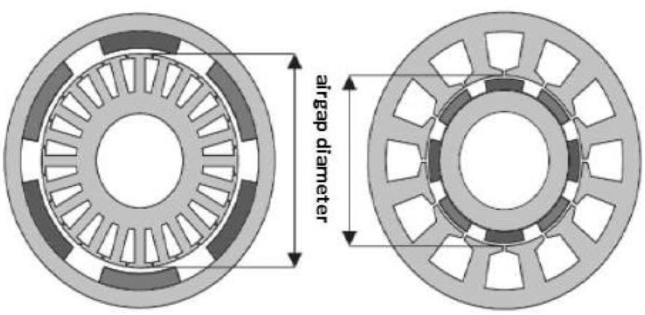

Fig. 4. Machine with outer or inner rotor

E. Permanent magnet machine with radial flux and double rotor

It was proposed in order to improve the power density and the output torque [10]. As illustrated in Fig. 5, the stator is laminated on its two surfaces. This lamination is necessary to avoid eddy current losses.

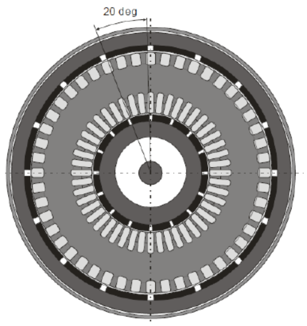

Fig. 5. PMM with radial flux and double rotor

III. AXIAL FLUX CONFIGURATIONS

As it is mentioned in Fig. 6, the flux inside the magnetic circuit circulates axially through the air gap while the currents circulate in the radial direction [9]. This machine can reach efficiency close to 98% and it has a high power and torque per mass among all configurations. Two axial flux configurations can be distinguished.

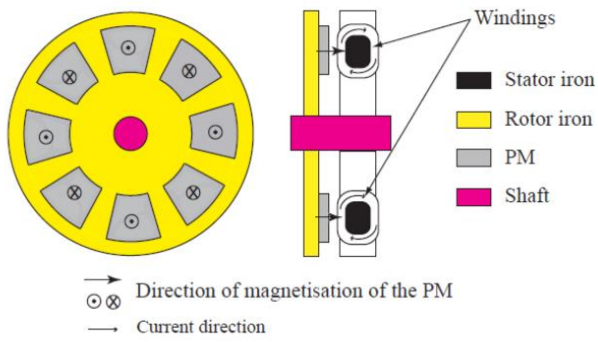

Fig. 6. Axial flux machine [5]

A. Axial flux machine with single sided

Fig. 7 shows the single sided structure of this machine [11]. This configuration has several problems of interaction between rotor and stator due to the axial forces exerted by the permanent magnet which leads to the distortion of the stator. In addition, the mechanical improvement of the problem is expensive.

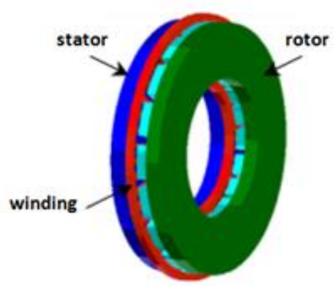

Fig. 7. Single sided axial flux machine

B. Axial flux machine double sided with inner or outer stator

This structure is presented in Fig. 8 [12]. For the attraction problem, the use of two rotors or two stators will allow the balance of attraction forces between different active parts of the machine.

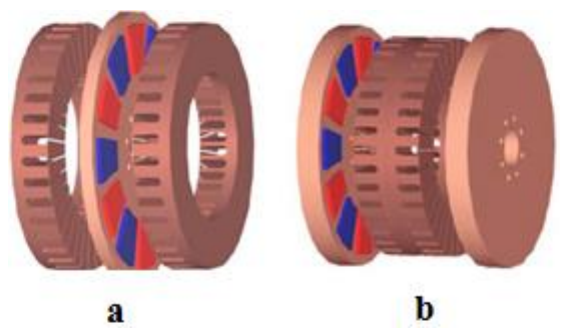

Fig. 8. Double sided Axial PMM

IV. TRANSVERSE FLUX MACHINE

This machine is well suited for low speed direct drive applications (Fig. 9). It has a high specific torque for the compactness of the geometry. But it suffers from a low power factor and a complex structure which leads to a high manufacturing cost.

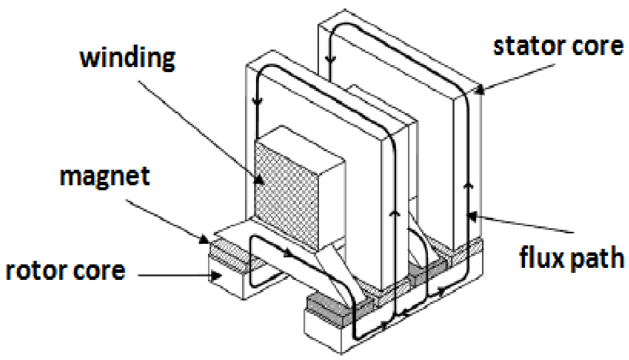

Fig. 9. Transverse flux machine

V. COMPARISON BETWEEN INTERNAL AND EXTERNAL ROTOR

The internal rotor structure allows a very compact construction but it has a low torque due to the low air gap radius. For the external rotor configuration, the radius of the air gap is higher than a certain value, so it produced a higher torque compared to internal rotor configuration. For the in-wheel motor application, which is our case, the PMM with external rotor is the best choice.

VI. COMPARISON BETWEEN RADIAL FLUX AND AXIAL FLUX MACHINE

The aim of this comparison is to choose the best configuration for in-wheel electric vehicle application. In [12], it was demonstrated that the two configurations have the same performances (torque density, torque per mass, efficiency) but the axial flux structure is with double sided, so we need more of permanent magnet mass which increase the machine cost.

VII. COMPARISON BETWEEN RADIAL FLUX AND TRANSVERSE FLUX MACHINE

The main advantage of the transverse flux machine is its high force density. But it has a low power factor which does not exceed 0.55 unlike the radial flux machine where it is close to 1. In addition, the three-dimensional flux path in transverse flux machine requires the use of a specific material which increases the machine cost.

VIII. COMPARISON BETWEEN DISTRIBUTED WINDING AND CONCENTRATED WINDING

In electric machine, the type of the stator winding is determined by three parameters: the number of slots N_s, the number of pole pair's p and the number of phases N_{ph}. The number of slots per pole and per phase q is then calculated.

$$q = \frac{N_s}{2N_{ph}\,p} \quad (1)$$

According to q is an integer or not, we have two windings.

- Distributed winding: q=integer. This type of machine has better performance; the magneto-motive force is sinusoidally distributed.
- Concentrated winding: q≠ integer. Each coil may be wound around a stator tooth. Two winding types can be distinguished: a single layer winding and a double layer one.

In [13], a comparison between the two types of winding was done. The machine with concentrated winding is advantageous in term of copper and iron losses but it has a higher eddy current loss. On the contrary, the machine with distributed winding is advantageous in term of eddy currant loss nevertheless it suffers from higher copper and iron losses, so this machine is selected for higher speed applications. Concerning the machine with concentrated winding, it is possible to have low relaxation torque, better fault tolerance and constant power over a wide constant speed range.

IX. WINDING FEASIBILITY

There are different theorical combinations of slots and poles. However, the combinations are only feasible if the number of slots per phase as well as the number of slots per number of winding cycle is an integer. Therefore, it should satisfy the following equation [5]:

$$\frac{N_s}{N_{ph} GCD(N_s, p)} = k \qquad (2)$$

Where k is integer and GCD is the greatest common divisor.

X. DETERMINATION OF THE WINDING CONFIGURATION FOR A DOUBLE LAYER WINDING

For a given combination of number of poles and slots, there are many possibilities to place the coils of each phase in the slots to determine the overall configuration of the winding. The most interesting one is that which gives the highest winding factor. Two methods are used to realize the winding: the CROS method [14] and the star of slots method [15].

XI. CONCLUSION

There are different configurations which are used in electric vehicle motoring. Which makes the choice of a specified topology a difficult task, in our case; we have a special type of motor which is in-wheel motor. So, we have many constraints to respect in order to facilitate the integration of the motor inside the wheel and to obtain the best performances. Therefore, in the present paper we present a comparison between different machines according to some criteria: simplicity of construction, cost, efficiency and power density. Then the most suitable machine is chosen to be used in the design of our in-wheel motor. This configuration will be subject of design an optimization.

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