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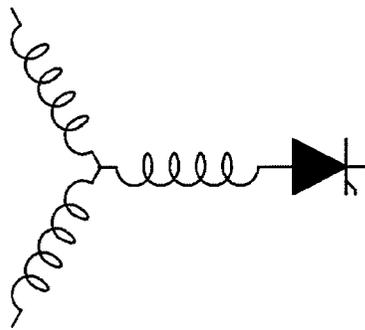
Sizing Equation Analysis for Field Controlled PM Machines: A Unified Approach

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Abstract -- In this paper, the sizing equation analyses are presented for two different radial and axial flux field controlled PM machines. These types of machines have two sources of excitation which allows one to easily control the airgap flux. Variable flux component provided by the field winding and fixed flux component obtained from PM converge into the airgap so that an additive or subtractive effect can be achieved over a wide range such that the machine speed range can be increased. A detailed analysis is made in order to evaluate the performance, power density and efficiency. In addition, guidelines for optimal design of the two machines are pointed out.

I. INTRODUCTION

The field controlled (FC) permanent magnet (PM) machine combines both fixed and variable excitation to provide an extensive airgap flux control. The field winding (located in the stator fed by a DC current) and PMs (located on the surface of the rotor) flux components interact in the airgap so that subtractive and additive effect of airgap flux can be achieved. The consequent pole permanent magnet (CPPM) [1-2] and field controlled PM (FCPM) machines [3-4] are two examples for radial and axial flux versions of this type of machine. Their particular magnetic configuration requires derivation of a new set of sizing equations for design and comparison purposes. The two-rotor section of these structures, in addition to the extra stator DC winding, establishes new conditions for the outer diameter and total length of the machine.

Sizing analysis has proven to be a powerful tool for the electrical machine design. In [5], a detailed analysis and comparison between different types of PM machine was carried out. Traditional axial and transverse flux configurations have been analyzed in the literature as well [6-8]. In this paper, a unified sizing equation analysis is presented for both radial and axial flux field controlled PM machines. Both radial and axial topologies are considered.

Operating conditions are taken into account to obtain a new set of sizing equation for design purposes. A number of design plots and optimization results are provided for the optimized designs. A comparative analysis is carried out between these two configurations.

II. DESCRIPTION OF THE FIELD CONTROLLED PM MACHINES

A. Radial Configuration

Fig. 1 shows the structure of the CPPM machine. The machine consists of a two-rotor section with partial surface-mounted permanent magnets structure, which are radially and consequently magnetized and one stator with a partially solid yoke to diminish the inter-lamination airgaps and a conventional three-phase winding. Additionally, a circumferential field winding located in the middle of the stator provides a variable excitation. The radial magnetization of the permanent magnets creates a nearly constant flux, which circulates from one pole to the next across the stator and rotor yoke, teeth, and PM pieces. This portion of the flux is determined mainly by the PM's geometry and the reluctance of its path. In this case, the airgap and magnet reluctances are important design values.

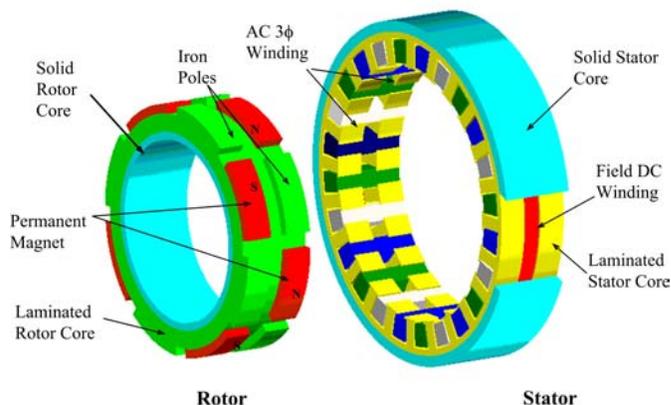


Fig 1. CPPM machine: a radial configuration of FT machine

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In addition, injecting DC current into the field winding generates a flux which travels from the one iron pole to another through the stator and rotor yoke with a path entirely

composed of iron material except for the main airgaps. Due to the comparative low reluctance of this path, the DC current flowing through the DC field winding can easily adjust this flux component. The combination of these two flux components produces a variable level of excitation in the machine according to the magnitude and direction of the DC current.

B. Axial Configuration

The axial configuration of the field controlled disc shaped PM machine comprise of two outer rotor discs and a stator structure sandwiched between the two rotors as shown in Fig. 2. The rotor structure (similar to radial configuration) is formed by two rotor discs, arc shaped iron pieces, arc shaped surface mounted permanent magnets and a shaft. The two disc shape rotors carry the axially magnetized Nd-Fe-B magnets which are mounted axially on the inner surfaces of the two rotor discs. It should be pointed out that a rotor pole is formed by half PM and half iron pieces as seen in Fig. 3 and there must exist some space between the magnets and the iron pieces in order to lessen the leakage.

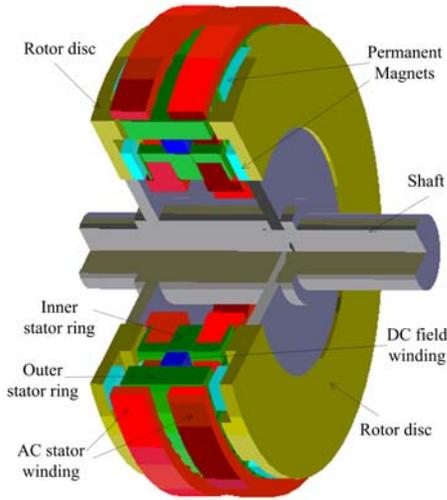


Fig 2. Field controlled axial flux PM machine

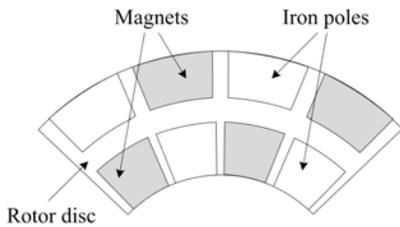


Fig 3. Rotor poles of FCPM machine

The polarity of the magnets on the outer side of the rotor is identical (say north) and the consequent south poles are formed on the inner sides. In other words, the location of the magnets is positioned such that the north poles are placed on the outer sides and south poles are placed on the inner sides

of the rotor disc. Two sets of 3-phase AC windings on both sides of the stator are placed into slots. To complete the stator structure, a circumferential field winding is placed in the center of the stator, which is excited by a DC current in a similar manner as the CPPM machine. The solid stator and rotor yoke provide a low reluctance path for the axial flux, which is an important component in the operation of the machine. The current of the field winding is externally controlled to provide variable excitation.

One can consider that one stator one rotor field control axial flux machine is the dual of the radial flux CPPM machine. The main differences between the CPPM machine and FCPM machine are that the FCPM machine has double rotor and single rotor while CPPM machine has single rotor single stator. Also the main PM flux is radial in the CPPM machine and axial in the FCPM machine.

III. SIZING EQUATIONS FOR THE FC MACHINES

The general purpose sizing equation for radial gap machines takes the form [5]

$$P_R = \frac{1}{1 + K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} \lambda_o D_o^2 L_e \quad (1)$$

while the axial machine configuration takes the form [4]

$$P_R = \frac{1}{1 + K_\phi} \frac{m}{m_1} \frac{\pi}{2} K_e K_i K_p \eta B_g A \frac{f}{p} (1 - \lambda_o^2) \frac{1 - \lambda_o}{2} D_o^2 L_e \quad (2)$$

where K_ϕ , K_i , K_e , K_p are defined in [5-6], λ_o is the diameter ratio of axial flux machine which is defined as the ratio of the inner diameter to outer diameter or;

$$\lambda_o = \frac{D_i}{D_o} \quad (3)$$

The total electrical loading A corresponds to the summation of the stator and rotor current loading

$$A = A_s + A_r \quad (4)$$

where the stator electrical loading A_s is defined as the ratio between total current circulating in the stator and airgap perimeter. It should be noted that here, the rotor electrical loading is zero because of the PM rotor structure. Due to the AC and DC windings present in the stator, the electrical loading in ampere turns (AT) becomes

$$A_s = A_{s-AC} + A_{s-DC} \quad (5)$$

where A_{s-AC} is AC winding electrical loading and A_{s-DC} is DC winding electrical loading.

Defining the ratio of the DC and AC stator electrical loading as

$$K_{As} = \frac{A_{s-DC}}{A_{s-AC}} \quad (6)$$

Then, equation (5) can be written as

$$A_s = A_{s-AC} + K_{As} A_{s-AC} = A_{s-AC} (1 + K_{As}) \quad (7)$$

This result represents the proportion of the Ampere-Turns, with respect to the AC winding AT, necessary to reach a specific airgap flux variation.

Due to the rotor characteristic (two airgap flux components), the airgap flux density B_g can be separated in accordance with the type of excitation. Thus, the airgap flux density can be written as

$$B_g = \frac{1}{2} B_{g-pm} + \frac{1}{2} B_{g-iron} \quad (8)$$

B_{g-pm} and B_{g-iron} are the average airgap flux density in front of the PM and iron poles section respectively. Using this definition, the induced voltage peak value can be separated into two components: One due to the PM excitation and the other one due to the field winding excitation. Also the airgap flux density ratio is defined as:

$$K_{pw} = \frac{B_{g-iron}}{B_{g-pm}} \quad (9)$$

In order to determine the proportion of the power developed for each side of the airgap, different design constraints have to be taken into account. The utilization level of the iron (mainly in the stator teeth and core), permanent magnet material and other geometric, magnetic, and technical considerations define the correct ratio between the power arising from the PM and field winding excitations. For excitations based on ferrite (lower remanence magnet material), the major component of the airgap flux arises from the field excitation. This fact suggests that $K_{pw} > 1$. For a rare earth type of PM (such as Nd-Fe-B), this factor is close to unity. Then equation can be written as

$$B_g = \frac{1}{2} B_{g-pm} (1 + K_{pw}) \quad (10)$$

IV. RADIAL FLUX FC MACHINE

For radial FC machines the stator core depth is determined [1] by the expression

$$d_{cs} = \frac{B_g}{K_{lg} B_c} \frac{D_i}{D_o} l_{pm} = \frac{B_g}{K_{lg} B_c} D_i K_a \quad (11)$$

where l_{pm} is the axial PM length and D_i is the stator inner diameter (defined in Fig. 4). The ratio $K_a = l_{pm}/D_o$ plays an important role in the design and optimization for the radial

flux configuration. In general this ratio is referred to as the *external aspect ratio* and considers axial length of the PM portion of the rotor and the outer stator diameter, which are closely related with the volume parameter of the machine.

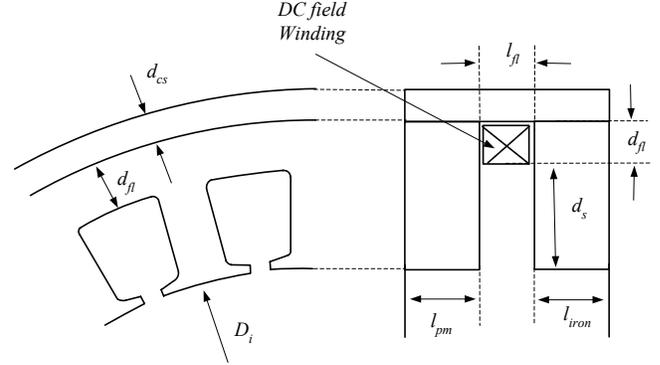


Fig 4. Stator yoke dimensions for radial flux FC machine

One of the effects resulting from allocating the DC field winding slot into the stator core is to reduce the optimum diameter ratio D_i/D_o . The required space for this slot is a function of the necessary amount of field Ampere-Turns to control the airgap flux. Because the airgap flux depends on airgap area (for a given airgap flux density), the DC slot geometry is ultimately a function the external aspect ratio, K_a . The extra space required to locate this field winding reduces the inner diameter if the outer diameter is kept constant (or increases the outer diameter to keep inner diameter constant). As a result, the machine performance is degraded with respect to the design without airgap flux control. Fig. 5 depicts the impact of the K_a over the optimum diameter ratio for different values of airgap flux density. As expected, higher values of K_a involves smaller D_i/D_o ratio for FC and non-FC machines. However, when the DC slot is included (controlled case) for the same B_g , this ratio become larger due to the space required to place the DC field winding

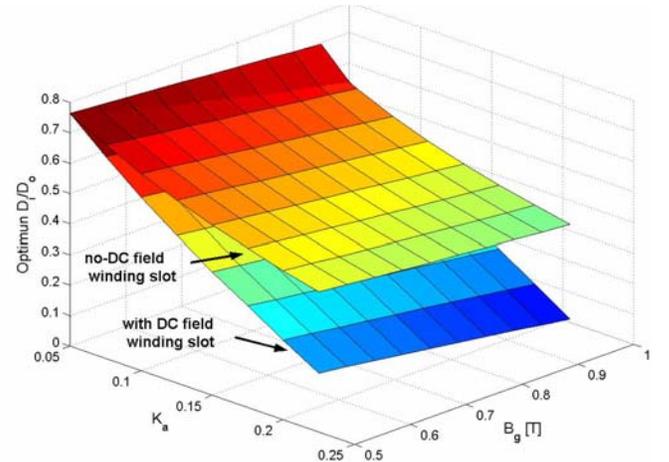


Fig 5. D_i/D_o ratio versus external ratio, K_a , and airgap flux density B_g . 8-pole, $f=100$ Hz, $l_{pm}=0.015$ m, $K_{s-rms}=400$ A/cm, $J_{s-rms}=5$ A/mm²

Power density and efficiency variations with respect to external aspect ratio for radial flux FC machine and airgap flux density are depicted in Figs. 6 and 7. As expected, better performance is achieved at lower values of K_a or diameter ratio. Lower values of inner diameters reduce the amount of torque produced by the machine for a given airgap flux and current density. Higher values of outer diameters increase the total machine volume. In addition, higher diameter values are not realistic for radial flux PM machine because of the end winding problem in the inner machine diameter. In both cases, the resultant power density or torque density including torque per weight is lower as the aspect ratio increases. Reducing output torque or increasing machine volume diminishes the machine efficiency. Lower output power due to the torque reduction and larger losses (iron and copper) due to the larger iron section and end-winding reduce the machine performance.

If the airgap flux increases, more torque can be obtained from the machine for a given value of inner diameter and current density. However, higher iron losses reduce the output power. Power density increases as the airgap flux increases but the machine efficiency decreases as expected.

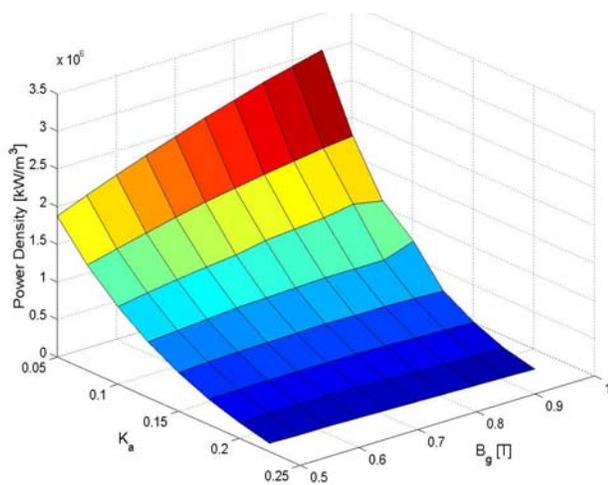


Fig 6. Power density versus external ratio, K_a , and airgap flux density B_g . 8-pole, $f=100$ Hz, $l_{pm}=0.015$ m, $K_{s-rms}=400$ A/cm, $J_{s-rms}=5$ A/mm²

In general, for a radial FC machine, the extra winding in the stator improves airgap flux control with minimum demagnetizing risk and non moving pieces required. However it somewhat reduces the machine power density, torque density and the efficiency.

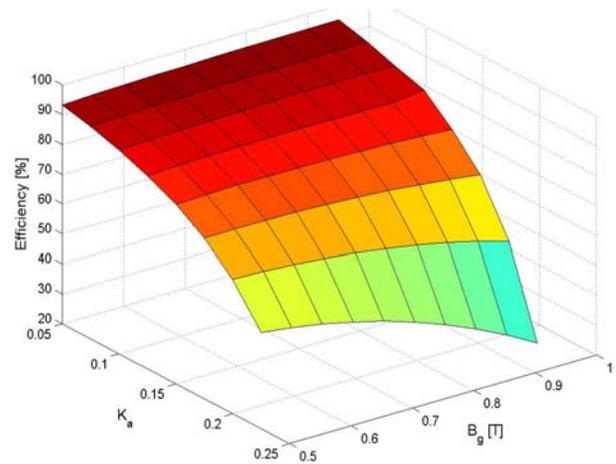


Fig 7. Efficiency versus external ratio, K_a , and airgap flux density B_g . 8-pole, $f=100$ Hz, $l_{pm}=0.015$ m, $K_{s-rms}=400$ A/cm, $J_{s-rms}=5$ A/mm²

V. AXIAL FLUX FC DOUBLE AIRGAP DISC MACHINE

One important design aspects of the axial flux PM machines is the size of the DC field winding. It is imperative that the total effective airgap of the machine should be smaller than the slot width of the DC field winding. As can be seen in Fig. 8, the total flux path that the DC flux has to travel must be greater than the total effective path that the PM flux has to travel. This condition has to be met not only to prevent the flux short circuit created by the DC field winding but also to effectively use (or to maximize the usage of) the DC flux. If the radial width of the field winding slot (H_{dc}) is small, some of the DC field flux becomes short circuit between the stator rings and some travels through the airgaps as can be seen in Fig. 8 (a). In order to avoid this situation and let the DC flux travel through the machine airgaps, H_{dc} should be large enough and the field ampere turns would be used effectively. Fig. 8 (b) shows the required PM and DC field flux paths.

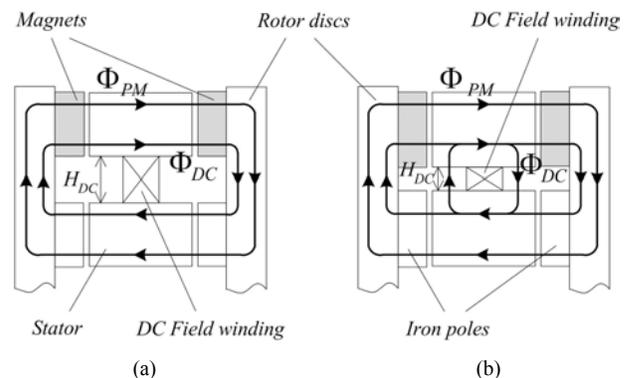


Fig 8. PM and DC field flux paths of the field controlled axial flux PM machine with small H_{DC} and large H_{DC}

A detailed investigation of the 2HP, 8 pole machine has been carried out for the field controlled axial flux PM

machine. Fig. 9 shows a power density plot of the FCPM machine as a function of airgap flux density and diameter ratio which is one of the crucial design parameters. The maximum power density (or torque density) point (MPDP) of the machine can easily be found and the machine can be designed for this point.

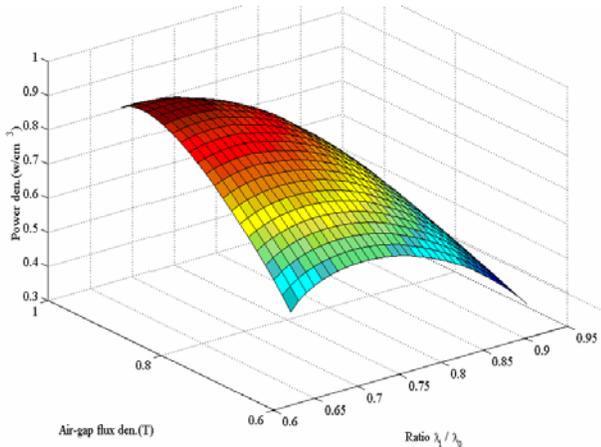


Fig 9. Power density plot as a function of airgap flux density and diameter ratio for 2 HP 8 pole machine without field winding
 $f=120$ Hz, $K_{s-rms}=300$ A/cm, $J_{s-rms}=5.5$ A/mm²

The same type of optimization procedure can be followed for the efficiency. Fig. 10 shows the efficiency plot as a function of airgap flux density and diameter ratio. It should be noted that DC field winding losses are not considered in this plot. This plot shows that the machine can also be designed for maximum efficiency point (MEP). However, as investigated in the first part the power density at MEP is lower than that of MPDP. It should be noted that the machine efficiency decreases for the bigger diameter ratios simply because of the fact that the end windings get much larger and the iron losses increase for increasing values of λ .

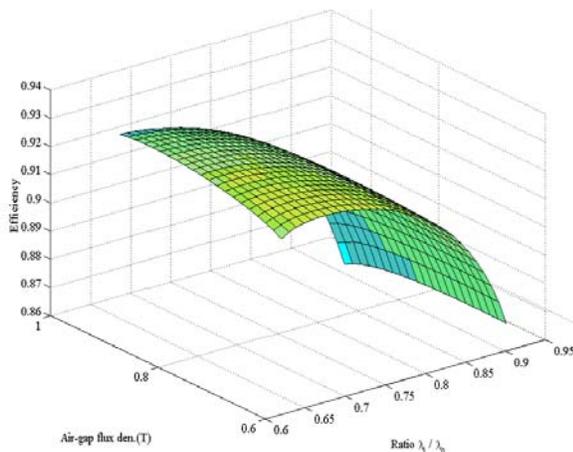


Fig 10. Efficiency plot as a function of airgap flux density and diameter ratio for 2 HP 8 pole machine without field winding
 $f=120$ Hz, $K_{s-rms}=300$ A/cm, $J_{s-rms}=5.5$ A/mm²

The 2D power density plots for increasing pole numbers are also obtained from the sizing approach described in Section III and illustrated in Fig. 11. These 2D curves are obtained for the maximum available power density curve. It shows that it is possible to increase the power density of the axial flux machine for the same power and speed. However, lower values of diameter ratio should be chosen in order to maximize the power density and keep the machine efficiency higher.

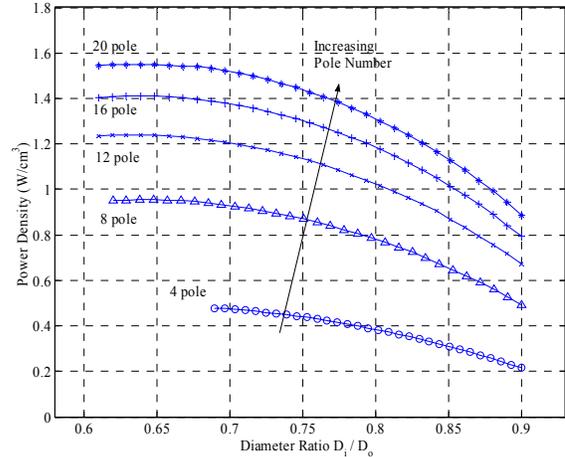


Fig 11. Power density plot as a function of diameter ratio for different pole numbers for the Field Controlled Axial Flux PM Machine

VI. CONCLUSIONS

In this paper, a unified sizing equation analysis method is proposed for the radial and axial flux field controlled PM machines. Both radial and axial configurations are analyzed and the operating principles are considered to develop a set of sizing equation for comparison and design purposes. Design plots using the design equations and optimization results are also illustrated for both radial and axial flux field controlled PM machines.

The extra DC field winding required for the airgap flux control in FC machines allows one to obtain a wide speed control range. One important feature of these machines is that they have simple field control capability with the help of DC field winding. However field winding also imposes several conditions for the design. Optimum diameter ratio is affected by the inclusion of the field winding, lower levels of power density and efficiency are encountered due to the space necessary to allocate this coil. In addition, in both radial and axial flux configurations, the air gap surface associated with this winding does not contribute to the energy conversion process. The stator yoke depth requirement for the radial configuration differs depending of the operation condition. Thus, some knowledge of the precise flux distribution is necessary.

These observations suggest that for radial FC machine is preferable to have a lower aspect ratio or to design the

machine with lower axial length. Conversely, in axial FC machine, larger axial length reduces the requirement in outer diameter.

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