

# Dual rotor single- stator axial air gap PMSM motor/generator drive for high torque vehicles applications

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**Abstract.** The actual e - continuously variable transmission (e-CVT) solution for the parallel Hybrid Electric Vehicle (HEV) requires two electric machines, two inverters, and a planetary gear. A distinct electric generator and a propulsion electric motor, both with full power converters, are typical for a series HEV. In an effort to simplify the planetary-gear e-CVT for the parallel HEV or the series HEV we hereby propose to replace the basically two electric machines and their two power converters by a single, axial-air-gap, electric machine central stator, fed from a single PWM converter with dual frequency voltage output and two independent PM rotors, destined for hybrid electric vehicles (HEV) and military vehicles applications. The proposed topologies and the magneto-motive force analysis are the core of the paper.

## 1. Introduction

The axial flux permanent magnet (AFPM) machine, also called the disc-type machine, is an attractive alternative due to its pancake shape, compact constructions and high power density. AFPM motors are particularly suitable for electrical vehicles, pumps, fans, valve control, centrifuges, machine tools, robots and industrial [9], [2].

Axial flux machines appeared in the technical literature in the early ‘70s and trading of axial flux induction motors started few years later [13], [4], [5], [11]. Nowadays, direct drive applications that require actuators or generators capable of operating at low speeds with large torques have revived the attention towards Axial Flux Machines, especially for the PM type, as they are capable of larger torque density and efficiency [13], [15], [8], [3], [6], [16].

However, AFPM Synchronous Machines become advantageous whenever a number of design prescriptions are fulfilled. Most notably, it is widely accepted that the number of pole pairs must be conveniently high [13], [12].

Fractional slot windings can be often realized in concentrated layouts: this happens when windings overhangs are not overlapped and the coils are wound individually around the stator teeth. Fractional Slot Concentrated Windings offer remarkable advantages both on the end user and to the manufacturer. In fact, they allow the physical separation of the phases and of the magnetic circuits of the phases, thus reducing the risk of phase-to-phase faults and minimizing the mutual inductance among the phases [13], [7].



The back iron cores of AFPM synchronous machines are usually made of laminated steel. However, Soft Magnetic Composites (SMC) is intensively studied since they are easy to machine and fit well higher frequencies [13].

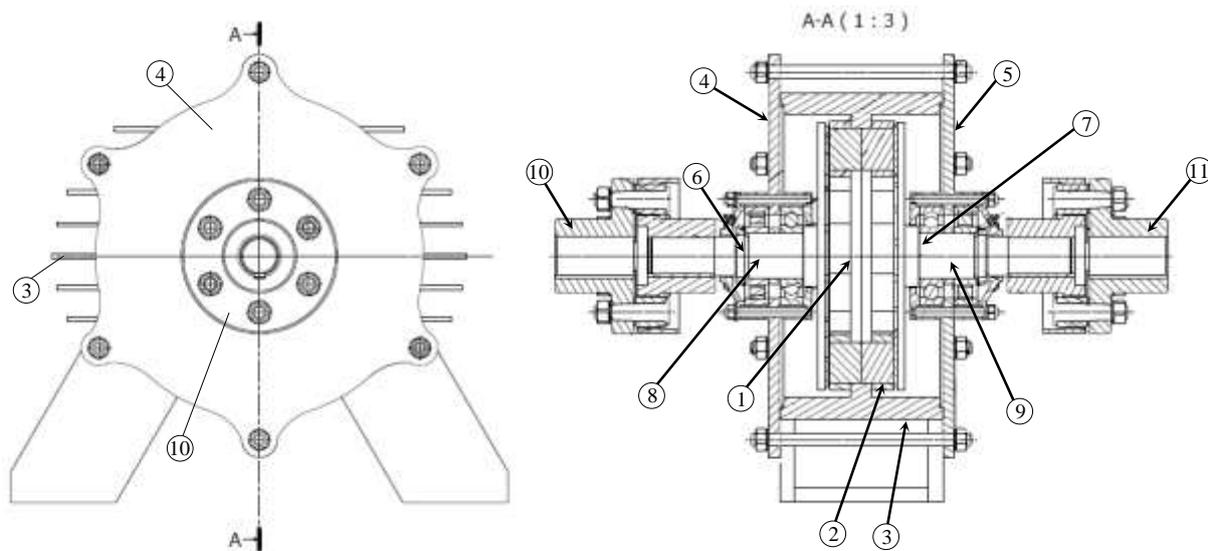
The desired high-performance can be achieved by using PM machines and new control methods such as direct torque control (DTC) or other high performance vector control methods [14-15].

The present paper proposes a new dual PM rotor, SM drive with basically a single stator (with a Gramme-ring or dual winding, one on each side of stator) and dual rotor with different pole counts and high winding factors, to reduce volume, weight and cost in either planetary-gear parallel HEV or in series HEV.

## 2. Constructive elements

In figure 1 a 2D drawing of the machine in front view and a longitudinal section are shown.

The single stator dual PM rotors axial synchronous machine having in centre the stator assembly (1) with the two three-phase windings (2) placed in open slots, fixed rigid in the casing (3) provided with two side covers (4), (5) in which the two ball bearings supports (6), (7), one radial and one axial, are introduced. The ball bearings allow the two shafts (8), (9) to rotate independently, each shaft having in the side towards the stator a disk of solid steel on which the permanent magnet poles are placed in circular and symmetric manner. The other end of the shaft is inserted into a half-coupling which is connected to the thermal engine (10) respectively to the gears towards the drive wheels (11).



**Figure 1.** Front view and longitudinal section through the dual PM rotors machine.

For the stator magnetic core soft magnetic composite (SMC) is suggested, but a rolled-lamination magnetic core is also feasible. The same rationale is valid for the rotors magnetic core.

A surface-mounted PM topology has been considered for the rotors, 14 poles for rotor 1 and 10 poles for rotor 2 (figure 2).

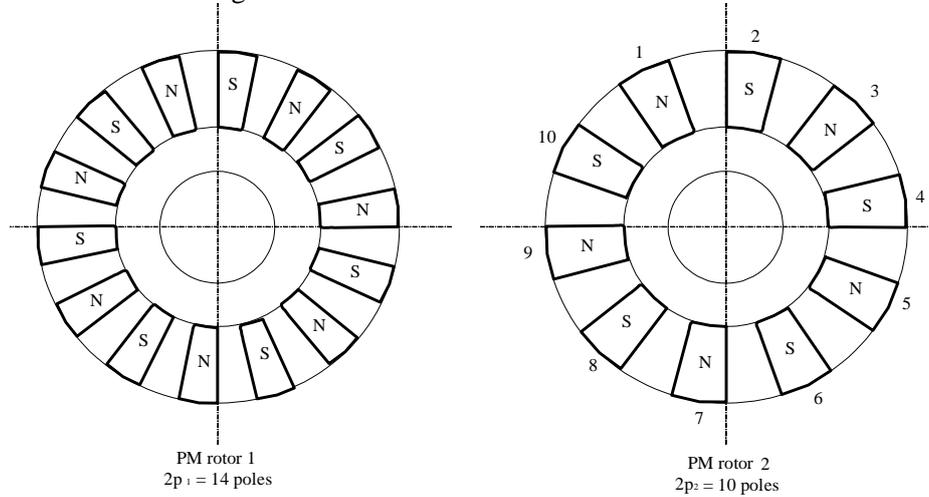
The material of the permanent magnets is the Neodymium Iron Boron (Nd-Fe-B) type MPN 40SH, with flux density remanence  $B_r = 1,13T$  and coercive field intensity  $H_c = 860 \cdot 10^3 A / m$ .

For this axial flux machine, the length of the air-gap  $g$  and the permanent magnet thickness  $h_{PM}$  can be related to the other machine diameter  $D_{out}$  by the expressions:

$$g = 6 \cdot 10^3 \cdot D_{out} \quad (1)$$

$$h_{PM} = \frac{4}{3} g \quad (2)$$

The machine designed in the paper has an external diameter  $D_{out}$  of 260 mm and an air-gap equal to 2 mm. The thickness of the magnet is 5 mm.



**Figure 2.** Rotor 1 with 14 PM poles (a) and rotor 2 with 10 PM poles (b).

### 3. Concentrated winding axial PM synchronous machine

#### 3.1. Analytical analysis

The distribution of the normal component of the magnetic flux density in the x-direction (circumferential) excited by PMs without armature reaction at the radius corresponding to the average pole pitch  $\tau$  can be described by the following equation [9]:

$$B_g(x) = \frac{1}{k_c} \cdot B_{ZPM}(x) + B_{sl}(x) \quad (3)$$

where the PM excitation flux density for smooth stator core is:

$$B_{ZPM}(x) = \sum_{v=1}^{\infty} \frac{1}{\sigma_{eM}} \frac{1}{k_c} B_g \cdot b_v \cdot \cos \left[ v \left( \frac{\pi}{\tau} x - \frac{\pi}{2} \right) \right] \quad (4)$$

$v = 1, 3, 5$ , and the magnetic flux density component due to stator slots is:

$$B_{sl}(x) = \lambda_{sl}(x) \cdot \frac{g'}{\mu_0} B_{ZPM}(x) \quad (5)$$

The peak values of the higher harmonics of the magnetic flux density distribution of equation (4) are  $B_{mgv} = (B_g / \sigma_{eM}) \cdot b_v$  [9].

In the equation (3), (4) and (5)  $k_c$  is Carter's coefficient according to [9]:

$$k_c = \frac{t_1}{t_1 - \gamma \cdot g} \quad (6)$$

where  $t_1$  is the average of slot pitch and  $\gamma$  an geometrical coefficient,  $b_v$  is according to [1]:

$$b_v = \frac{4}{\tau} \left[ \frac{c_p}{c_p^2 + \beta_v^2} \sinh \alpha - 6 \left( \frac{1}{\beta_v} \right)^4 \cdot \frac{1}{b_t^3} \cosh \alpha + 3 \left( \frac{1}{\beta_v} \right)^4 \cdot \frac{2}{\tau - b_p} \cosh \alpha \right] \cdot \sin \left( v \cdot \frac{\pi}{2} \right) \quad (7)$$

$$\cdot \sin \left( v \cdot \frac{\pi b_t}{2\tau} \right) + \frac{4}{\tau} \left[ \frac{\beta_v}{c_p^2 + \beta_v^2} + 6 \left( \frac{1}{\beta_v} \right)^3 \cdot \frac{1}{b_t^2} - \frac{1}{\beta_v} \right] \cdot \cosh \alpha \cdot \sin \left( v \cdot \frac{\pi}{2} \right) \cdot \cos \left( \beta_v \cdot \frac{b_t}{\tau} \right)$$

$$\beta_v = v \cdot \frac{\pi}{2} \quad (8)$$

$$b_t = \frac{\tau - b_p}{2}, \quad c_p = 2 \cdot \frac{\alpha}{b_p} . \quad (9)$$

The parameter  $\alpha$  depends on the shape of the distribution of the normal component of the magnetic flux density (usually  $b_v$  is for  $\alpha=0$ ). The parameter  $\tau$  is the average pole pitch

$$\tau = \frac{\pi D}{2p} , \quad (10)$$

where  $D$  is the average diameter

$$D = \frac{D_{out} + D_{in}}{2} , \quad (11)$$

with  $D_{in}$  the inner diameter of PMs.

With  $k_{sat} \geq 1$  the saturation factor in the  $d$  axis and  $k_{satq} \geq 1$  in the  $q$  axis and  $\mu_{rec}$  the relative recoil permeability of the PM [9]

$$g' = g \cdot k_c \cdot k_{sat} + \frac{h_{PM}}{\mu_{rec}} , \quad (12)$$

$$g'_q = g \cdot k_c \cdot k_{satq} + h_{PM} , \quad (13)$$

$$B_g \approx \frac{B_r \cdot h_{PM}}{h_{PM} + \mu_{rec} \cdot g} . \quad (14)$$

$B_g$  is the flat-tapped value of the magnetic flux density,  $\phi_M$  is the full equivalent flux of the PM and  $\phi_g$  is the air gap magnetic flux:

$$\sigma_{eM} = \frac{\phi_M}{\phi_g} , \quad (15)$$

and  $\lambda_{sl}$  is the relative slot leakage permeance given by:

$$\lambda_{sl}(x) = - \sum_{v=1}^{\infty} a_v \cdot \cos \left( v \cdot \frac{2\pi}{t_1} \cdot x \right) , \quad (16)$$

where

$$t_1 = \frac{2p \cdot \tau}{N_{st}} , \quad (17)$$

and  $a_v$  the amplitude of slot harmonics.

### 3.2. Armature windings design

An AFPM machine can compete with the traditional radial-flux machines in terms of torque and power density if the number of pole-pairs is sufficiently high and the ratio axial length/outer diameter is low [9], [2], [16].

The term non-overlap (concentrated coil) windings defined here refer to the windings of which the coils do not overlap. As with overlap windings non-overlap windings can be of single or double layer, concentrated or distributed, integral or fractional and air-cored or iron-cored. In double layer, non-overlap slotted iron-cored windings two coils are sharing a slot (two coil layers per slot), which means that all teeth are wound. Consequently these windings are sometimes called tooth windings [9].

The various combinations of slots and poles which allow the realization of balanced winding can be determined by the relation:

$$\frac{N_{st}}{[\text{GCD}(N_{st}, 2p)]} = 3k , \quad (18)$$

where  $N_{st}$  is the number of slots,  $p$  the number of pair of poles and  $k$  an integer number. (GCD: Greatest Common Divisor). As is well known, the number of slots per pole and per phase of an electrical machine is equal to:

$$q = \frac{N_{st}}{2pm} \quad , \quad (19)$$

where m is number of phases.

Fixing  $N_{st}$ , if the machine has a high number of pole pairs, q decreases.

Winding arrangements with a number of slots per pole and per phase lower than unity become sometimes mandatory for the construction of fractional power machines with large number of pole pairs. In some cases, adopting a layout of the kind makes it possible to realize concentrated non overlapping windings that at the same time yield high values of the fundamental winding factor.

In concentrated non-overlap windings, there is only one coil in a coil group or coil phase belt ( $z=1$ ). The distribution factor for the fundamental space harmonic is calculated by [9]:

$$k_{d1} = \frac{\sin\left(\frac{\pi}{2m}\right)}{z \cdot \sin\left(\frac{\pi}{2mz}\right)} \quad , \quad (20)$$

and the pitch factor for the fundamental space harmonic is [9]:

$$k_{p1} = \sin\left(\frac{\pi}{2} \cdot \frac{y}{\tau}\right) \quad , \quad (21)$$

where y is the pitch of one coil and  $\tau$  the pole pitch. The fundamental winding factor:

$$k_{w1} = k_{d1} \cdot k_{p1} \quad . \quad (22)$$

For our case  $k_{w1} = 0.966$  for both windings. ( $N_{st}=12$ ,  $p_1 = 7$ ,  $p_2 = 5$ ).

The design of windings was performed by plotting the space vectors of the induced EMF in the slots and the windings arrangement. It is possible to envisage few simple rules to calculate the following parameters:

- the greatest common divider between the number of slots and the number of pole pairs

$$t' = \text{GCD}(N_{st}, p) = \text{GCD}(12, 5) = 1 \quad , \quad (23)$$

$$t'' = \text{GCD}(12, 7) = 1 \quad , \quad (24)$$

- the number of vectors of star

$$r' = \frac{N_{st}}{t} = \frac{12}{1} = 12 = r'' \quad , \quad (25)$$

- the angle between two adjacent vectors

$$\alpha_1' = \frac{2\pi \cdot t'}{N_{st}} = \frac{\pi}{6} = \alpha_1'' \quad , \quad (26)$$

- the phase lag between two vectors of two adjacent phases:

$$\alpha' = \frac{2\pi \cdot p}{N_{st}} = \frac{2\pi \cdot 5}{12} = \frac{5\pi}{6} \quad , \quad (27)$$

$$\alpha'' = \frac{2\pi \cdot 7}{12} = \frac{7\pi}{6} \quad . \quad (28)$$

### 3.3. MMF analysis

The MMFs  $F_{ad}$  and  $F_{aq}$  in the d-axis and q-axis are [9]:

$$F_{ad} = \frac{m_1 \sqrt{2}}{\pi} \cdot \frac{N_1 \cdot k_{w1}}{p} \cdot I_{ad} \quad , \quad (29)$$

$$F_{aq} = \frac{m_1 \sqrt{2}}{\pi} \cdot \frac{N_1 \cdot k_{w1}}{p} \cdot I_{aq} \quad , \quad (30)$$

where  $I_{ad}$  and  $I_{aq}$  are the d and q axis stator (armature) currents respectively.

Let us consider the case where the concentrated winding PM machine is fed by sinusoidal currents, with a maximum current  $I$  in phase “A” ( $i_A=I$  and  $i_B=i_C=-I/2$ ).

In order to investigate the spatial distribution of the armature MMF, the surface mounted PMs in the rotor are supposed to be discarded. Giving the fact that each phase is made up of  $N$  coils, the MMF  $F_{A1}$  produced by one coil ( $A^+, A^-$ ) is expressed as [10]:

$$F_{A1}(\theta) = \begin{cases} (2-\beta) \cdot \frac{N \cdot I}{8}, & -\frac{\delta}{2} < \theta < \frac{\delta}{2} \\ -\beta \cdot \frac{N \cdot I}{8}, & \text{elsewhere} \end{cases}, \quad (31)$$

where  $\beta$  is the coil pitch ratio, such that

$$\beta = \frac{\delta}{\tau_{st}}, \quad (32)$$

where  $\tau_{st}$  is the armature pole pitch. Taking into account the hypothesis which considers that the magnetic circuit is not saturated, one can apply the superposition theorem in order to obtain the magneto-motive force (MMF)  $F_A(\theta)$  of phase “A” as follows:

$$F_A(\theta) = F_{A1}(\theta) + F_{A2}(\theta) + F_{A3}(\theta) + F_{A4}(\theta), \quad (33)$$

With

$$\begin{cases} F_{A2}(\theta) = -F_{A1}\left(\theta - \frac{\pi}{6}\right) \\ F_{A3}(\theta) = -F_{A1}(\theta - \pi) \\ F_{A4}(\theta) = F_{A1}\left(\theta - \frac{7\pi}{6}\right) \end{cases}, \quad (34)$$

Now let us consider the spatial distribution of the MMFs produced by phases “B” and “C”, which are deduced from the one produced by phase “A” as follows:

$$\begin{cases} F_B(\theta) = -\frac{1}{2} F_A\left(\theta + \frac{2\pi}{3}\right) \\ F_C(\theta) = -\frac{1}{2} F_A\left(\theta - \frac{2\pi}{3}\right) \end{cases}. \quad (35)$$

#### 4. Conclusions

Using an analytical design method or the 2D finite element analysis (FEA) only for the average radius on the machine does not generally yield sufficiently accurate computation results. With the 3D FEA, it is possible to take into consideration the actual 3D structure of the machine, but performing the computations is too often time-consuming, especially if the objective is to achieve a preliminary design of the machine. The basic idea of the hereby proposed design method is to firstly subdivide the axial flux machine into a sufficient amount of independent computation plans, next perform the required 2D computations on each plane, and finally compose the overall performance of the machine from the computation results obtained for each design plan.

The single stator dual-rotor permanent magnet axial synchronous machine can be controlled by a single inverter and two frequencies, the two rotors being able to operate both as motor and as generator in a wide speed range, in the same or opposite directions of motion. The transitory regime due to speed equalization in the two rotors is surpassed without catastrophic oscillations in torque and speed.

The peak value of the torque, the overload capability and very fast dynamic response make this electric drive system very good for military vehicles applications.

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