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Optimal Design and Modelling of an Innovated Structure of DC Current Motor with Concentrated Winding

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Abstract: In this paper we presented the structure and methodology of designing of an innovated DC motor with permanent magnets and axial flux. Progress in the field of sliding contacts manufacturing, the simplicity of the structure of the engine as the control simplicity of DC motors make this structure an attractive solution to the problem of electric cars drive. In this context, a dimensioning model of this engine structure is developed. This model is based on the analytical design method of electric actuators. The overall design approach is based on justified simplifying assumptions, leading to a simplification of the resolution of the sizing problem. Finally, this paper provides a comprehensive tool for sizing and modeling of this type of actuator.

Keywords: DC Motor, Permanent Magnets, Design, Analytical Method, Modelling, Optimization

1. Introduction

DC motors are the first engines used in industrial applications. These engines have many advantages including:

- Simplicity of the structure.
- Variable excitation for engines with wound inductor.
- Simple and easy control.
- By consequence, these engines have been somewhat neglected in the near past for they present drawbacks, namely:
- Significant induced magnetic reaction making it impossible to overcome current.
- Cost of maintenance of sliding contact.
- Significant copper losses in the inductor.

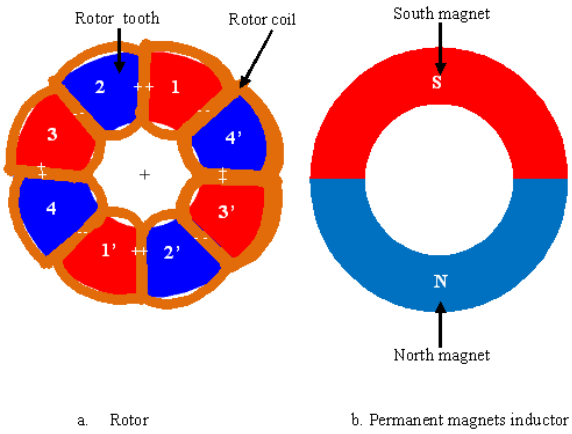
Nowadays permanent magnet motors have taken the relief to motors with wound inductor. For this reason we are led to seek solutions combining the advantages of DC motors with wound inductor and those with permanent magnets particularly in light of interesting advances in the field of sliding contacts manufacturing. In this context, a spindle motor structure with permanent magnets and simple to perform combining the advantages of structures with wound inductor and those of permanent magnets is sought. A design and modeling program based on analytical method of this structure is developed and presented in this paper [1-7].

2. Motor Structure

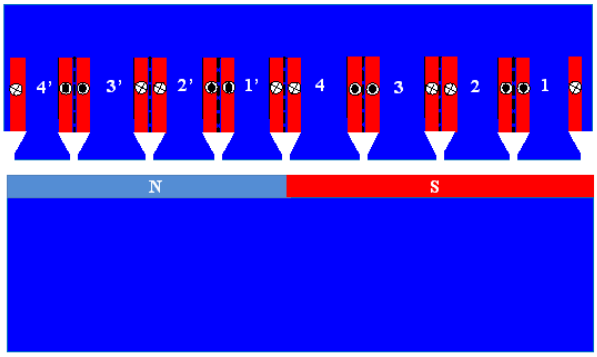
An engine innovated structure with DC permanent magnet axial flux to one pole pair is illustrated in figure 1 and another with two pairs of poles is shown in figure 2.

These two structures are simple to manufacture, compact and with concentrated winding. They have the following advantages:

- High power density.
- Low manufacturing cost.
- High efficiency (Absence of copper losses to the inductor).
- Modular design: possibility of overcoming power by adding additional modules perpendicular to the axis of the motor.
- Ease of control.
- Possibility of automation of the manufacturing process of these motor structures, especially the coils are concentrated type which facilitates the procedure for their insertions in a single block.
- The slots are straight and semi open.

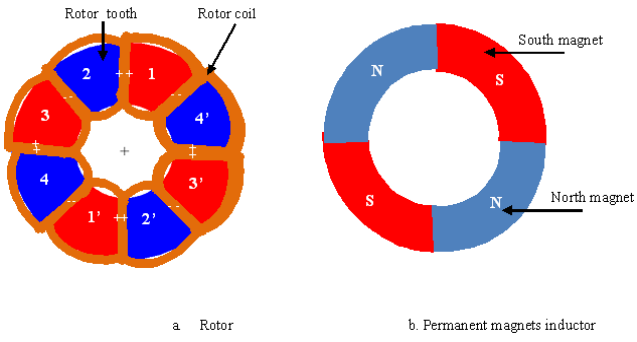


1. Engine Front View

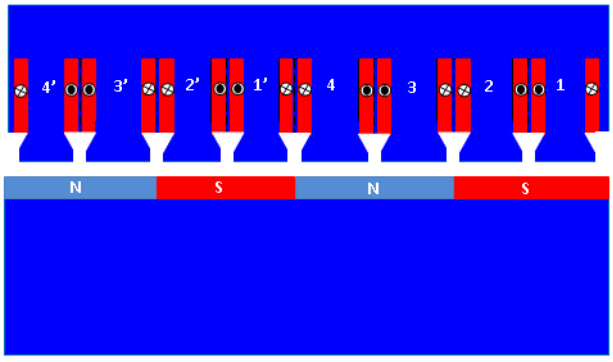


2. Engine cylindrical Cup

Figure 1. *Structure of engine in novated with one pair of pole.*



1. Engine Front View



2. Engine cylindrical Cup

Figure 2. *Structure of the motor innovated with two pole pairs.*

3. Modelling and Sizing of the Motor

Electric motors sizing problem is usually solved by the finite element method [1-5]. A series of simulations is necessary in this case to solve the design problem. This method is accurate, but it is heavy and therefore it is not compatible with optimizations approaches. However, the analytical method provides solutions quickly and without iterations and provides a comprehensive design tool for electrical machines since it is based on simplifying assumptions justified. This method leads to design programs highly parameterized of electrical devices. So our choice is focused on the analytical method to solve the design problem of the studied engine structures [1-6].

3.1. Modeling of the Back Electromotive Force

Elementary back electromotive forces in the terminals of each two diametrically opposite coils are illustrated in figure 3. All rotor coils should be connected in series with a reversal of the direction of coil so as to have a continuous resulting electromotive force (Figure 3) [5].

Flux received by a coil is expressed by the following relationship [5]:

$$\Phi_b = \int_{\theta=0}^{\theta=\left(\pi+\frac{\pi}{N_b}\right)} B_e(\theta)\times ds(\theta) \tag{1}$$

Relation (1) can be converted to the following equation [5]:

$$\Phi_b = B_e \times s_d - 2\times B_e \times \frac{\left(D_e^2 - D_i^2\right)}{4}\times\frac{\theta}{2} \tag{2}$$

Where Be is the flux density in the air-gap, θ is the mechanical angle, sd is the heads teeth section, De and Di are respectively the internal and external diameters of the motor and ds is the surface element through which the magnetic flux.

The back electromotive force can be derived from the following relationship:

$$E = -2\times P\times N_{sb}\times\frac{d\Phi_b}{dt} \tag{3}$$

Where P is pole pair number and Nsb is the number of turns per coil.

The expression of the induced back electromotive force takes the following form:

$$E = P\times N_{sb}\times\frac{\left(D_e^2 - D_i^2\right)}{2}\times B_e\times\Omega \tag{4}$$

where Ω the angular speed of the motor.

This leads to the general expression of back electromotive force:

$$E = K_e\times\Omega \tag{5}$$

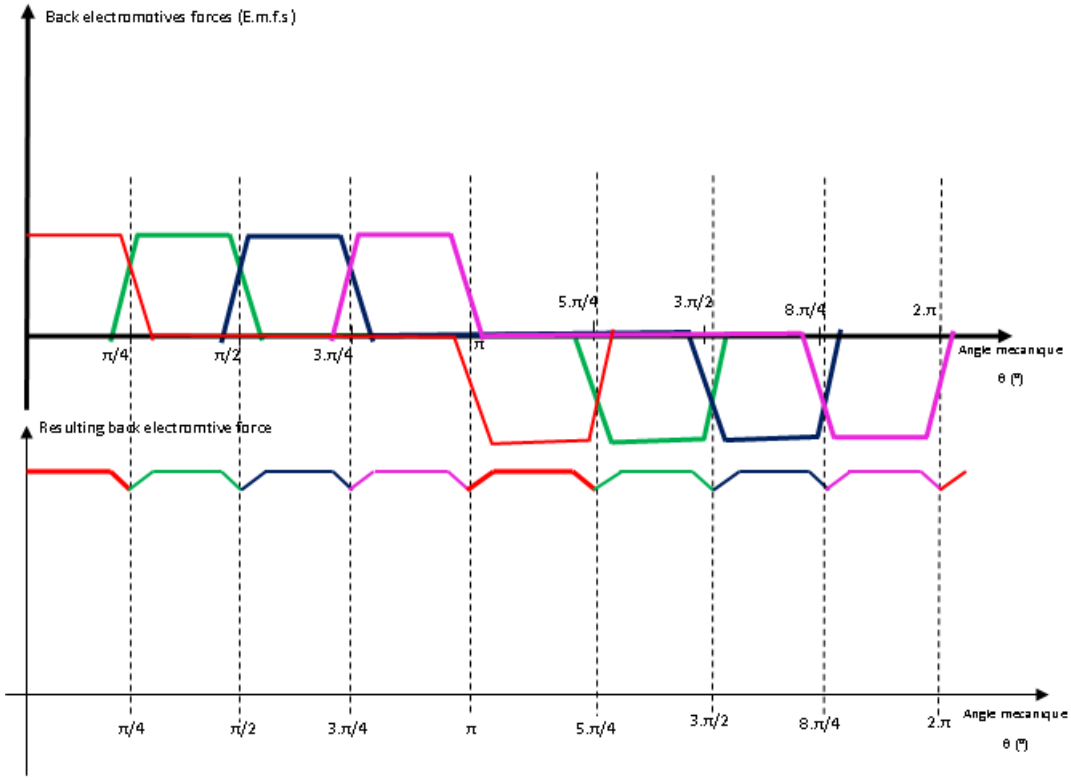


Figure 3. *Pace of the back electromotive force.*

3.2. Sizing of the Motor

The rotor slot width is given by the following relationship:

$$L_{encr} = \frac{D_e + D_i}{2} \times \sin\left(\frac{1}{2} \times \left(\frac{2\times\pi}{N_b} - A_{dentrm} - A_{dentrim}\right)\right) \quad (6)$$

where A_{dentrm} is the average angular width of the rotor tooth, $A_{dentrim}$ is the average angular width of the rotor inserted tooth and N_b number of coils.

The lower angular width of a slot is expressed by the following relationship:

$$A_{encr1} = 2\times A\sin\left(\frac{\frac{L_{encr}}{2}}{\frac{D_i}{2}}\right) \quad (7)$$

The upper angular width of a slot is expressed by the following relationship:

$$A_{encr2} = 2\times A\sin\left(\frac{\frac{L_{encr}}{2}}{\frac{D_e}{2}}\right) \quad (8)$$

The average angular width of a rotor tooth is given by the following relationship:

$$A_{dentrm} = \frac{2\times\pi}{N_b} \times \alpha \quad (9)$$

Where α is the opening ratio of a rotor tooth (α < 1).

The average angular width of an interposed rotor tooth is given by the following relationship:

$$A_{dentrim} = r_{did} \times A_{dentrm} \quad (10)$$

Where r_{did} the is the ratio between the average angular width of an inserted tooth and that of a tooth.

The average angular width of a slot is given by the following relationship:

$$A_{encrm} = \frac{1}{2} \times \left(\frac{2\times\pi}{N_b} - A_{dentrm} - A_{dentrim}\right) \quad (11)$$

The lower angle of a tooth is given by the following relationship:

$$A_{dentr1} = A_{dentrm} - A_{encrm} - A_{encr1} \quad (12)$$

The upper angle of a tooth is given by the following relationship:

$$A_{dentr2} = A_{dentrm} - A_{encrm} - A_{encr2} \quad (13)$$

The lower angle of an inserted tooth is given by the following relationship:

$$A_{dentrim1} = \frac{2\times\pi}{N_b} - A_{dentr1} - 2\times A_{aencr1} \quad (14)$$

The upper angle of an inserted tooth is given by the following relationship:

$$A_{dentrim2} = \frac{2\times\pi}{N_b} - A_{dentr2} - 2\times A_{aencr2} \quad (15)$$

The angle of dental development (A_d) is given by the following equation:

$$A_d = \frac{2\times\pi}{N_b}\times\beta \quad (16)$$

where β is the fulfillment of a rotor tooth coefficient ($\alpha < \beta < 1$).

The height of the teeth is expressed as follows:

$$H_d = \frac{N_{sb}\times I_{dim}}{K_f\times\delta\times L_{encr}} \quad (17)$$

I_{dim} is the dimensionnig current, K_f is the filling factor and δ copper admissible current density.

The dimensionnig current is expressed by the flowing relation:

$$I_{dim} = \varepsilon\times\frac{R_r\times M_v}{r_d\times}\times\left(\frac{V_b}{t_d} + g\times\sin(\lambda)\right) \quad (18)$$

Where $\varepsilon < 1$ it is usually close to 0.9, and R_r the radius of the wheel of the car, M_v is the mass of the car, r_d is the reduction ratio, t_d is the car's start time from speed equal 0 to the base speed (V_b) of the car, g is the gravity acceleration and λ is the angle with the horizontal road.

The height of the rotor yoke is calculated by applying the flux conservation theorem for a maximum flux position in the cylinder head:

$$H_{cr} = \frac{B_e}{B_{cr}}\times\frac{s_d}{\frac{D_e - D_i}{2}} \quad (19)$$

The tooth height of the heads is calculated by applying the flux conservation theorem to avoid saturation:

$$H_{de} = \frac{B_e}{B_d}\times\frac{(s_{de} - s_d)}{D_e + D_i} \quad (20)$$

Where B_d is the flux density in the tooth and s_{de} is the heads teeth section.

The height of magnet necessary for a magnetic induction in the gap B_e is derived by applying the Ampere theorem on a closed contour at a tooth [1-5]:

$$H_a = \frac{\mu_r\times B_e\times e}{B_r - B_e} \quad (21)$$

The height of the inductor head is calculated by applying the flow conservation theorem for a maximum flux position in the cylinder head [1-5]:

$$H_{cs} = \frac{B_e}{B_{cs}}\times\frac{s_d}{\frac{D_e - D_i}{2}} \quad (22)$$

4. Electric Parameters of the Motor

The inductance of the rotor winding is given by the following relationship [11]:

$$L = \mu_0\times N_b\times\left(\frac{\frac{s_d}{2}}{2\times(e + H_a)} + \frac{\left(\frac{D_e - D_i}{2}\right)\times H_d}{2\times L_{enc_r}} + \frac{H_{de}\times\frac{D_e - D_i}{2}}{\left(\frac{2\times\pi}{N_b} - A_d\right)\times\frac{D_e + D_i}{4}}\right)\times N_{sb}^2 \quad (23)$$

The magnetic induction due to the power of the rotor winding by the demagnetization current of the magnet (I_d) is given by the following relationship:

$$B_{ei} = \frac{\mu_0\times N_{sb}\times I_d}{H_a + e} \quad (24)$$

The demagnetization of the magnets is provided that:

$$B_e - B_{ei} = B_c \quad (25)$$

where B_c is the demagnetization magnetic induction of the magnets.

The demagnetization current is to not exceeded to avoid demagnetization of the magnets. It is expressed by the following relationship:

$$I_d = \left(\frac{H_a\times B_r}{H_a + \mu_r\times e} - B_c\right)\times\frac{(H_a + e)}{\mu_0\times N_{sb}} \quad (26)$$

where B_r is the residual inductionet and μ_r is the relative permeabilty of magnets.

The length of one turn is expressed by the following relationship:

$$L_{sp} = 2\times\left(\left(\frac{D_e}{2} - \frac{D_i}{2}\right) + L_{encr}\right) + 2\times\left(\left(\frac{D_e + D_i}{4}\right)\times A_{dentrm} + L_{encr}\right) \quad (27)$$

The resistivity of copper is expressed by the following relationship:

$$\rho = r_{cu} \times \left(1 - \alpha_t \times \left(T_b - 20\right)\right) \quad (28)$$

where Tb is the temperature of copper and αt is the temperature coefficient at 20 °C.

Hence the expression for the resistance of the rotor winding is deduced by the following equation:

$$R = \rho \times L_{sp} \times N_{sb} \times N_b \times \frac{I_{dim}}{\delta} \quad (29)$$

The motor electrical constant is deduced from the equations (4) and (5).

$$K_e = P \times N_{sb} \times \frac{\left(D_e^2 - D_i^2\right)}{2} \times B_e \quad (30)$$

The DC bus voltage is calculated in such a way that the vehicle can reach a maximum speed with a low torque undulation and without weakening. This voltage is calculated assuming that the engine runs at a stabilized maximum speed. At this operating point (Figure 4) the electromagnetic torque to be developed by the motor is expressed by the following equation [10-31]:

$$T_{udc} = \frac{P_f}{\Omega_{max}} + T_d + \left(T_b + T_{vb} + T_{fr}\right) + \frac{T_r + T_a + T_c}{r_d} \quad (31)$$

The different torques are expressed by the following equations:

$$T_b = s \times \frac{v}{|v|} \quad (32)$$

$$T_{vb} = \chi \times v \quad (33)$$

$$T_{fr} = k \times v \times |v| \quad (34)$$

$$T_r = R_w \times f_r \times M_v \times g \quad (35)$$

$$T_a = R_w \times \frac{\left(M_{va} \times C_x \times A_f\right)}{2} \times V^2 \quad (36)$$

$$T_c = M_v \times g \times \sin\left(\lambda\right) \quad (37)$$

Figure 4 shows the evolution of useful torque (T_u) and load torque (T_R) for operation at maximum speed (Ω_{max}):

From figure 4, we deduce the expression of the DC bus voltage:

$$U_{dc} = K_e \times \Omega_{max} + R \times I_{dc} \quad (38)$$

Where I_{dc} is the current drawn by the motor at maximum stabilized speed:

$$I_{dc} = \frac{T_{udc}}{K_e} \quad (39)$$

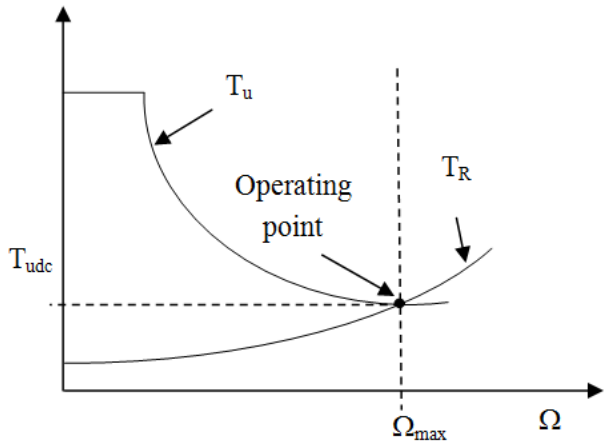


Figure 4. *Evolution of useful torque and load torque for operation at maximum speed.*

5. Motor Model

The transient voltage equation of the engine is given by the following equation:

$$u\left(t\right) = R \times i\left(t\right) + L \times \frac{di\left(t\right)}{dt} + e\left(t\right) \quad (40)$$

where i is the current drawn by the motor.

The transient back electromotive force is expressed as follows:

$$e\left(t\right) = K_e \times \Omega\left(t\right) \quad (41)$$

The electromagnetic torque is given by the following relationship:

$$T_{em} = K_e \times I \quad (42)$$

The iron losses is approximated by the following relation:

$$P_{fs} = q \times \left(\frac{f}{50}\right)^{1.5} \times \left(2 \times P \times \frac{M_d}{N_b} \times B_e^2 + 2 \times P \times \frac{M_{cs}}{N_b} \times B_{cs}^2\right) \quad (43)$$

$$f = \frac{P \times \Omega}{2 \times \pi} \quad (44)$$

where f is frequency of the elementary back electromotive forces, M_d is the teeth mass, M_{cs} is the stator yoke mass, B_{cs} the flux densty in the inductor yoke and q is the quality factor of metal sheet.

Mechanical losses are expressed by the flowing relation:

$$P_m = \left(s \times \frac{\Omega}{\Omega} + v \times \Omega + k \times \Omega \times |\Omega|\right)\Omega \quad (45)$$

where s is the dry friction coefficient, ν is the viscous friction coefficient and k is the fluid friction coefficient.

6. Motor Efficiency Optimization Problem

The motor efficiency is expressed by the following relation:

$$\eta = \frac{u \times i - R \times i^2 - P_{fs} - P_m}{u \times i} \tag{46}$$

The efficiency can be optimized by Genetic Algorithms method. The formalization of the optimization problem is summarized as follow [6-12]:

$$\begin{gathered} \text{Maximiser} \quad \eta \\ 100\,\text{mm} \le D_i \le 250\,\text{mm} \\ 300\,\text{mm} \le D_e \le 700\,\text{mm} \\ U_{dc} \le 150\,\text{V} \\ 5\,\text{A/mm}^2 \le \delta \le 7\,\text{A/mm}^2 \\ 10 \le N_{sb} \le 200 \\ 0.4\,\text{Tesla} \le B_e \le 1.6\,\text{Tesla} \\ 0.4\,\text{Tesla} \le B_{cr} \le 1.6\,\text{Tesla} \end{gathered} \tag{47}$$

7. Torque Ripple Minimization

The torque ripple is directly related to the ripple of the resultant back electromotive force. Two parameters strongly influence the torque ripple are namely:

- The α parameter close to 1. This parameter should be the maximum possible, but for values of α very close to 1 a triggering of short circuits is activated between magnetic heads teeth, for that we are going to offer to optimize this parameter by finite element method.
- The β parameter (α < β <1). This parameter affects the ripple torque, the length in the axial direction of the engine and also leads to local saturation at levels of teeth. This parameter setting is also optimized by the finite element method.

A series of simulations of the evolution of the electromagnetic torque and saturations at the teeth were allowed to set α = 0.7 and β = 0.9 as optimal values minimizing torque ripple and local saturations.

8. Conclusion

In this paper we presented and studied an innovated DC engine structure with permanent magnet and axial flux with reduced production cost and high power density. A sizing and modeling program highly parameterized is developed. This program has led to joint optimization problems of performance, torque ripple and local saturations.

As prospects, this study can be validated by the finite element method and experimentally on a realized prototype.

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