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A COMPUTER-SIMULATED ENVIRONMENT FOR MODELING AND DYNAMIC- BEHAVIOR-ANALYSIS OF SPECIAL BRUSHLESS MOTORS FOR MECHATRONIC MOBILE ROBOTICS SYSTEMS

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Abstract: A computer-simulated environment for design and analysis of outrunners brushless motors and its validation by measuring the main parameters in real motors is presented. The simulation environment is based on two complementary models for design and analysis. These models allow obtaining the main constants that govern the behavior of a brushless motor. The first is a concentrated parameters model for the design and analysis Brushless outrunners Motors. This model is used for the main physical characteristics of the motor under design or its overall performance in case of analysis. The second model is based on 2D Electromagnetic Finite Element Analysis (FEA) on a CAD, of the motor under study. This analysis includes obtaining Torque and Speed constants (Kt and Kv), Torque Ripple, Cogging Torque, Back-Electromotive Force (BEMF), Optimal phase commutation point, among others. The iterative process that achieves the desired performance characteristics is described. This process has been tested in several prototypes which ensure optimum motor design for the desired application. Last but not less, the work include one validation method, with physical measuring of real dynamic behavior and the main motor constants (Kt, Kv, BEMF) in three real motors and comparison with the values obtained in the simulation environment. The three motors used for validation have significantly different power, torque and size. So we confirm the validity of the models in a high range of use. In this way, simulation environment will be use as central stages of Deming continuous improvement cycle, Plan-Do-Check, Act, in that case for better design of special brushless motors for mechatronic mobile robot's systems and exoskeletons

Keywords: Brushless motor, design, analysis, simulation, FEA, systematic validation

1. INTRODUCTION

Electrical permanent magnet motors (PMM), especially those known as Brushless DC Motors (BLDC) and Permanent Magnet Syncrhronous Motors (PMSM), gained popularity for its excellent torque density, low maintenance, high efficiency, high slot fill factor, mechanical simplicity, etc. [1-8]. On the way to develop better motors we find the need for design tools and simulation ever better that deliver accurate results. Simulation tools are used increasingly to predict the behavior of motors that have not yet been built and are a powerful method for optimizing them [9]. Particularly, motors acting as exoskeleton articulations, they must have a very high ratio Torque/Weight and Torque/Volume, requiring the designer and design tools a step further, since it must work with coefficients very little security. In the development of an exoskeleton for various applications together the TU-WIEN and UTN-FRBA, we need a validated analysis and simulation environment to develop the articulations motor. These motors will be coupled to a special speed reducer, patented and developed by members of TU-WIEN and UTN-FRBA [10]. Our working group has been working extensively on the use of simulators as tools for systematic validation [11]

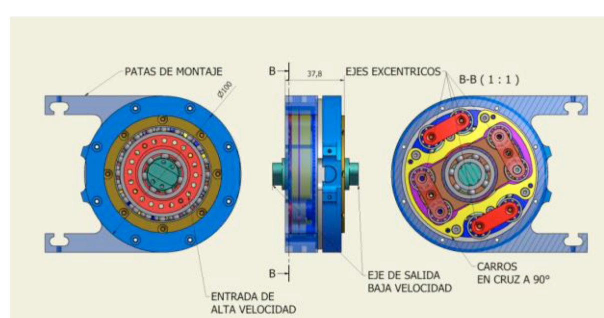

Figure 1 Special speed Reducer for Exoskeletons [10]

2. Permanent Magnet Motor Analysis

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A permanent magnet motor can be modeled as an ideal voltage source dependent of rotational speed, in series with an inductor and a resistor. The ideal voltage source, or induced voltage (BEMF) $E(\theta_e)$, is a consequence of relative movement of the coils in a magnetic field. If we show one phase of a three-phase motor, the model is as shown in Figure 2 [12]:

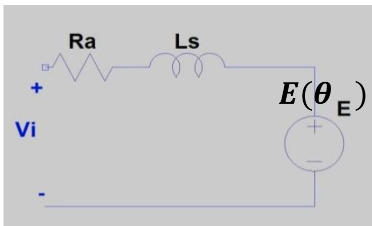

Figura 2: Motor model for analysis

This model is valid for all motors beyond the shape of $K_t(\theta_e)$ since nothing is assumed in respect that. It can be applied to motors with sinusoidal BEMF as pseudo-sinusoidal.

Extrapolating the model of Figure 2 as three identical phases, with the BEMF phase 120° shifted, it shows that the instantaneous power and the average power delivered by the motor can be written as:

$$P_{(t)} = 3 \cdot I(t) \cdot E(t) = \tau_m(t) \cdot \omega_m \qquad (1)$$

$$P_{avg} = 3\frac{1}{T}\int_0^t I(t) \cdot E(t) \cdot dt = \tau_{avg} \cdot \omega_m \qquad (2)$$

Being ω_m the mechanical rotation speed. The constant $K_t(\theta_e)$ governs both the behavior of the machine as a motor and generator mode. For a first approximation of the constant, we start from the Lorentz equation:

$$\vec{F} = I \cdot \vec{L} \times \vec{B}$$

Focusing in a motor: $\vec{L} = 2 \cdot N \cdot L$

$$F = 2 \cdot N \cdot I \cdot L \cdot B_g$$

Being B_g the magnetic flux density in the Air Gap, N the numbers of windings and L the stator length. We can approximate B_g as:

$$B_g = B_r\frac{t}{t+g}$$

The Torque due this force is:

$$\tau = F \cdot d = 2 \cdot N \cdot I \cdot L \cdot B_g \cdot R$$

Being R the air gap radius. And finally:

$$K_t = \frac{\tau}{I} = 2 \cdot N \cdot L \cdot B_g \cdot R$$

In brushless motors with fractional concentrated windings, the coils do not equally contribute to the total motor torque at each instant. Therefore a constant called Winding Factor (wf) is used, adapting the above formula in this particular case of motors [13].

$$K_t = 2 \cdot N \cdot L \cdot B_g \cdot R \cdot wf \qquad (3)$$

In this way we obtain the value of the Torque Constant (K_t) which is one of the most important parameters of an electric motor, governing the relationship between the generated torque for a given excitation current. But this approach does not tell us anything about how change the K_t value, which is not constant over 360 electrical degrees. In this analysis, the Winding Factor absorbs the difference, although this is useful for a first analysis, this is not enough, as we shall see.

As mentioned above, the constant K_t also relates the magnitude (and shape) of the BEMF in function of motor speed. This makes sense, because this is an ideal transformer, must not to contradict the first law of thermodynamics.

Accordingly, we have the dual role of K_t:

$$K_t := \frac{T(\theta_e)}{I(t)} \qquad \left[\frac{Nm}{A}\right]$$

$$K_t := \frac{E(\theta_e)}{\omega_m} \qquad \left[\frac{V}{rad/_s}\right]$$

To prove this affirmation we can start from Faraday Law:

$$E = \frac{d\lambda}{dt} = B\frac{d(\text{Flux Area})}{dt} = 2 \cdot B \cdot L \cdot v$$

$$v = R.\omega_m$$

$$E = 2 \cdot B \cdot L \cdot R \cdot \omega_m$$

If we have a motor with N turns winding:

$$E = 2 \cdot N \cdot B \cdot L \cdot R \cdot \omega_m \qquad (4)$$

As we have seen: $K_t = 2 \cdot N \cdot B \cdot L \cdot R \qquad (5)$

By combining (4) and (5) we have: $k_t = \frac{E}{\omega_m}$

To complete the model, we obtain the value of the resistance and inductance. In the case of resistance, it is simple to obtain analytically