Model Proposals for the Analysis of Magnetic Interactions in a Permanent Magnets Array

Pedro Ponce, Carlos Varas, Fernando Sánchez O, Julio Luna

Instituto Tecnológico y de Estudios Superiores de Monterrey
Campus Ciudad de México

ABSTRACT. **Permanent magnets are used in several applications; however, they have not been studied as a possible source of renewable energy by transforming the magnetic energy stored into another kind of energy. The main purpose of this work is to propose different models for the analysis of the transformation of the magnetic energy stored in the magnets into a mechanical energy. The main characteristics and properties of the permanent magnets are studied for the comprehension of how the internal energy can be used.**

Key words -- magnetic energy, magnetic interaction, magnetic models, neodymium magnets, magnets array.

I. Introduction

All materials have different magnetic properties that are useful in the energy transformation. To understand this kind of energy transformation it is necessary to understand some basic definitions and principles of this phenomenon.

Every material has an intrinsic magnetic field which is caused by the orientation of its magnetic atomic moments, the behavior of this magnetic atomic moments before an external magnetic field defines the classification of the materials according to its magnetic properties, there are three kinds of materials, ferromagnetic, paramagnetic and diamagnetic.[8]

The magnetic permeability is the capacity of a material to attract and permit the movement of magnetic field through it; this property is defined by a relation between the magnetic field intensity and the magnetic induction in the material.[2]

$$\mu = \frac{B}{H} \qquad \text{eq. 1}$$

Where B is the magnetic flux density and H is the magnetic field intensity.

Permanent magnets are materials that can generate an external magnetic field; they represent an alternative for energy generation and energy storage that have not been deeply studied with the absence of external energy sources.

Nowadays there are several industrial applications where permanent magnets are used such as impurities separators, DC motors, presses for plastic injection molds, electromagnetic brakes and electromagnetic clutches. Also there are some international patents about continuous rotary motion machines that work under permanent magnets repulsion.[1]

In order to study these continuous rotary motion machines its necessary to study them from different model proposals, this work as purpose to show the study and results of several models analyzed, the sections are manly divided in the analysis of a mechanical model, a finite element model, a mathematical model, and a fuzzy model which integrates the results of the previous proposed models. The proposed models are based on an equidistant circular array with variable tangential angle, the variation of this angle generate advantages and disadvantages to the system, but the objective of this angle variations is to generate a continuous rotary motion.[5]

II. Model Proposals

A. Mechanical Model

A mechanical prototype was manufactured, in order to study and analyze how do the magnetic field lines interact between magnets, how does the angle of each magnet affect in the torque produced, and how does the air gap between the magnets of the rotor and stator is involved in the change of the generated torque. Both prototypes use NdFeB N40 magnets, where each of them can produce a magnetic field of 12800 Gauss, this magnets have a cylindrical shape with 0.5 in of height and 0.5 in of diameter.[4]

As shown in figure 1, this prototype is a circular arrange of magnets, where the distance between each magnet of the stator is the same with the magnets of the rotor, and the angle of each magnet can be changed. It was observed that at bigger angle, the torque generated was bigger as well.

There were mainly two effects observed. The first one occurred when a magnet of the rotor was aligned with one of the stator, which produced an unsteady state and the rotor to move. If the rotor could be in this state, it would move continuously until the energy in the magnets boost out. Unfortunately a second effect appeared when a magnet of the rotor was between two magnets of the stator. This effect produced a steady state, so that the magnetic lines between the positive and negative poles became stable and the motion of the rotor stopped.

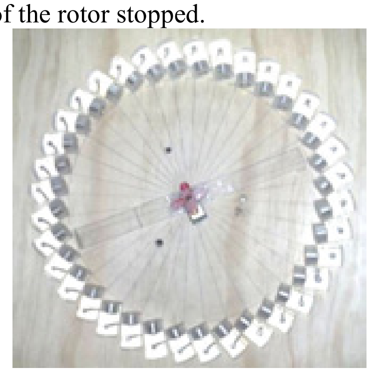

Fig. 1 Mechanical Model

The rotor was mounted on a servo, which current was measured in order to analyze the torque produced by the magnets and understand the barrier produced by the second effect. The figure 2 shows that the instability state generated a positive torque, while the stability state produced a negative torque. The negative torque behaves as a barrier that needs to be broken, and that is the main reason why the diamagnetic materials were studied.

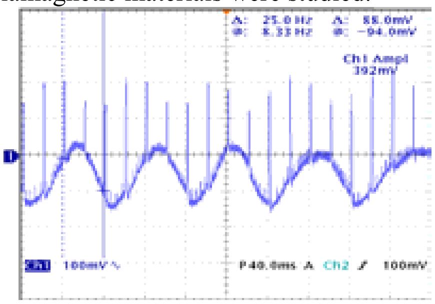

Fig. 2 Measurement of the servo's current

The pyrolytic graphite was chosen as a possible material for blocking magnetic field lines. At first a plate with 5mm of thickness was placed in front of a magnet, and another magnet was placed in the other side, for observing if the magnetic field was blocked. However the result was negative and the magnetic field stayed with the same magnitude. Then a plate of 15.38mm x 13.72 mm x 260µm was placed above the magnets, and it was observed that the plate generated a magnetic field in the opposite way as the ones of the magnets. The figure 3 shows the plate levitating as result of the generated field; however the magnetic field was not blocked at all. It was concluded that the magnetic field of the magnets is too big for being blocked.

Fig. 3 Graphite levitating over magnets

B. Finite Element Model

The Finite Element Analysis (FEA) is a numerical approach to an approximated solution of a highly complex geometrical problem. For the magnetic fields analysis, this method is a powerful tool that can be used not only in steady state, but also in transient state problems. There exist many softwares and applications that use this method, and for this work, it was used the Maxwell 3D because of the facility to import CAD designs of the mechanical model, as shown in figure 4.

The first parameter that has to be defined is the material and its characteristics. For this model, there were used four different materials; air, as the environment; Plexiglas, for the structure of the rotor and the stator; stainless steel in the joints of the model; and NdFeB magnets, with a magnetic field of 1.28 Tesla.

The second parameter defined for a transient state analysis was the magnitude and direction of the motion. And the last parameter to define is the mesh that is used for the model geometry; in this case, the maximum length of elements was 50 mm. For this length, the mesh has between 150 and 200 thousand elements.

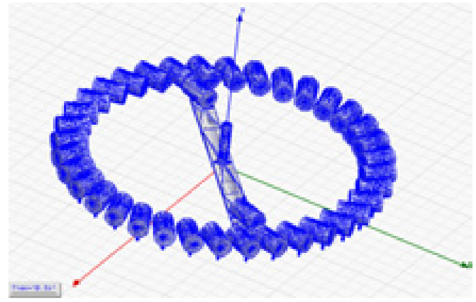

Fig. 4 Mesh of the Finite Element Model

With the Maxwell 3D, it is possible to analyze all the forces that interact with the magnets, therefore it were analyzed the forces that feels one of the rotor's magnet, when moving along the stator. For the first simulation, it was only analyzed the interaction between to magnets (one in the rotor and one in the stator). The results are shown in the figure 5. In order to have a more accurate model, it was made a second analysis with all the 36 magnets in the stator and only one in the rotor.

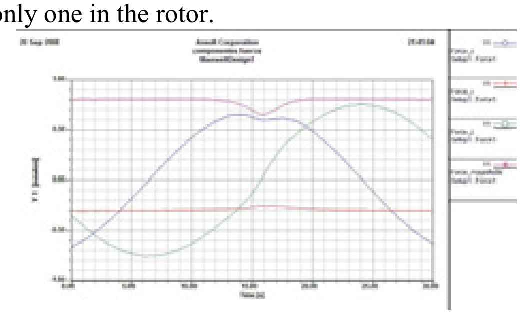

Fig. 5 Forces for one magnet in the stator

The results of the FEA are given as a function of the coordinate system (X, Y, Z), and for this reason, the magnitude of X and Z vectors were converted into the resultant of the Torque vector.

Also, the transient analysis in the software, does not realizes the enough number of iterations to minimize the error and approximate an accurate result. Because of this, it can be observed an offset in the magnitude of the forces. To reduce this offset, it was calculated the average of the force and used as a negative offset.

In the figure 6 is shown the force (in Newton) as a function of the position (in degrees), as result of the interaction between one magnet in the stator, and the one of the rotor.

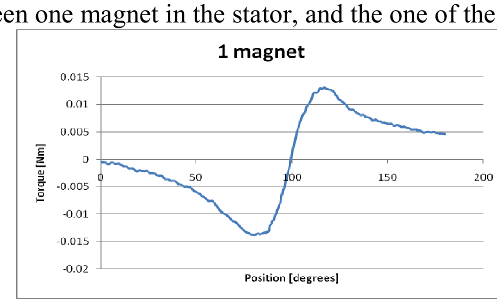

Fig. 6 Force as function of the position for one magnet in the rotor

To complete the model, the same procedure was applied to the result of the 36 stator magnets, and the interaction is shown in the figure 7.

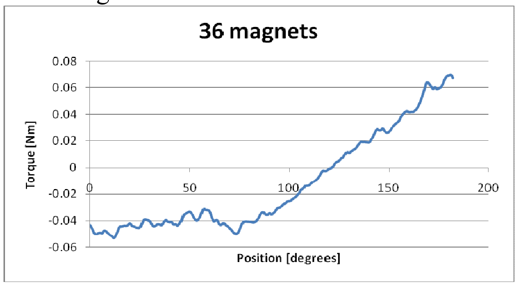

Fig. 7 Force as function of the position for 36 magnets in the stator

In this last figure, it can be seen the effect of not doing multiple iterations on each step of the analysis. The initial error is accumulated, an as result, the last steps of the graph are above of the real value that was expected.

Model analysis with diamagnetic material

In order to analyze the model using a diamagnetic material, it was added a piece of pyrolytic graphite with dimensions of 12.5 x 12.5 x 1 mm.

The diamagnetic property of the graphite is given by the permeability, and this value was set to 0.9994, as it is in the real world. The position of this piece was in one side of the rotor's magnet as it is shown in the figure 8.[3]

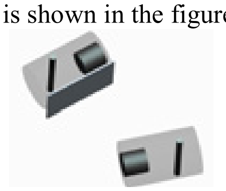

Fig. 8 CAD model with the diamagnetic graphite

The result of this analysis is presented in the figure 9. In this graph, the curve of force vs. position is different compared to the previous results. In this model is seen that the model only generates a positive Torque.

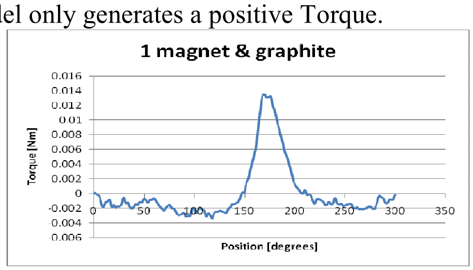

Fig. 9 Analysis of the model using diamagnetic graphite

C. Mathematical Model

The Magnetic Torque is the result of the cross product between the field vector and the Magnetic Dipole Moment. This relation is represented in the equation 2. Also, the Magnetic Dipole Moment is represented, as a function of the current in a coil, in the equation 3.

$$T = \vec{\mu} \times \vec{B} \quad \text{eq. 2}$$

$$\vec{\mu} = N \cdot I \cdot \vec{A} \quad \text{eq. 3}$$

The dipole moment can be found not only in coils, but also in any kind of material. This characteristic depends in the structure and orientation of dipoles, and for example, in a magnet, the dipole moment can be found with a higher magnitude because almost all the dipoles are oriented in the same direction.

The equation for the magnetic Torque is used for the mathematical representation of DC motors, and it can be used as the model for the interaction between permanent magnets. To do this, it has to be evaluated the dipole moment of the magnets, and the magnetic field for every condition.

In order to measure the magnetic dipole moment of the magnets, it was applied a known magnetic field and calculated the torque generated with the equation 4.

$$T = I \cdot \omega^2 \quad \text{eq. 4}$$

To generate the known field, there were used the Helmholtz coils shown in figure 10. This system is a couple of coils with radius R and a distance between them of the same length R. The field has to be aligned from East to West, to avoid the magnetic noise generated from the earth's field. Also, in the field vector's magnitude, has to be considered the earth's magnetic field, which is about 0.5 Gauss.

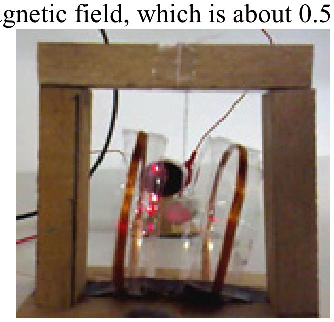

Fig. 10 Helmholtz coils with a magnet

The oscillation frequency was measured with a laser sensor, and the magnets used were the same that those in the mechanical model (NdFeB N40). First, it was measured with two magnets and after that, there were used three magnets. In the figure 11, it is shown the relation between the Field and the Torque generated. The slope in this straight line represents the magnetic dipole moment.

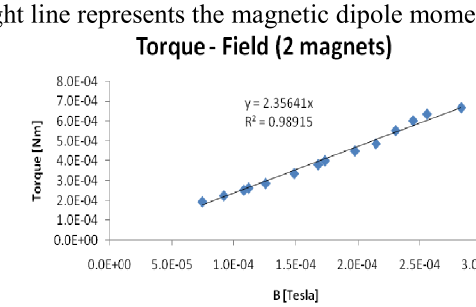

Fig. 11 Graph of Torque vs. Field

Assuming that the dipolar moment is lineal, it can be done an extrapolation in order to know the magnitude for only one magnet from the result of two and three magnets, the result is shown below.

Moment	**1.155724**	**[A m^2]**

For the representation of the field lines of the magnets in the stator, it is used an elliptic approximation using different ellipses with different size but the same eccentricity. This last constant is represented in the equation 5.

$$e = \frac{c}{a} = \frac{6.35}{\sqrt{80.645}} \quad \text{eq. 5}$$

In the equation 6, it is used an offset for the Y axis, indicated as Yc = b – 6.35 mm. The equation that relates the parameters a, b and c is represented in equation 7.

$$\frac{x^2}{a^2} + \frac{(y - y_c)^2}{b^2} = 1 \quad \text{eq. 6}$$

$$a^2 = b^2 + c^2 \quad \text{eq. 7}$$

With these 3 equations, it is possible to calculate the function of the ellipse that crosses every point (X, Y) where the rotor is. With this ellipse, it is calculated the direction of the field vector using the first derivate at the given position, as shown in equation 8.

$$m = -\frac{b^2 X_0}{a^2 Y_0} \quad \text{eq. 8}$$

For the mathematical model, there were evaluated several positions with the rotor's vector moving along the magnetic field of only one magnet in the stator, from 90 degrees to -90 degrees. In the figure 12, it is shown the rotor movement and all the ellipses calculated.

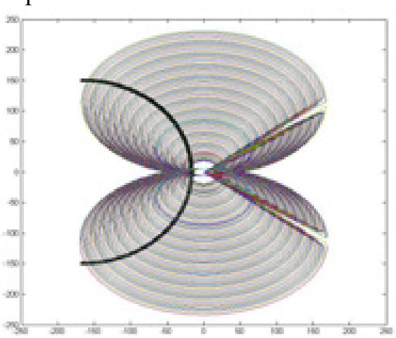

Fig. 12 Approximation of the field lines using ellipses

With this equations, there were calculated every one of the slopes. With this vector and the magnetic dipole moment, it was calculated the cross product, the result is the magnetic Torque generated by the magnets and it is shown in the figure 13.

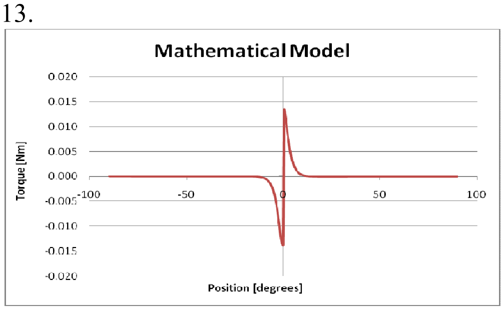

Fig. 13 Torque graph using the mathematical model based on the dipolar moment.

D. Fuzzy Model

Fuzzy models describe systems by linguistic rules of IF-THEN type; these rules correlate the input with the output in order to get an output value. A fuzzy model has the following stages:

Input → Fuzzification → "If-Then" rules → Defuzzification → Output

Fig. 14 Diagram of the stages of a fuzzy model

The fuzzification process characterizes the input by membership functions, these functions can have different forms such as triangles, gauss bells, trapezes and other non conventional forms but its goal is to assign membership values from zero to one.

The linguistic rules IF-THEN are the fundament of fuzzy models, with these rules the system can give an output value without the need of transfer functions, this means without the need of a mathematical description of the model, just the experience and the recompilation of the results.

Defuzzifications process assign membership functions to the outputs, the output value is calculated when an input value is evaluated in these membership functions.

In order to have a more robust model that is able to get together the mathematical model, finite element model and mechanical model fuzzy models were defined.

Fuzzy model from the finite element model

The input parameter for this model was the spin angle of the rotor from 0° to 180°. The output data was the tangential force that generates a torque in the system.

There were seven membership functions for this model; the form of these functions was Gauss bells because the error percentage acquired was smaller than with triangles, trapezes and other functions.

The fuzzy model was made in the fuzzy block of Matlab, the data acquired from finite element model was introduced by a data file and Matlab trained the fuzzy model.[6]

The input membership functions are shown in the figure 15.

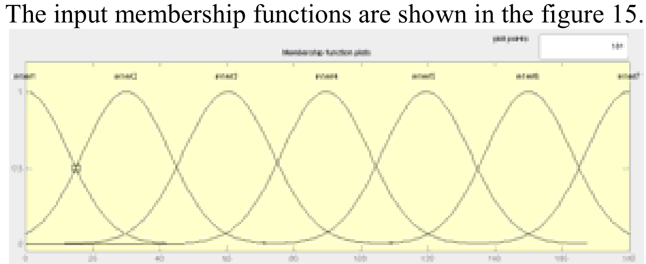

Fig. 15 Input membership functions

With these parameters was possible to train a fuzzy model with just 0.2% of error, therefore the fuzzy model describes very well the behavior of the system. In the figure 16, it is possible to observe the comparison between the finite element model and the fuzzy model.

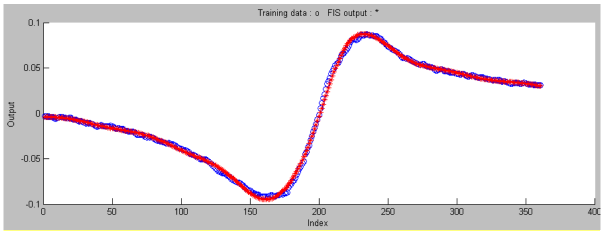

Fig. 16 Comparison between fuzzy model and finite element model

Fuzzy model from the mechanical model

Another fuzzy model was created to represent the behavior of the system with the complete arrays of permanent magnets. The figure 2 shows the current on a dc motor attached to the rotor; this current is directly correlated to the torque of the system by the equation of the DC motors.[7]

$$T = K \cdot \Phi \cdot I \qquad \text{eq. 9}$$

Where, K is a constant due to the physical construction, Φ is the flux inside the motor and I is the current of the motor

The input data for this model was the wave form of the current, there were only five membership functions to represent the system and they were of Gauss bell type. This kind of functions were chosen because they had the smaller error percentage to represent the system and because they could filter the noise in the current signal

The resultant model was a very good approximation to the real behavior of the system, with this fuzzy model is possible to estimate at any value of the rotor spin angle the torque than the system is generating, in figure 17, the comparison between the mechanical model and the fuzzy model is shown.

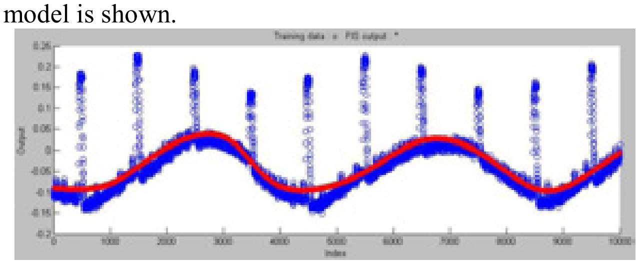

Fig. 17 Comparison between mechanical model and fuzzy model

III. Results

The analysis of all these model proposals has as objective to determine the behavior of the resultant forces due to the interaction of two or more permanent magnets. This project presented the study of four different models and all of them were focused on showing the behavior of the torque generated by permanent magnet arrays under different spin angle positions.

The theoretical part of this project raised two models, the first one was the finite element model that was simulated in the software Ansoft Maxwell version 11.1, and the second one was the mathematical model of the magnetic torque. The comparison between these two theoretical models is shown in the figure 18.

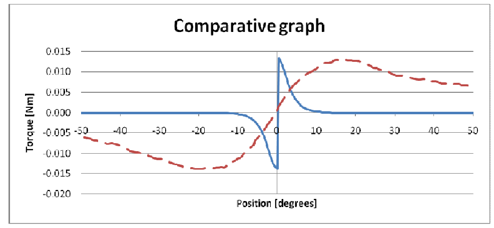

Fig. 18 Comparative graph between mathematical and FEA models

In above figure two main characteristics can be observed. The first one is that the maximum magnitude of both curves is very similar; it has an estimated value of 13mNm. The second characteristic is the wave form, in the mathematical model there is an asymptotic behavior, however, in the finite element model the wave form is sinusoidal.

There is an important issue in the finite element model, it accumulates an error because the software does not make enough iterations to minimize the error in the transcendent analysis, this accumulated error is shown in the figure 7.

The third model that was proposed was the mechanical one, a servo motor was coupled to stator in order to make it spin, the variations of the torque in the system due to the interactions between the magnets of the stator and rotor could be inferred because the relationship of the torque and current in a DC motor.

However, the acquired current signal had too much noise and could not be analyzed directly. That is why it was proposed a final model that could integrate the previous models. This was the fuzzy model and the results are shown in the figure 19.

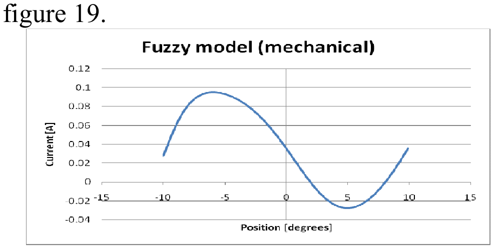

Fig. 19 Graph of the fuzzy model from the mechanical model

The wave form of these results can be compared; in the fuzzy model and in the finite element model the behavior of the torque in the system is sinusoidal. Also, for angles higher than 10° in interactions between two magnets the magnitude of the torque is very close to zero, this characteristic is also observed in the mechanical model.

In the four models there is symmetry in the repulsion of the permanent magnets, this means that the repulsion force in the system is the same when an rotor magnet is getting closer to a stator magnet than when a rotor magnet is getting away to a stator magnet. In order to avoid this phenomenon and to create a condition to have a positive torque in the system a diamagnetic material was included in two of the model proposals; the mechanical model and the finite element model. The chosen material is one of the most diamagnetic materials known and is pyrolytic graphite.

In the finite element model with pyrolytic graphite a little sheet of 1mm of thickness was placed next to the permanent magnets of the stator, the result of this simulation is shown in the figure 9.

In this graph, the torque generated by the system is positive and the negative peak has disappeared, so it seems that there is a condition to generate continuous rotary motion.

However, when a sheet of graphite was placed next to the stator magnets in the mechanical model the results were very different. The graphite could not block in an effective way the magnetic field of the stator magnet, so the negative peak of the torque in the system still were there and there could not be a favorable condition to a continuous rotary motion .

IV. Conclusions

The permanent magnets are used in a wide range of applications and have been studied since many years ago. However, the transformation of the magnetic energy stored in the magnets has not been studied before.

In this work different proposals were made in order to study the interaction between permanent magnets for transforming the magnetic energy into mechanical energy. Those models proposed were analyzed and experimentally validated; however, the results show that it is not possible to transform the magnetic energy into mechanical without an external source of energy.

This conclusion is based on the results from the models proposed. The mechanical model, provided the real behavior of the system, but in order to have a complete understanding of the system, theoretical models were analyzed. The FEA and the mathematical models were an important part of this work, because together, these models described in an accurate way the phenomenon of the magnetic fields interactions.

Another aspect, on which the conclusion is based, consists in the impossibility of blocking or redirecting the field lines, so it is not possible to generate a positive torque. That means that it has been impossible to generate a bigger torque in one direction as in the other one, therefore the motor cannot make more than one turn by itself.

Considering the two mentioned points, a hypothesis is made. The magnetic energy cannot be used because it tends to an equilibrium point, which means, a stable system. For this reason, in order to use the magnetic energy stored in the permanent magnets, it would be necessary to make an unstable system.

To generate motion in the system, an additional element that provides instability is required, for example, a device that inverts the polarity of the magnetic field, like a coil in the stator or in the rotor that could give the system an extra impulse for restarting the cycle.

Although the coil is a solution for the transformation of magnetic energy into mechanical energy, that is not the purpose of this work, because that would be the same principle as conventional motors. In this case the transformed energy would not be provided by the permanent magnets; instead it would be provided by the electrical power added to the system.

It should be considered as a possibility, the development of applications where the magnetic stability is an advantage instead of a disadvantage. In the case of the transformation of magnetic energy into mechanical energy, the equilibrium of the system makes impossible its implementation, however, any method of mechanical power transfer could be considered.

Finally, with the research and experimentation process it can be concluded that the energy stored in the permanent magnets is not a form of energy that could be transformed into work. That is because every single arrange tries to stabilize in an equilibrium point. However, this phenomenon could be considered as a new possibility for applications where the magnetic field energy is an advantage.

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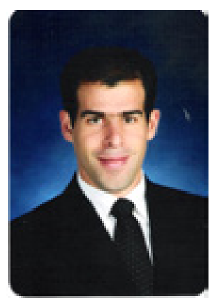

Carlos Varas Ibarra was born in Mexico City in1985. He owns a BS degree in Mechatronics Engineering from the Instituto Tecnológico y de Estudios Superiores de Monterrey. He has a professional concentration in aeronautics with studies at INSA Lyon. His areas of interest are related with the development of sustainable technology for the aerospace areas. Carlos speaks Spanish, German, French and English and has participated in many contests including CanSat organized by NASA.

Fernando Sánchez O. Ariza was born in Mexico City in 1985. He graduated as Mechatronic Engineer from the Instituto Tecnológico y de Estudios Superiores de Monterrey, campus Mexico City. Fernando has worked in the areas related with processes control and automation in different industries. His areas of interest are focused in the control systems, electronics and electric motors drives. Also Fernando is committed with the environment and all kind of sustainable sources of energy.

Luis Julio Luna Calderón was born in 1986 in Mexico City. He studied Mechatronic engineering at the Instituto Tecnológico y de Estudios Superiores de Monterrey Campus México city. His personal interests are focused in the development and research of new technologies for energy extraction and conversion, and in automotive engineering. He has leaded a project of an electrical racing go kart and has participated in the study of a motor supplied by alternative energy.