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ULTRA-HIGH-SPEED VARIABLE RELUCTANCE MOTOR (VRM) APPLIED ON GRAVIMETRIC CALIBRATION DEVICE WITH MAGNETIC SUSPENSION

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Abstract: Variable Reluctance Motors (VRM) have great advantages for applications in the most diverse areas of the industry and equipment, due to its versatility, robustness, stability and the possibility of precise control of rotation, power and torque. In view of these advantages, it was decided to develop and simulate this type of motor for the on-screen prototype, which is intended for the calibration of gravimeters, intended for the detection of gravitational waves through the effect of these waves on rotating objects in ultra-high rotations of the order of 500,000 rpm. The proposed device requires a 1: 10,000 rpm error control, which will be possible due to the stability characteristics of the MRV. Due to the extremely low permissible vibration, the system uses magnetic bearings of the Lenz type in the rotor, with neodymium magnets interacting with the aluminum shaft, ensuring low friction and vibration. All of these aspects can be simulated using Matlab / Simulink, allowing a MRV performance perspective on the prototype.

1.Introduction

The Graviton Group is a research Brazilian group dedicated to the study of Gravitational Waves, such waves travel through space probably at the speed of light but it has never been directly measured. That is the reason the group is devoted to this study. The detection of gravitational waves came after a long road of experiments planned in 2010 [1], in 2016 finally the detection was made [2,3]. Gravitational waves got a very strong evidence with the **PSR B1913+16** (also known as **PSR J1915+1606**, **PSR 1913+16**, and the **Hulse–Taylor binary** after its discoverers) is a pulsar (a radiating neutron star) which together with another neutron star thus forming a binary star system. PSR 1913+16 was the first binary pulsar to be discovered and its orbital period is decreasing with time due the emission of gravitational waves [4]. The first attempts to gravitational wave detection starts in the early sixties [5] with the resonant mass gravitational wave detection [6,7,8,9]. The Brazilian efforts towards the detection of gravitational waves are centered on the Schenberg detector. In the Schenberg detector six sensors are connected to the surface of the sphere, arranged according to the distribution of Merkowitz and Johnson [10]. These transducers

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are located as if they were in the center of 6 pentagons connected in a surface corresponding to half dodecahedron. Each transducer amplifies the motion occurring on the region of the sphere in which it is connected. The already amplified movement excites the membrane of one resonant cavity. In the resonant cavity microwaves are pumped, which generate the electronic signal that will return taking all the information of the OG's. Intensity and direction of the OGs can be obtained from the analysis of the output signal of these 6 transducers [11,12,13].

To reach the resonant cavities, first the microwaves are conducted from the outside of the dewar (thermo flask where every antenna system is contained) by cabling to microstrip antennas. These antennas, located in front of the parametric transducers, conduct the microwaves into the resonant cavity and another set of antennas pick up the returned signal. The Brazilian efforts on the field can be summarized in [14-31]. The Brazilian detector is shown in Figure 1.

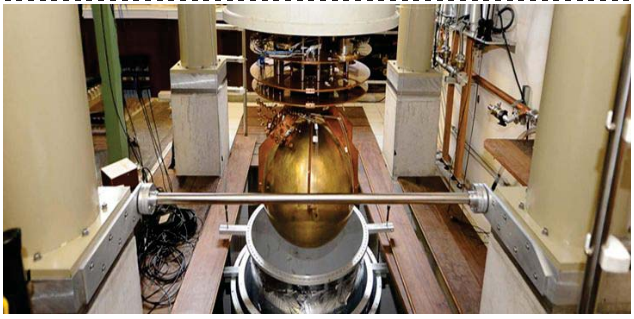

Figure 1: Gravitational wave detector of the Institute of Physics donated to INPE - Photo: Marcos Santos / USP Images

2 Objective

The objective of this article is to describe and simulate the application of the Variable Reluctance Engine (SRM) in the computational environment using the prototype gravimetric calibration device. This type of engine has a good efficiency and features relatively simple compared to other electric motors and can achieve the ultra high rotations required with high reliability and energy efficiency.

3 Propriedades do SRM

In SRM only the stator has electric windings [34], while the rotor consists of steel blades without windings or magnets. This extremely simple construction, which does not use brushes or switches, coupled with the current advantages of electronic controls for solid state components such as Insulated Gate Bipolar Transistor (IGBT).

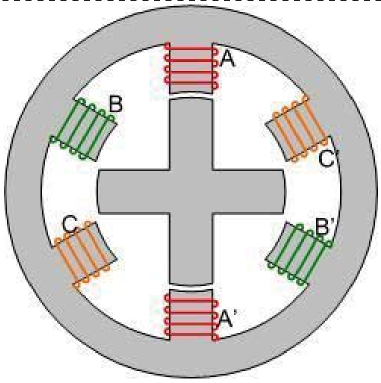

Figure 2: Switched Reluctance Motor - Source**:** https://people.ucalgary.ca/~aknigh/electrical_machines/images/oth/sr.jpg

As an unfavorable point, the configuration of the motor with protruding poles introduces nonlinear characteristics from the magnetic point of view, which produces a certain acoustic noise and also a ripple torque, which is a peculiarity of these motors, mainly due to the successive current changes in the poles of the stator and its protruding poles on the stator and rotor [35].

The SRM structure configuration applied to the gravimetric calibration prototype under study will be in the 6/4 configuration, ie 6 poles in the stator and 4 poles in the rotor. Each pole of the stator has a coil in its surroundings, and the opposite coil is connected in series, so it is possible to use 3 switched phases to magnetize the 6 poles of the stator, connected in pairs. The rotor has no permanent windings or magnets.

The stator and rotor are made of silicon steel, laminates, aimed at reducing the so-called eddy current [36], also called "parasitic" currents, which is the induced current inside the stator and rotor when subjected to the variable magnetic field due to Faraday's induction law, where the magnetic flux is defined by the surface integral:

$$\phi_B = \iint_{\Sigma(t)} B\ (r,\ t)\ .\ dA \qquad (1)$$

By limiting the surface, ie by constructing the rotor and the stator in thin blades and not in solid blocks, the magnetic flux that produces the loss by parasitic currents is reduced.

Also desirable for the developing prototype are thin steel blades since the switching frequency of the stator poles will be from about 100 kHz to 500,000 rpm. This frequency is calculated based on the motor pitch angle (θ), given by the equation [37]:

$$\theta = \frac{2\pi}{q\ .\ n_r} \qquad (2)$$

That:
q = number of stator phases
n_r = number of rotor poles

We have the result as follow:

$$\theta = \frac{2\pi}{3\ .4}$$

$$\theta = \pi\ /\ 6 \text{ rad, or } \theta = 30\ °$$

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That is, for each rotation of the rotor it takes 12 steps, or 100,000 Hz at 500,000 rpm, which is the desirable rotation for the equipment.

The limitations of SRM are:
1 - High ripple torque and acoustic noise, compared to electric induction motors;
2 - Structure of the stator and rotor with protruding poles, provoking a great magnetic nonlinear characteristic;
3 - Always requires electronic switching circuit and does not allow to be driven directly by an AC or DC bus.

SRM torque is produced due to the alignment tendency of the rotor and stator poles as the latter are magnetized through the coils. The rotor motion is produced due to the variable reluctance produced by the air-separated distance between the rotor and the stator. When the stator coil is energized, a torque is produced to move the rotor pole to the least reluctant position, ie in total alignment with the stator pole. At this moment of total alignment the torque is null because the magnetic field lines of both poles are fully aligned, thus the magnetic reluctance is minimal, while the inductance is maximum. For effective rotation, it is necessary to commutate the following pair of stator coils, in order to increase reluctance, producing torque and allowing continued rotation of the rotor.

A - Torque Generated:

The torque depends on the position of the rotor (θ) and the current in the phases I = (I_1 , I_2, I_3 , ... , I_n), where this function is called coenergy $\overline{W}$ (I, θ). Similarly, the energy W will be calculated as a function of the magnetic flux Ψ of the n phases $\Psi = (\Psi_1 + \Psi_2 \Psi_1 + \ldots + \Psi_n)$[36] of the position of the rotor θ .
Thus, due to the protruding poles of the motor, the partial derivative of the energy as a function of the relative position of the rotor allows the calculation of the torque T of this:

$$T(\Psi_1, \Psi_2 \ldots \Psi_n, \theta) = \frac{\partial W}{\partial \theta}(\Psi_1, \Psi_2 \ldots \Psi_n, \theta) \tag{3}$$

B - Electromagnetic Characteristics:

When the stator coil is energized, the magnetization of the respective pole occurs due to Faraday's law [38]:

$$V = R.I + \frac{\partial \Psi}{\partial I}\frac{dI}{dt} + \frac{\partial \Psi}{\partial \theta}\frac{d\theta}{dt} \tag{4}$$

Where we can understand that the instantaneous inductance is $L(\theta. I)$ *or* $\partial\Psi/\partial I$.

C - Motor Starter

The electronic drive of the motor will be executed by transistors type Insulated Gate Bipolar Transistor (IGBT), driven by microprocessor controller.

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4 Operating simulations

In order to evaluate the behavior of the SRM during operation in the prototype, the behavior of the engine was simulated through the Matlab / Simulink Software [39] using the schematic below:

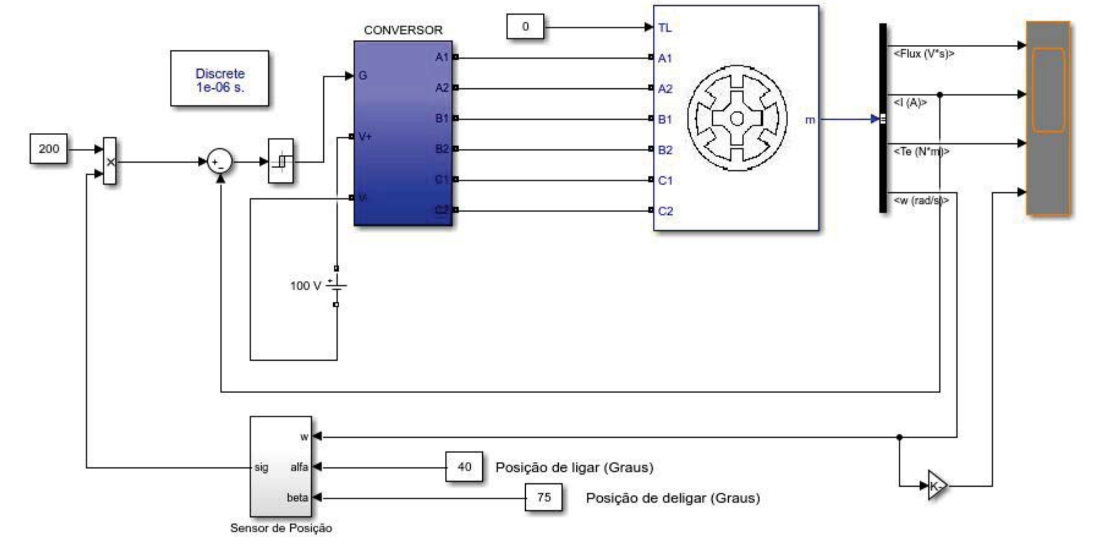

Figure 3: Matlab model schematic **- Source: Eduardo Sanchez**

The following initial parameters were stipulated for the simulated motor:

Stator Resistance = 0,05 Ohm
Inertia = 0,05 Kg.m.m
Friction = 0,02 N.m.s

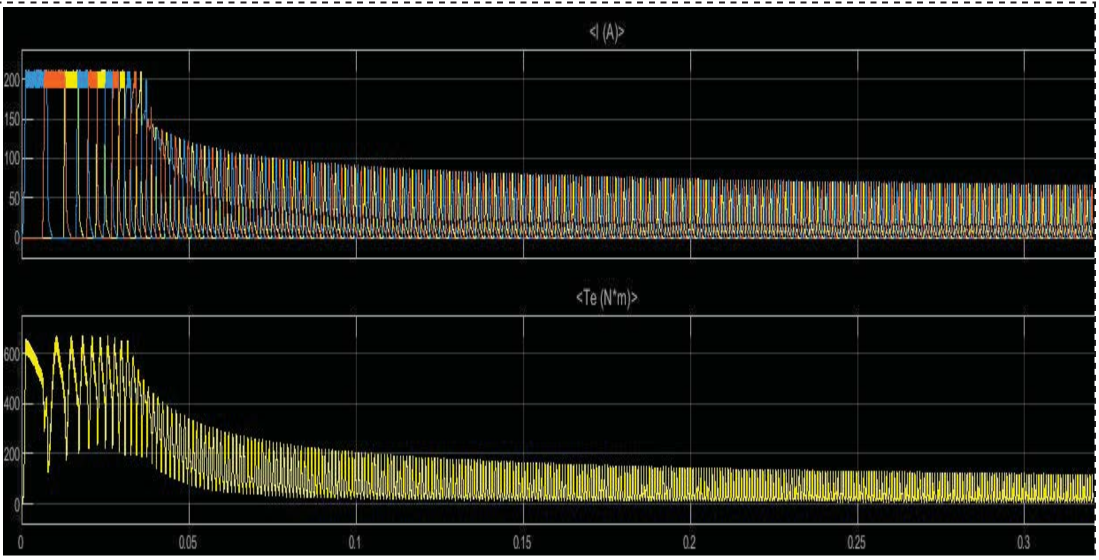

Figure 4: Start moment **- Source: Eduardo Sanchez**

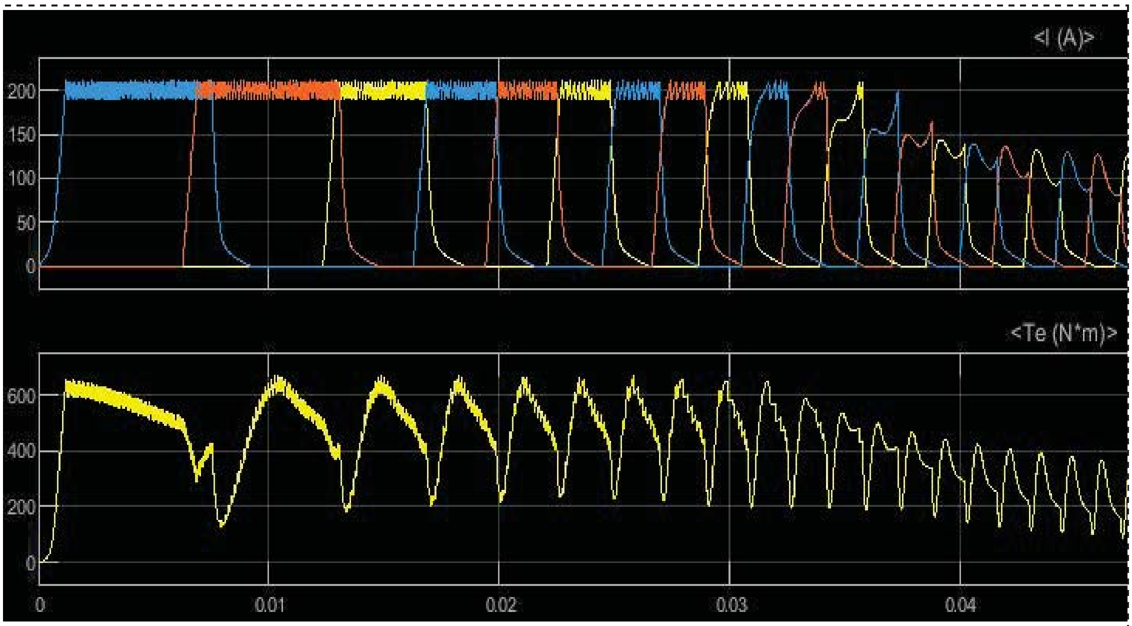

Figure 5: Start moment **- Source: Eduardo Sanchez**

As shown in Figures 3 and 4, the highest torque values coincide with those of current, indicating the direct correlation between current, magnetic flux and consequently motor torque variations. It is also noted that as the motor accelerates and evolves in speed, the corresponding current and torque drops occur because the inertia and power gain of the system are exceeded, allowing the system to enter into a stable operating mode. Better responses can be obtained by applying control strategies on the parameters, notably current and rotation, allowing a better response and rotation stability, as desired for the prototype, which requires 1: 10,000 rpm error control.

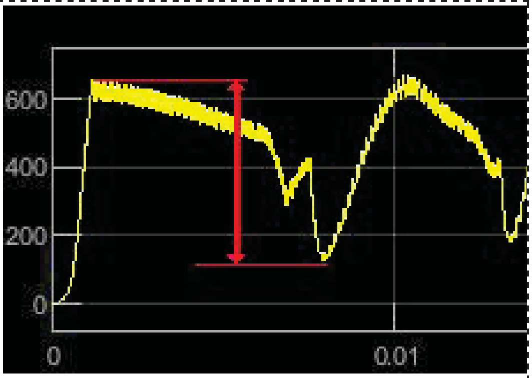

Figure 6: Torque Ripple at Start moment - **Source: Eduardo Sanchez**

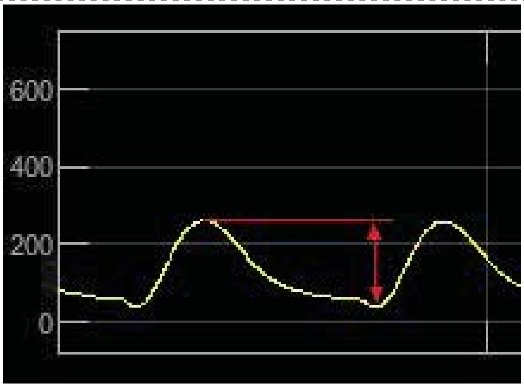

Figure 7: Torque Ripple at stabilized rotation - **Source: Eduardo Sanchez**

Due to the variable reluctance of the motor poles in relation to the stator, due to its electrical switching and protrusions in the rotor and stator, it is evident the existence of ripple torque (Figures 5 and 6), which remains present from the start to the continuous operating regime.

5. Conclusion

As observed, the SRM presents advantages and adequate performance for the application in the gravimetric calibration device, allowing to reach the desired rotations by means of magnetic suspension in the bearings, also aiming at diminishing the vibrations provoked by the torque ripple, and with the precisely controlled rotation through closed-loop microprocessor system, with the intention of maintaining 1: 10,000 rpm error control. The robustness of the SRM coupled with the advances observed in today's microelectronics and power electronics are key to success in screen design and future detection of gravitational waves.

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References
[1] The Gravitational Waves International Committee Roadmap (GWIC). A global pan. June 2010. Glasgow: Univerty of Glasgow - Department of Physics and Astronomy - Kelvin Building (G12 8QQ), 117p.
[2] Taylor J H, Hulse R A, Fowler L A, Gullahorn GE, Rankin J M 1976 *Astrophysical Journal* **206** L53
[3] Weber J 1960 *Physical Review* **117** 306
[4] Thorne K S 1987 "300 years of gravitation". Cambridge: Cambridge University Press: 1987, p.330.
[5] Blair D G "The detection of Gravitational Waves." 1991 Cambridge: Cambridge University Press
[6] Richard J P 1984 *Physical Review Letters* **167** 165
[7] Aguiar O D *et al.* 2006 *Journal Class. Quantum Grav.* **23**, 239
[8] Frajuca C *et al.* 2004 *Class. Quantum Grav.* **21** 1107
[9] Velloso W F, Aguiar OD and Magalhaes NS *Proc. First International Workshop for an Omnidirectional Gravitational Radiation Observatory* 1997 Singapore:World Scientific
[10] Merkowitz S M and Johnson W W 1993 P*hys. Rev. Lett.* **70**, 2367
[11] Locke C R, Tobar M E and Ivanov E N 2000 *Rev. Sci. Instrum.* **71,** 2737
[12] Ribeiro K L *et al.* 2004 *Class. Quantum Grav.* **21,** 1225
[13] Andrade L A *et al.* 2004 *Class. Quantum Grav.* **21,** 1215
[14] Aguiar O D et al. 2012 *Journal of Physics: Conference Series* **363,** 012003
[15] Aguiar O D et. al. 2005 *Class. Quantum Grav.* **22**, 209
[16] Frajuca *et al* 2002 *Class. Quantum Grav.* **19** 1961
[17] Magalhaes N S *et al.* 1997 *Astrophysical Journal* **475**, 462
[18] Magalhaes N S *et al.* 1995 *MNRAS* **274**, 670
[19] Frajuca C, Bortoli F S, Magalhaes N S 2005 *Brazilian Journal of Physics* **35** 1201
[20] Frajuca C, Bortoli F S, Magalhaes N S 2006 *Journal of Physics: Conference Series* **32** 319
[21] Aguiar O D et al. 2004 *Class. Quantum Grav.* **21** 459
[22] Frajuca C, Magalhaes N S, Horiguti A M 2008 *Journal of Physics: Conference Series* **122** 012029
[23] Bortoli F S *et al* 2010 *Journal of Physics: Conference Series* **228** 012011.
[24] Magalhaes N S *et al* 1997 *Gen. Relat. Grav.* **29** 1511
[25] Aguiar O D *et al 2002 Brazilian Journal of Physics* **32** 866
[27] Bortoli F S *et al* 2019 *Brazilian Journal of Physic* **49** 133
[28] Frajuca C, Bortoli F S, Magalhaes N S, Horiguti A M 2008 *Journal of Physics: Conference Series* **122** 012029
[29] Frajuca C, Bortoli F S 2006 *Journal of Physics: Conference Series* **32** 315
[30] Bortoli F S *et al* 2016 *Brazilian Journal of Physic* **46** 308
[31] Frajuca C *et al.* 2018 *Journal of the Brazilian Society of Mechanical Sciences and Engineering* **40** 319
[32] Ruiz W 2014 2015 *Experimento para medir a velocidade da interação gravitacional utilizando um motor de relutância variável*
[33] Ramalho W C S. *Transdutor de Safira para medicao da velocidade da interacao gravitacional*
[34] Bouiabady M M, Aliabad A D, A. Ebrahim *Switched Reluctance Motor Topologies: A Comprehensive Review*
[35] Soares F, BRANCO P J C. *Simulation of a 6/4 Switched Reluctance Motor Based on Matlab/Simulink Environment* 2001, p.990
[37] Moron C, Garcia A, Somolinos J A . *Mathematical Model Switched Reluctance Motor* 2015, p.87-91
[38] Memon A A, Hussain I, Shah w, Chandio M S. *Modeling of Switched Reluctance Motor* 2012, p.572
[39] Jambulingam V. *Matlab Simulink Implementation of Switched Reluctance Motor with Direct Torque Control Technique* 2016 p.49