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ELECTRO-MECHANICAL SIMULATION OF A HYBRID STEPPER MOTOR

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Abstract: *In this paper modern simulation methods are used for modelling the functioning principles of a hybrid stepper motor, which is widely used in commercially available mechatronics systems, where exact positioning is necessary, such as the case of modern 3D printers. The simulation created and its results are presented, results from which further mechatronic simulations can be derived. From the standard black-box simulation and design of electric-machines, FEA simulations allow the engineers to create models that take into account the shape of the elements of an electric motor, shapes that have a great influence on the well-functioning of such motors. In the end, we present further simulation possibilities.*

Keywords: *Stepper motor, variable reluctance motor, switched reluctance motor, hybrid motor, electro-mechanical simulation, Simcenter3D, Simcenter MAGNET*

1. Introduction

Stepper motors are widely used to drive all kind of machines, from simple plotters to complex machines such as modern 3D printers [1] [2]. The versatility of this electrical machine, given by its ability to be driven in discrete steps, thus making it possible to position its shaft to the desired location. In addition, with the advent of the new and better IC drivers, using stepper motors became a lot easier.
Using a microcontroller to control the steps outputted by the stepper motor driver, gave these electrical machines the ability to be present all around us.
One important application in which stepper motors are essential is the field of additive manufacturing. When a component is created using Additive manufacturing [3] [4] techniques, a printing head or a mirror needs to be positioned with great precision, and stepper motors makes this possible. However, one element that really contributes to the precision of a working stepper motor is its driver, as this is the one that creates the waveforms that drives each phase of the stepper motor.
As stated earlier, an important field in which stepper motor show their power is the Additive manufacturing one, but there is one more reason why they are so important, and that is the apparition of the new generation of 3D printers, the ones that make use of more degrees of freedom to create the part, using the FDM process [5] [6].
In the usual case, a classical 3D printer using the FDM process makes use of only 3 degrees of freedom and thus it has 3 axes only which usually represent the 3 Cartesian axes. Other types of 3D printers with 3 axes are the Delta 3D printers or the Polar 3D printers, which make use of a cylindrical coordinate system. However, for the 3D printers of the new generation, which we believe will represent in a few years the new norm, is mandatory to use at least one new axis to increase the DOF's of the part.
The new axes used are usually rotation axes, as the only degrees of freedom remaining are the rotation ones. These rotations are created with the use of a stepper motor and thus a perfect positioning system is needed.
This calls for better motor design and better stepper motor driver design, as most of the parameters that govern the correct functioning of the stepper motor are dependent on the temperature.
Because the stepper motors will be subjected to varying loads, as the parts created will increase the moment of inertia that the motor has to overcome, this moment of inertia varies as well with the inclination of the printing bed.
In this paper, we propose a way to simulate the functioning of a hybrid stepper motor using the *FEA* software *Simcenter3D*, thus gaining an insight into how different parameters affect the motor

functioning. This is the basis for further development of a better stepper motor to be used in advanced mechatronics applications.

2. Stepper motor functioning principles

2.1. Classification of stepper motor electrical machines

A variety of electrical machines can be defined as stepper motors, meaning that the shaft is positioned in discrete steps, but what differentiates them is how the magnetic fields are produced that make it possible to move the shaft in discrete steps.
The working principle of all stepper motors is that of the variable reluctance. The main idea behind it is that if you let a bar of iron suspended in air, which is free to rotate around an axis, and if you apply a magnetic field, the bar will tend to align itself with the magnetic field. If the magnetic field is rotated, then the bar will tend to align accordingly.
Based on this principle, there exists two main types of stepper motors [7]:

- Variable Reluctance types
- Hybrid types

The only difference between them is the way that the magnetic field is created, but the working principle of them both is almost the same. Thus, in the Variable Reluctance type, the magnetic field is created by stationary coils wound around the stator teeth, whereas the hybrid type also has inside its rotor a permanent magnet. Although their function is almost identical, their use is different as the *Variable Reluctance* motors usually tend to be used in applications which need larger step angles (usually 15°, 30° or even 45°), whereas the *hybrid* ones tend to be used for smaller angle steps (0.9°, 1.8°).

2.2 How the hybrid stepper motor works

For additive manufacturing the stepper motor need to drive small angular increments, usually necessary in the case of 3D printers, thus it is better to describe the workings of the hybrid stepper motor.
In **Fig. 1.** several different sections of the inside structure of a hybrid stepper motor are presented, with a design specific to a *Variable Reluctance* motor, as it has some number of teeth (this number is

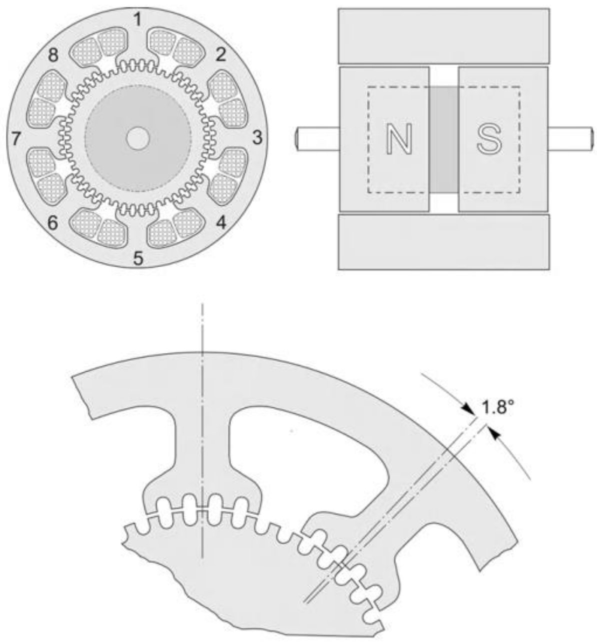

Fig. 1. Graphical description of a hybrid stepper motor [7]

important for the computation of the stepping angle). In the upper right corner of Fig. 1, we can see a section from the side view of the stepper motor, and we can see that inside the rotor, which is composed

of two cups, there is a permanent magnet. This permanent magnet has a uniform orientation along the axis of rotation, thus its magnetic field intersects the teeth on the stator.
The step angle is given by the following formula:

$$\theta_{step} = \frac{360\,°}{N_{rotor\ teeth} * N_{stator\ phases}} \quad (1)$$

For a common hybrid motor, such as a NEMA 17, used in a lot of commonly used 3D printers, the rotor has 50 teeth on each cup, which are rotated one to the other, with an angle equal to half a stepping angle (this is due to the aligning tendency of the teeth on the rotor to the ones on the stator), which makes for a total of 100 teeth on the rotor. Usually this kind of motor has two phases connected to 8 stator poles (4 poles per each phase) thus we get the common stepping angle of 1.8° or 200 steps per full revolution of the motor.
It can be seen that in order to rotate the rotor a certain amount, the stator coils needs to be energized in a certain order that would tend to align the teeth in the correct position. In order to do this, usually a microcontroller is paired with an integrated circuit driver, which switches the current to the correct phase, thus we see that these types of motor, the stepper motors, need to have intelligent electronic devices accompanying them.
Coming back to Fig. 1, we can see in the left upper corner the front section of the hybrid stepper motor. As stated earlier, this motor usually has two phases and the coils that make up these windings are the following:

- Phase A : Coils 1, 3, 5 and 7
- Phase B : Coils 2, 4, 6 and 8

When Phase A is energized, the coils opposite (1 and 5) form a north pole whereas coils 3 and 7 form a south pole. The teeth on the north side of the rotor tend to align to the south pole created by the coils, and the teeth on the south side of the rotor tend to align with the north pole created. When the teeth tend to align themselves, phase A is switched off and phase B is energized either positively or negatively, depending on the direction of rotation wanted [7].
Thus we can observe that for the correct functioning of the motor, the phases needs to be energized in the sequence A+, B-, A- and A+ which gives a clockwise rotation of the shaft. For an anti-clockwise direction of rotation the phases should be energized as A+, B+, A-, A+ [7].

2.3. Control circuit

The usual control circuit is made out of a microcontroller, a supply source, a motor driver and the stepper motor as it can be seen in the following image.

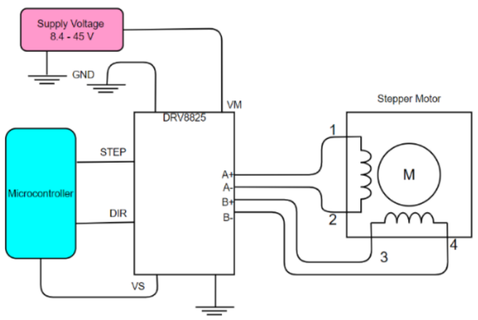

Fig. 2. Schematics of stepper motor control circuit

In Fig. 2, the driver represents the interface between the logic level, at which the microcontroller operates and the power level which represents the level at which the stepper motor works (usually 12V with 2A per each phase). This separation is needed, as to protect the microcontroller, who only just sends signals corresponding to the number of steps and the direction wanted. The driver does the real work, as it decides which phase to energize and at what rate to obtain the desired number of steps in the desired direction.

In the above figure, we have used the following notation:

- *STEP* : represents the input pin on the driver for the number of steps that the motor has to make
- *DIR* : represents the input pin on the driver for the direction of rotation of the stepper motor
- *VM* : represents the driving voltage which is usually in the range of 8.4 to 45 V
- *VS* : represents the logic power supply voltage which needs to have a value of 5V
- *A+, A-*, *B+, B-* : represents the output of the driver and their letters corresponds to the letters of the phases ends.

3. Simulation

3.1. Motivation behind creating an *FEA* analysis of a hybrid stepper motor

As stated in the introduction chapter, stepper motors are a companion to modern electro-mechanical devices, which by correct application of phase currents to the stator windings, these motors can be made to rotate in well-defined steps ranging down to a fraction of a degree per pulse [8].
Being able to analyze the complex working of such motors, can help with choosing the right motor for the specific application or it may help the electrical engineers in design better stepper motors, which work more efficiently.
Another reason in setting up this simulation is to be able to get the defining parameters of a stepper motor before it is being created. This way we can create a mechatronic model in Simulink where the stepper motor is defined as a black-box which only has the parameters obtained from the *FEA* analysis, thus making it easier for the mechatronic engineer to design a proper control system.

3.2 Model set-up

In order to create the simulation, it is necessary to create a correct 3D CAD model of the stepper motor with all the elements inside of it. For this, we used the capabilities of *Simcenter3D*, which allows its users to both design the motor and to also set-up the simulation inside the same environment.
To have a good understanding of what elements the stepper motor is composed of, an existing NEMA 17 motor was dismantled and measured, and based on it we created the following CAD model.
It can be seen that the stator has castellated poles, to better increase the accuracy of positioning of the

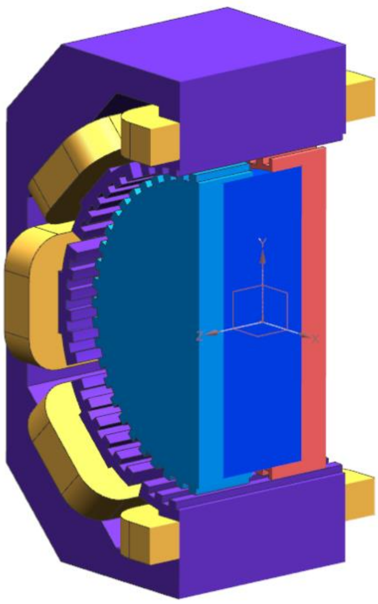

Fig. 3. CAD model of the stepper motor, created with the use of Simcenter3D

rotor. The stator coils are in number of eight and are represented with the yellowish colour. *Simcenter3D* allows to create the coils as simple blocks, and then assign them the correct parameters, such as number of turns, conductor area per turn and optionally the resistance and inductance of each coil. The

rotor is composed of two cups, each having 50 teeth on them, but the cups are rotated one with respect to another with an angle equal to half a step angle. Inside the cups, the permanent magnet resides, which has an uniform orientation of its magnetic field, parallel to the axis of rotation of the rotor.
Another element that it is not figured in the previous image is the airbox that surrounds the stepper motor. This is an important element in computing the magnetic field. Another important element is the remesh region, which represents the air gap between the rotor and stator. This is an important region as here are computed the magnetic forces and torque created.

3.3. *FEM* model set-up

In order to set-up the simulation, the CAD model must be divided into a mesh with specific materials, so that the solver can compute the correct parameters. In Fig. 4, the FEM model is presented.

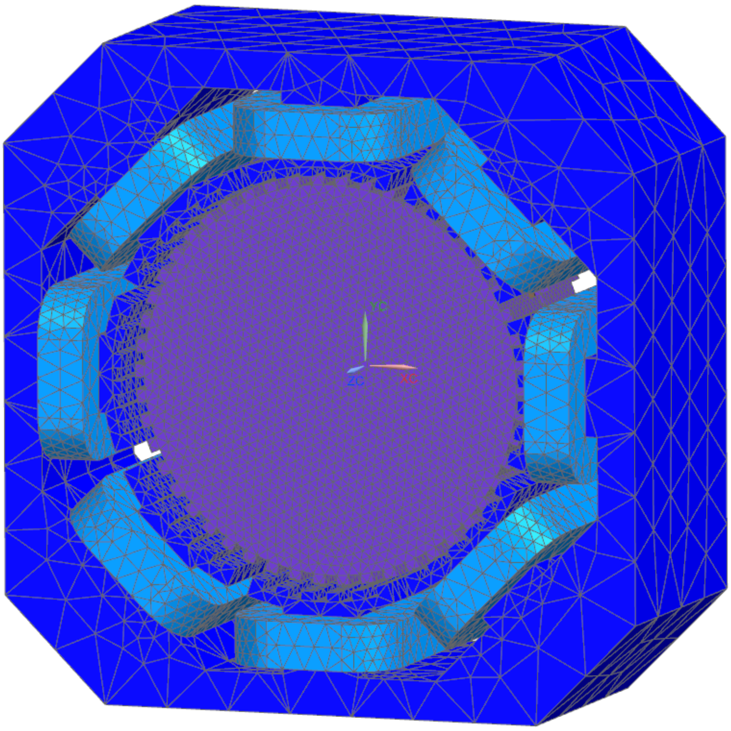

Fig. 4. FEM model of the stepper motor

Each mesh is represented with a different color, such that the properties of each material can be taken into account. The materials used are the following:

- M19 26 Ga : non-oriented steel for the stator and the two rotor cups
- N38 : neodymium – iron – boron (*NdFeB)* permanent magnet [9]
- Copper with a conductance of 5.77e7 Siemens / meter for the coils
- Air for the airbox and remesh regions.

These materials are commonly used in the creation of electric machines.
The remesh region is not represented again, because this region contains the biggest number of elements. This is due to the necessity of computational precision and due to the small air gap that exists between the rotor and the stator.
After setting-up the *FEM* model, the simulation model has to be set-up, in which the coils are connected according to the previous explanations, and the motion component, which is composed of the two rotor cups, the permanent magnet and the rotor airbox.

3.4. Simulation results

One important result obtained from the static simulation is that of how the teeth influence on the distribution of the magnetic field inside the rotor. Using the N38 permanent magnet, in the following image we can see the distribution of the magnetic field inside around the rotor.

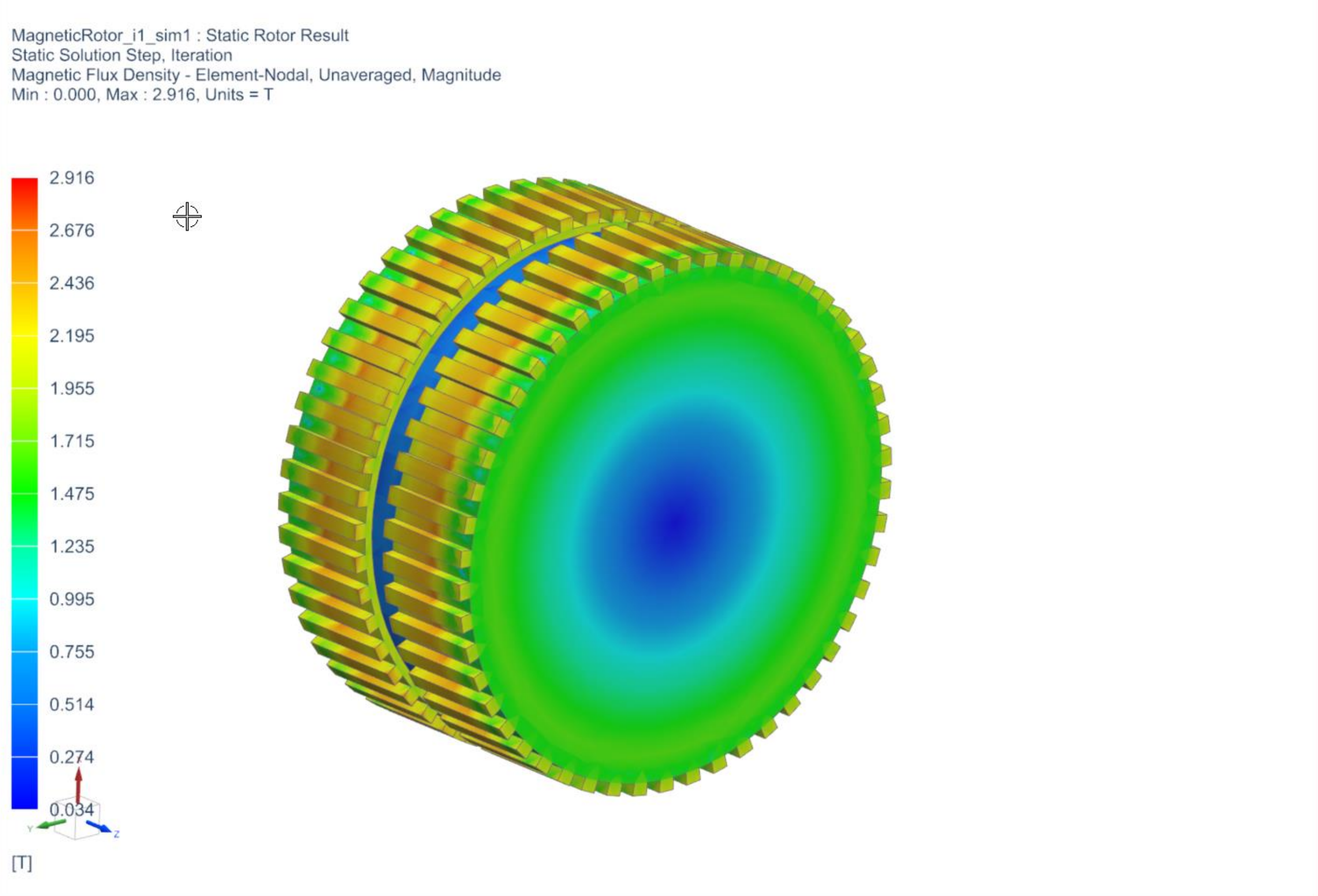

Fig. 5. Distribution of the magnetic field inside the rotor

It can be seen that the presence of teeth allow for a better flow of the magnetic field inside the rotor, thus making each teeth a pole. The magnetic field of the permanent magnet is directed along the Z-axis, represented in Fig. 5.
Another important result, obtained from the static solution, is that of the surface nodal forces distribution, as this one helps explain how the rotor teeth will be pulled into the correct position by the magnetic forces. These results are obtained by energizing the phase B coils, and by keeping the rotor fixed, thus the force acting on each element of the stator and rotor can be seen.
These forces are also relevant for further studies of acoustics problems, as these forces tend to modify both their magnitude and direction during the functioning of the motor. These forces create the noise usually heard during operation, and by careful study of them, coupled with physical measurements, improved control algorithms can be created.
In the following image, we can see that the greatest forces appear on the stator teeth of the stator poles that has the energized coils. Some forces also appear on the poles that are not energized, because the magnetic field flows to them as well, because the stator is made out of connected stator poles.

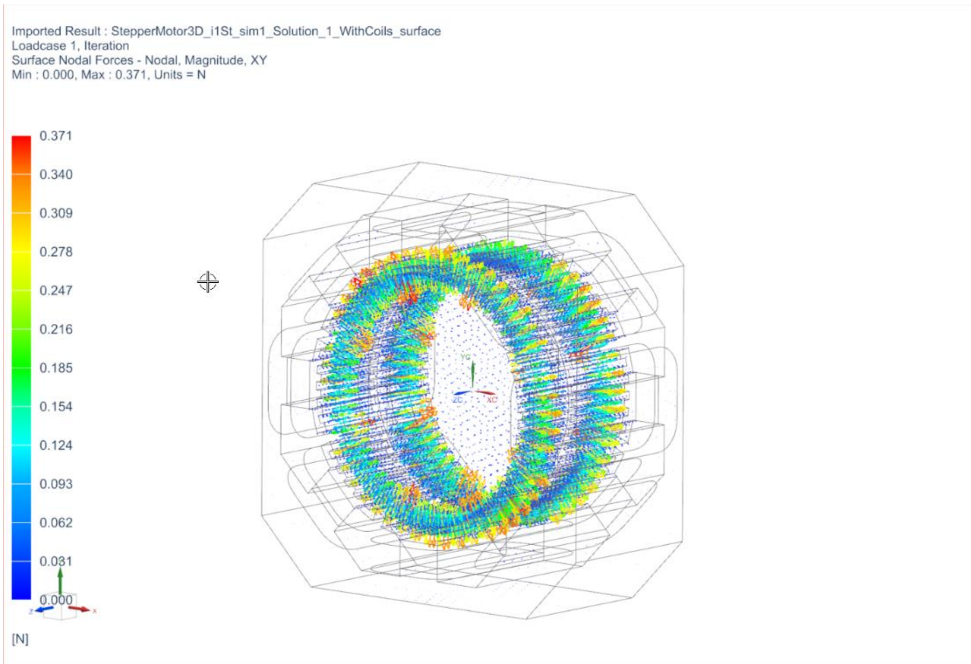

Fig. 6. Distribution of surface nodal forces on the stator

One important result, that represents the solution of the transient simulation, is the value of the back EMF. This constant, specific to a certain speed, represents one of the black-box parameters that can be used in a mechatronic simulation in Simulink.
This result is obtained by allowing the rotor to rotate with a certain speed and not energizing the coils. The non-energizing state of the coils can be modelled by connecting them to a current source whose output is null.

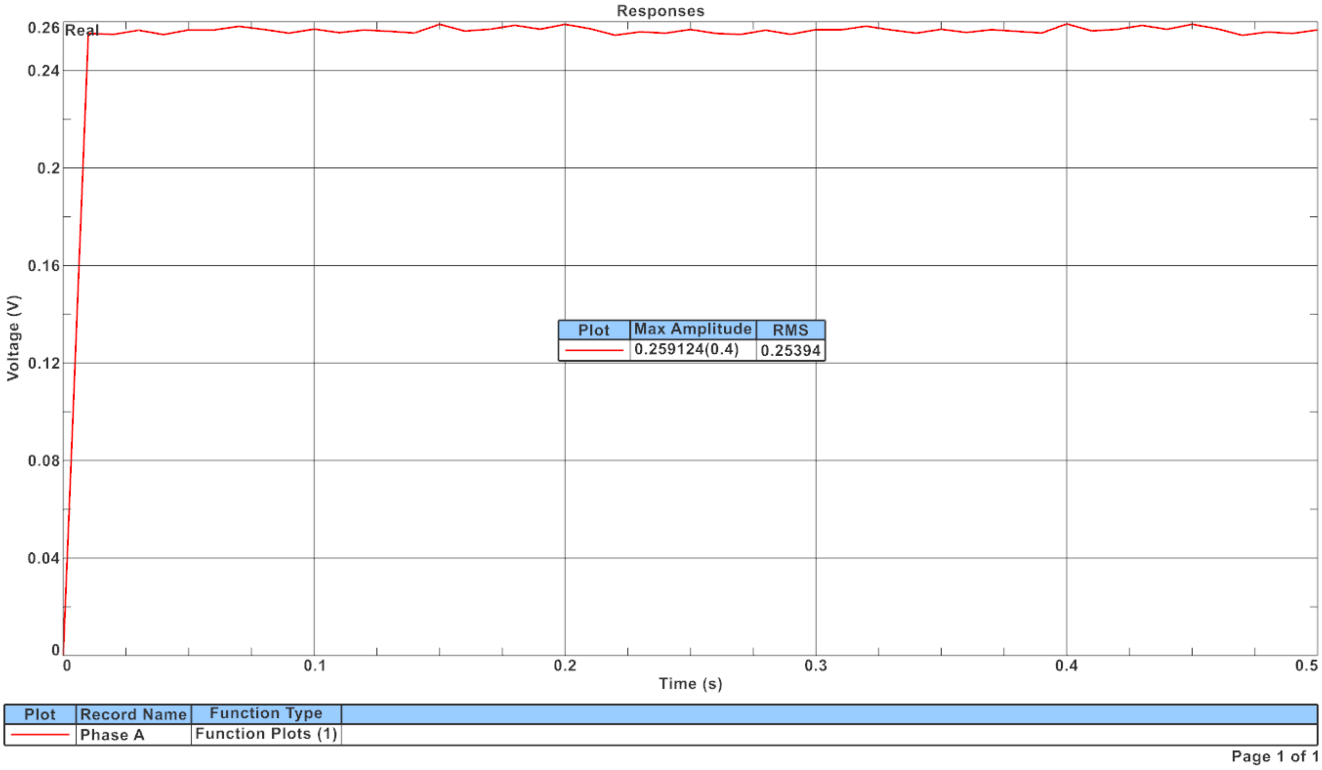

Fig. 7. Back-EMF corresponding to Phase A of the stepper motor

From Fig. 7, we can see that the maximum value of the back-EMF is equal to *0.259 V*. This parameter has an RMS value of *0.254 V*, and the peak value can be further used in the Simulink simulation.
This parameter is necessary to describe the functioning of the stepper motor, as it is governing the equivalent circuit of the stepper motor during constant operation, as can be seen in the following formulas [10]:

$$V_{supply} = iR + \frac{d\lambda(\theta)}{dt} \tag{2}$$

In equation (2) we used the following notation:

- V_{supply} : represents the voltage supply of a phase
- i : represents the current through the coils of the phase
- R : represents the resistance of the coils
- λ : represents the flux linkage through the coils, which is dependent of the rotation angle θ

From this equation, we can derive the exact differential equation that governs the functioning of the stepper motor:

$$V_{supply} = iR + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{dt} = iR + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{d\theta}\frac{d\theta}{dt} \tag{3}$$

The last term in equation (3) represents the back-EMF, which we will denote as ε, as can be seen in the following equation:

$$V_{supply} = iR + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{dt}\,\omega_{rotor} \tag{4}$$

Thus, from Fig. 7, we can obtain the motor velocity constant, which is defined as following:

$$K_v = \frac{\omega_{no\,load}}{V_{peak}} \tag{5}$$

In our case, this constant has the following value:

$$K_v = 48.5188\frac{Vs}{rad} \tag{6}$$

This is useful as the stepper motor has the following equivalent circuit [10]:

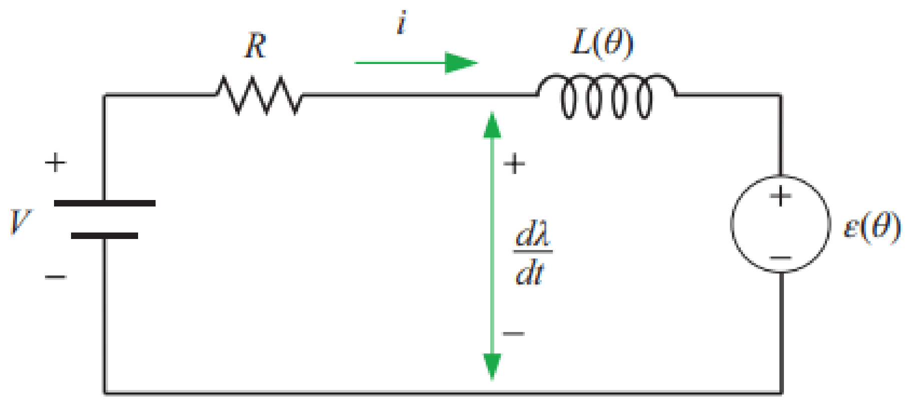

Fig. 8. The equivalent circuit for the hybrid stepper motor

This is an acceptable approximation of the stepper motor, as this type of motor is a type of brushless DC motor, during constant operation.

4. Conclusions

This paper is the basis for further *FEA* analysis of the hybrid stepper motor design, created to give the authors a better understanding of the electromagnetic phenomena that happens during the operation of said electric machines.
Further improvements are to be made, especially in the field of comparing the results obtained with physical measurements, which will help in the future to create better digital twins of real-world applications. This is an important step in the development of mechatronic systems, as it will allow the engineers to create and test different rigs, in the phase of design such systems.
One point that we think that will be of important study in the future, is the acoustic simulation, which will give an insight into how the stepper motor creates vibration and thus we can come up with better solutions to counteract its negative impacts on the functioning of systems that employ such electric machines.

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