Simulation of an Organic Magnet in Switched Reluctance Motor Application

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Abstract

A comparison method (Increased Current Factor per displacement) is developed to help further researches and design consideration for Organic Electric Motors and Hybrid Organic-Metallic Electric Motors. One specific polymer referred to as "PhanPol2", has been tested in different configurations for the Switched Reluctance Motor. This magnetic polymer was used to develop a comparison method and to provide data from the first simulations of an organic magnet in electric machines applications. Considerations on using the Increased Current Factor in the design stage is presented, suggesting a control system and design tweaking to lower the exciting current of the coils in Hybrid Organic Stator Motors. Ideas for further research on organic magnets in electric machines are presented as well as discussion on the importance of using these materials in motors and generators. This is still a new field and certainly, more research is needed in the future for real-world applications, both on the design and, especially, the chemical perspective.

Introduction

The addressed research aims to simulate a Switched Reluctance Motor (SRM) which working is based on organic magnets. In more detail, the usage of organic- and molecule-based magnets instead of conventional ferromagnetic materials (e.g. Cobalt, Iron, etc.) in the rotor and stator of the motor is intended. Hybrid configurations are also the focus of this research (where the rotor or the stator is organic).
Organic conductors are not investigated. Thus, in the simulations, the coils will not be organic based.

Different research is already taking place about the usage of organic electronics in different applications, and some of them are already being used in hodiern society (e.g. OLEDs in mobile phones and other applications). Usually, when talking about organic materials that show magnetic properties the operation point is a very low temperature (below 77 K) or not stable at room temperature [1], but recent researches have presented new materials and research techniques, that show ferromagnetism and stability at room temperature [2] [3]. Also, hybrid materials (metallic and organic) are available in the literature, but not the focus of this research (e.g. [4]).

The usage of organic materials in motor applications can have different benefits for the motors and the environment. Currently used magnetic materials are fabricated with high energy demanding metallurgic methods, and some of them possess elements limited in supply (rare earth metals) [5]. However, organic magnetic materials can be produced with lower energy demand and can be annealed at lower temperatures [1] [2] [3]. This means that less CO_2 is emitted in the production of the organic magnets compared to their metallic counterpart.
Also, these materials are much lower in density (example shown in Methodology Section). Organic magnets probably also have higher resistances (as they have a polymer nature), and thinner BH curves, leading to lower losses. Some of them are also flexible so they might even be useful in new designs for certain types of motor (e.g., linear motors).

In few words, achieving an organic electric motor with similar, if not equal, properties to their non-organic counterpart would mean, fewer earth resources used, simpler production methods, less energy consumed in production, less CO_2 emitted in the atmosphere, lighter motors, lower losses, lower cost, and the possibility to introduce flexibility if needed.
Moreover, the scientific community is confident that in the future organic magnets will even be more magnetic than metals.

The report is organised as follows. The used methodology for acquiring and comparing data is presented first. Then, the acquired data is shown and discussed, leading to conclusions and ideas for further research.

Methodology

All simulations for this research are performed using Finite Element Analysis, in specific using the software EMS from EMWorks [6].

After a long comparison and selection of organic materials, only the use of “Polymer 2” as described by Phan et al. [2] is chosen, and it is referred to as “**PhanPol2**” in the research and Supplementary Notes. This decision is driven by the fact that more data is available for this material compared to others, plus, it is stable at room temperature. The density of the material is approximated to be 2.207 g/cm^3. Supplementary Notes contain have more information on how the density and BH curve of this material is calculated.
For the non-organic materials, M19 and M36 silicon steels and CoFe Hiperco 50 are chosen, as their data is available in the EMS material library, and the material density can be found in [7]. It is decided also to compare **PhanPol2** to Soft Magnetic Composites (SMC); in specific, three materials by Höganäs AB, since they provide full magnetic data and density (among other values). The used SMCs are Somaloy 110i 1P, Somaloy 700 3P, Somaloy 130i 5P [8] [9] [10]; in this way, different grade materials are studied.

The comparison method used in the research is based on the same motor design, the only changes are on the material. For the design, since it is not the concern of this research, the basic example from EMS, which is a 6/4 pole configuration, is used (shown in Figure 1). For the coils copper was chosen as material, the number of turns was 360 per phase (each phase is 2 coils), and an AWG value of 30. Hence, this research ignores the improvements that a design based on the specific material could have [5], or how other design considerations could affect the motor [11]. Thus, the only thing changing (and on which the comparison is based on) is the density in the rotor and the BH curve of the material in both rotor and stator, and the current applied in the coils.

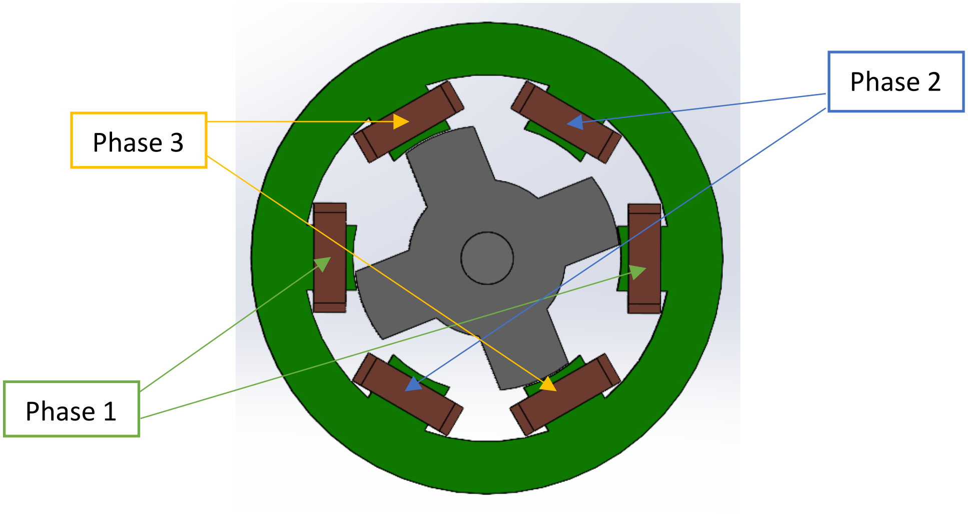


Figure 1: SRM model used in the research

What is compared between motor models is the displacement reached by a full metallic motor at an applied current in a small amount of time, and how much current more is needed by the organic materials to achieve a similar angular displacement. The **Increased Current Factor per displacement** is calculated with Equation (1).

$$X\ IC\ Factor = \frac{hybrid\ or\ full\ organic\ coil\ current\ per\ Y\ displacement}{full\ metallic\ coil\ current\ per\ Y\ displacement} \tag{1}$$

where:

- *X* is the type of IC factor:
  - **Organic Increased Current Factor (OIC Factor or OICF)**, this will refer to a full organic motor
  - **Hybrid Rotor Increased Current Factor (HRIC Factor or HRICF)**, this will refer to a hybrid solution where the rotor is the organic part or Organic Rotor Hybrid Motor
  - **Hybrid Stator Increased Current Factor (HSIC Factor or HSICF)**, this will refer to a hybrid solution where the stator is the organic part or Organic Stator Hybrid Motor
- *Y* is there to indicate the same displacement obtained for the motor in the test/simulation.

Of course, we would like this factor to be as low as possible, ideally 1 (meaning that the organic/hybrid motor moves like the metallic one used for comparison).

The first tests are run only with Phase 1 on, for a time of 0.015 seconds. Only for M19, a longer 3-Phase test is performed. The simulation parameters and methods are described in more detail in Supplementary Notes.

From the 1-Phase Tests, the IC factors are evaluated. The way these factors are calculated is:

- A full metallic motor test is performed at 0.4 A, and the peak displacement at 0.015 seconds is taken as consideration parameter.
- Then, “trial and error” method for different coil currents of the hybrid/full-organic motor is used to find a peak displacement value at 0.015 seconds similar to the full-metal counterpart (Supplementary Notes - Figure S4).
- After alike values are found for the peak displacement, a comparison of the whole curve is made (Supplementary Notes - Figure S5 & S6; e.g. Figure 5a).

- At this point, the IC Factor is calculated based on the found current value.

Results & Discussion

The OICF value in all scenarios is greater than 100. Moreover, the torque has odd behaviour that might need more research. Thus, with PhanPol2, and more generally for organic magnets nowadays, it is not possible to design a full organic motor, as it needs unreasonable exciting current to show a small movement. An example of the displacement of a full PhanPol2 motor at 40 A is shown in Figure 2. More information can be found in Supplementary Notes.

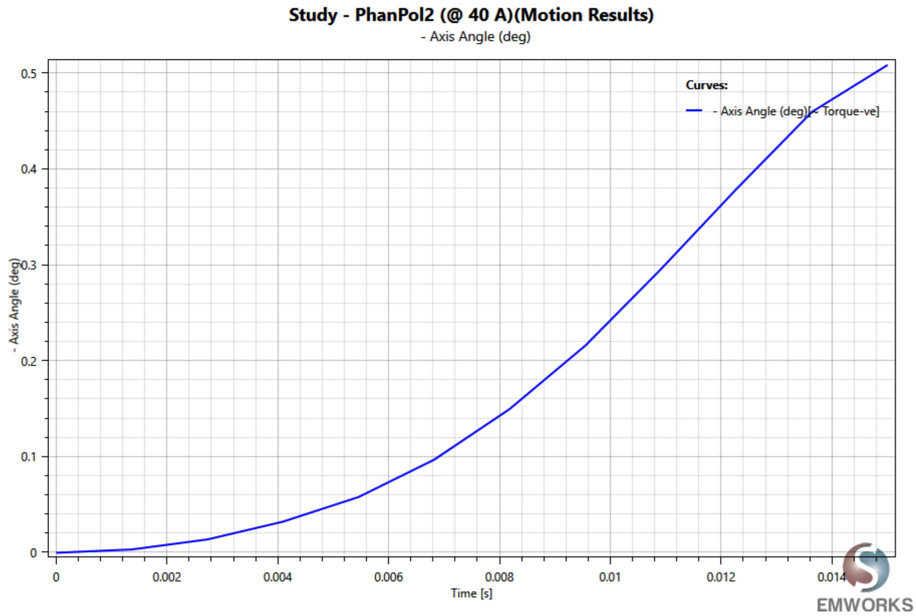


Figure 2: Angle Displacement in PhanPol2 full organic motor at 40 A

The HRICF value is "Not Defined" as the torque behaviour is odd, as it changes from negative to positive really fast (Figure 3). This does not allow a clear comparison to the metallic counterparts, where the torque stays negative. More information can be found in Supplementary Notes. More research is required for this hybrid motor version, especially for the torque.

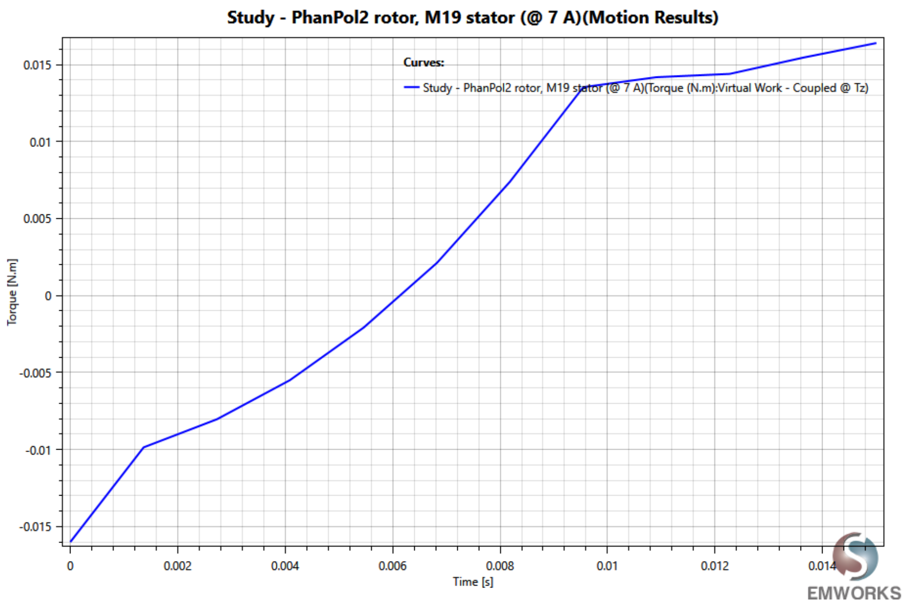


Figure 3: Torque in Organic Rotor Hybrid Motor test at 7 A

The Organic Stator Hybrid Motor tests do not show the same torque problems as the other two solutions. The HSICF calculated values are shown in Figure 4.

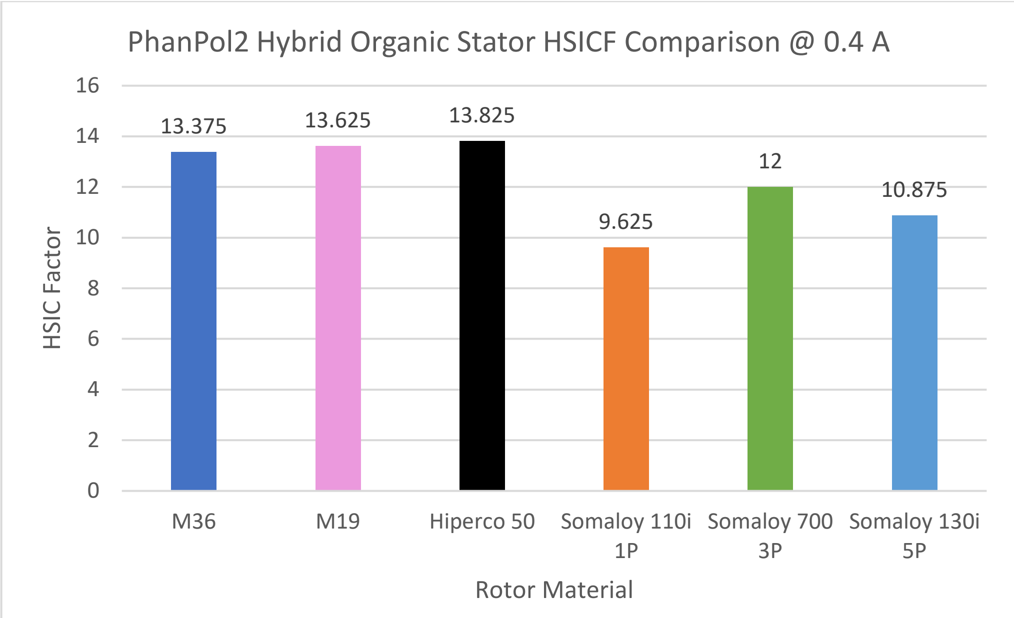
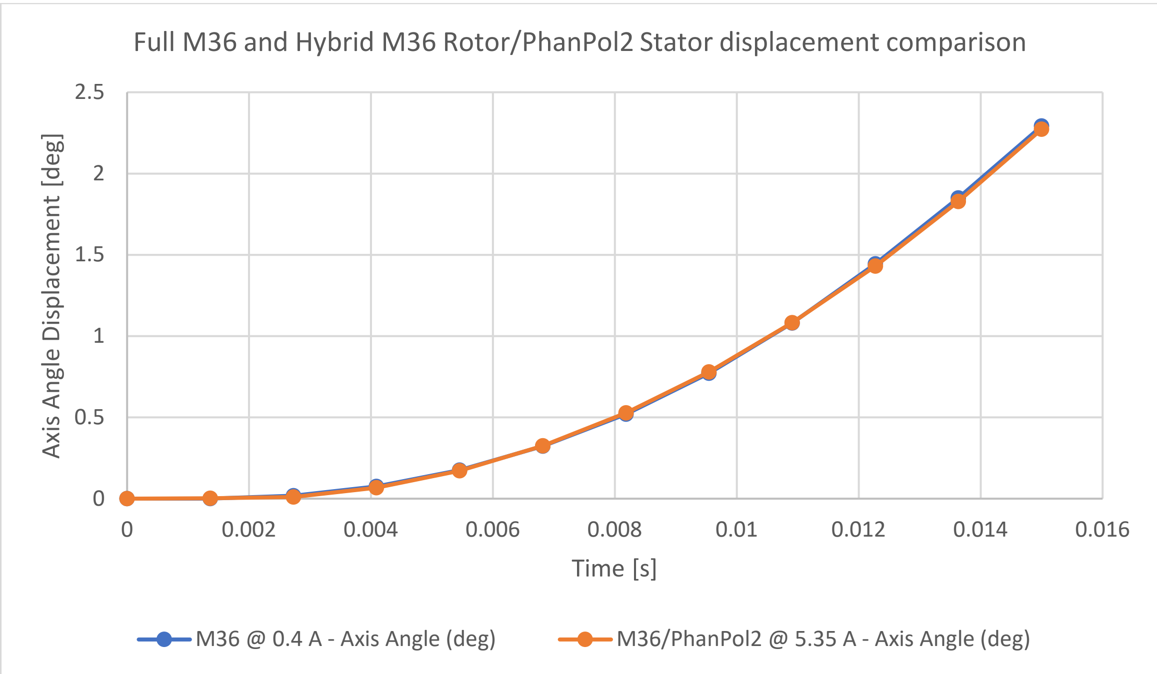
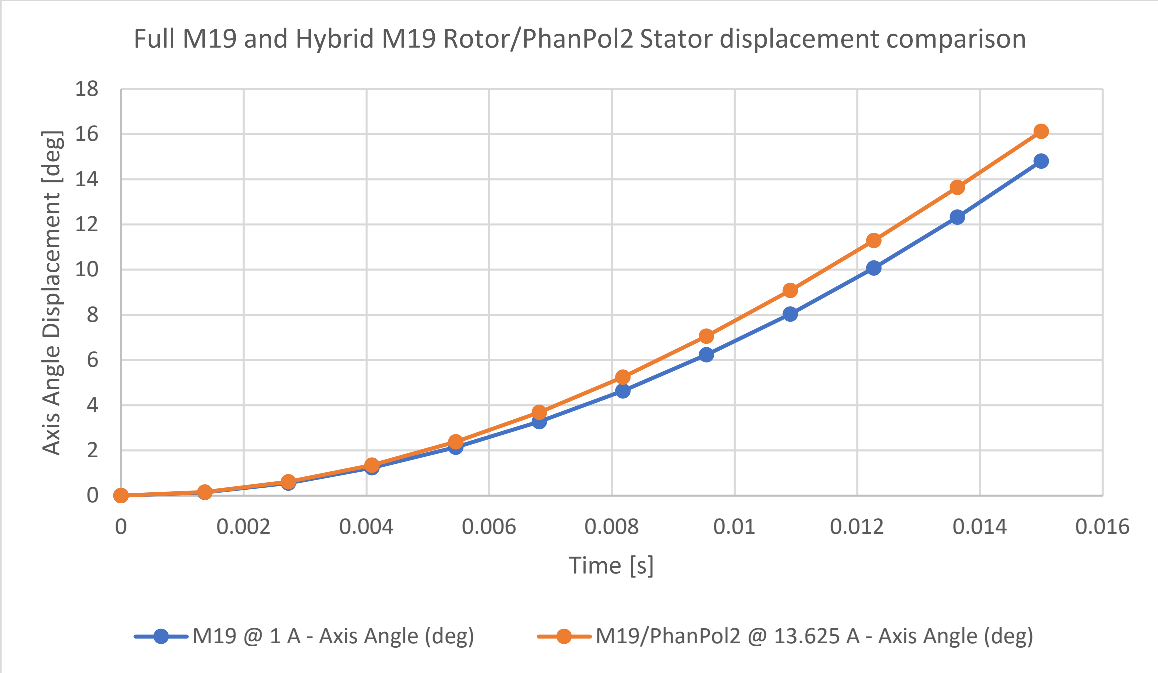


Figure 4: HSIC Factor - Comparison of different metallic materials

However, in Figure S4 (Supplementary Notes) it is visible that the curves tend to follow a non-linear increase in displacement from an increase in current indicating already that the IC Factor is not linear. This is also confirmed by the fact that a subsequent test of M19 at 1 A and its hybrid stator version at 13.625 (Figure 5b) shows that the higher the current the lower the HSICF value (as in this case the hybrid acceleration was higher).



(a)



(b)

Figure 5: Hybrid/Metallic displacement comparison for M19 at same HSICF value but different base currents, 0.4 A (a) and 1 A (b)

However, it is probably for the best interest to keep the IC Factor based on a low comparison current (e.g. 0.4 A), as this represents the worst-case scenario, i.e., the highest HSICF.

After the 1-Phase Tests, longer 3-Phase tests are run for M19 motors (as described in Supplementary Notes). The angle displacement is shown in Figure 7. An example of the Magnetic Flux Density in the motor during a 3-Phase Test can be seen in Figure 6, and a GIF version of all the tested timesteps for this simulation are available online [12].

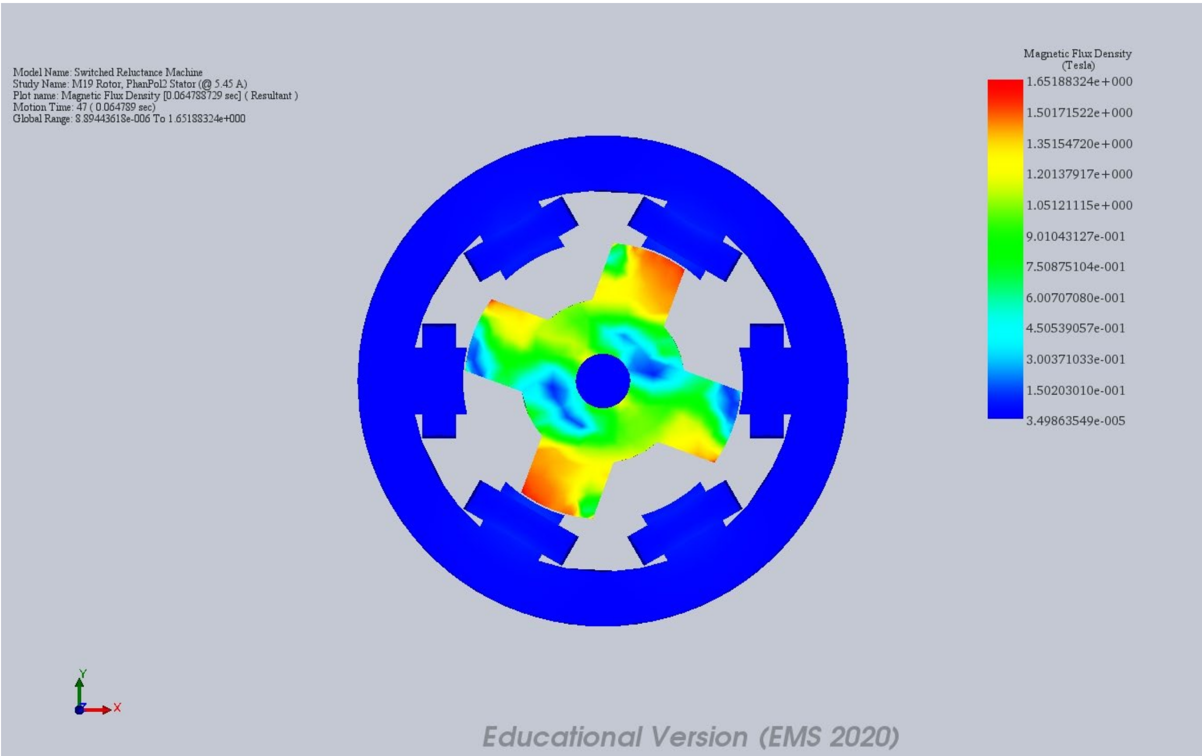


Figure 6: Magnetic Flux Density for "M19 Rotor, PhanPol2 Stator @5.45 A" study at 47th time step

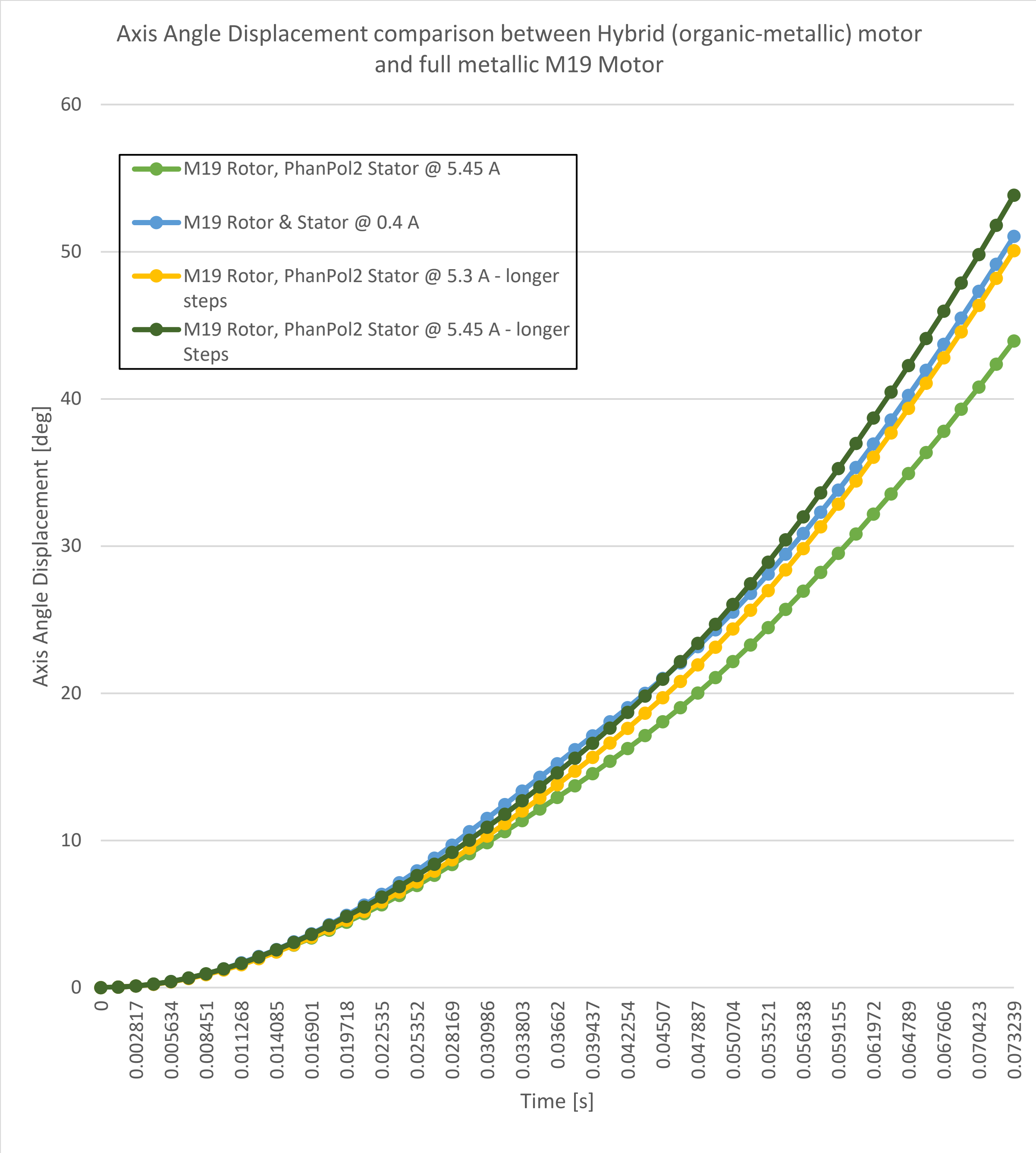


Figure 7: Axis Angle Displacement comparison between Hybrid (organic-metallic) motor and full metallic M19 Motor

The conclusions that can be made looking at Figure 7 are interesting. First, with the HSICF suggested value (5.45 A), under the same control conditions used with the full M19 one, the performance is worse. In the first time steps the curves overlap, but as more time passes, the acceleration of the hybrid motor results slower than its counterpart. However, by changing slightly the control pulses an even higher acceleration was achieved.

Also, it is clear that with an appropriate calibration of the control system, a lower current value than the one suggested by the IC factor can be used to achieve a similar acceleration.

In addition, in order to show how the current and the speed of the motor are related in the bigger picture, a longer simulation with MATLAB's default Switched Reluctance Motor is run, shown in Figure 8.

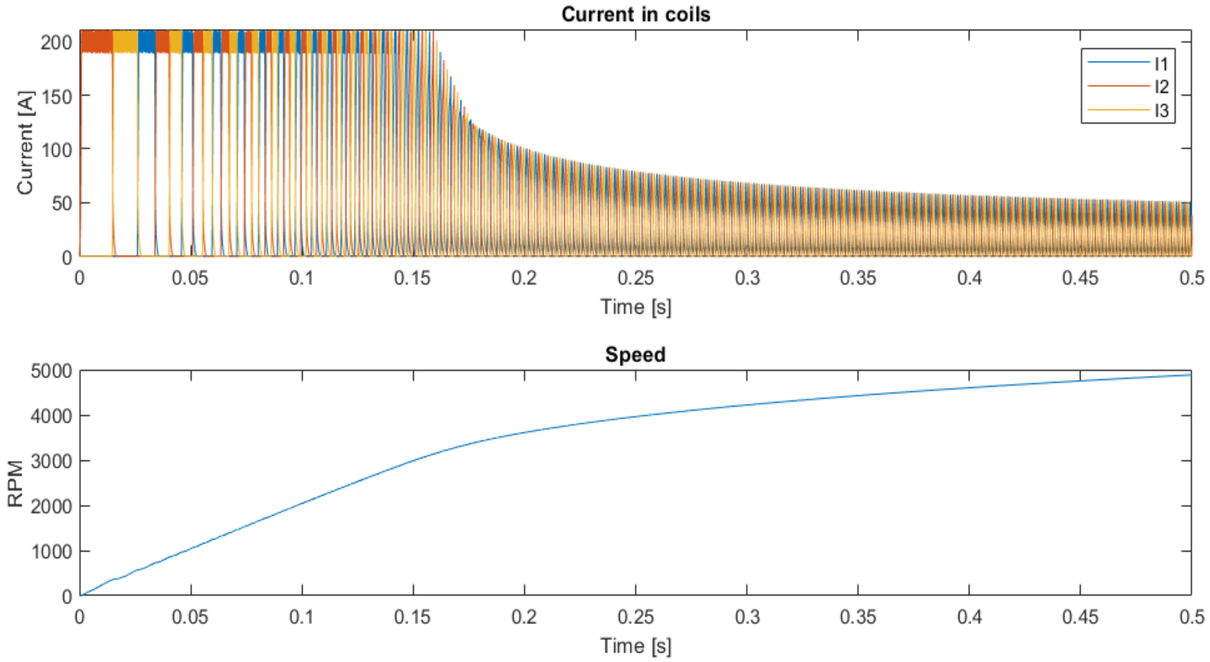


Figure 8: MATLAB's SRM simulation

Thus, for higher speeds, the current in the coils goes down abruptly, and this should be taken into consideration when designing in the future a stator hybrid motor.

This indicates that the IC Factors are indeed important for a first consideration and comparison of organic materials. But tweaking the design and the control system, a lower current value can be used to achieve similar performances. Also, the FEM analysis was performed in a start-up condition. More tests similar to the one in MATLAB need to be performed to understand better how the Organic Stator Hybrid motor behaves in the longer term.

Conclusions & Further Research

A comparison method for Organic Materials in Switched Reluctance Motor applications has been developed and applied. It has been shown that IC factors can be used as a rough comparison method, and as an indication of the coil exciting current value needed for early design stages.
It has been shown that a full organic motor with hodiern organic magnetic materials is not feasible, as it has in all scenarios an OICF greater than 100.
Some Organic Rotor Hybrid Motor tests were run, but the odd behaviour in torque did not allow clear comparison with the metal motors. Hence, HRICF is not defined in this research.
Organic Stator Hybrid Motor simulations were shown, and their HSICFs have been declared.
Various tests showed the non-linearity of the IC Factor, but a calculation of the ICF at low current has been suggested, as it represents the worst-case scenario. It has also been shown that carefully designing the 3-Phase control, a lower current than the one suggested by the ICF is possible to use achieving a similar acceleration to a full-metallic one. For informational purposes, it was also shown how the current behaves with the motor speed.
It has been shown that at present-day an Organic Stator Hybrid Motor might be possible to build. However, more simulations and tests are required to achieve the best design and control system for it. The use of this motor would undoubtedly be less-power efficient, but also much lighter given the low density of the organic magnet. For these reasons, it might or might not find any real-world applications.

Besides design and control research on the motor, and with other types of motors, more research is needed on all other parameters not considered here, e.g., mechanical strength, losses, behaviour at lower temperatures, etc.
Moreover, it might be interesting to research the use of this material as a rotor in a generator. The much lower density in the rotor should make it move faster under same torque conditions compared to a metallic counterpart. However, higher rotational speed in the rotor might not make up for the weaker magnetization of the polymer.

Supplementary Notes

Available at: https://www.researchgate.net/project/Simulation-of-an-Organic-Magnet-in-Switched-Reluctance-Motor-Application

Acknowledgement

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I wish to thank ElectroMagneticWorks, Inc. for granting me access to their software EMS [6].

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Simulation of an Organic Magnet in Switched Reluctance Motor Application – Supplementary Notes

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Date: 23/07/2020

Contents

PhanPol2 Data

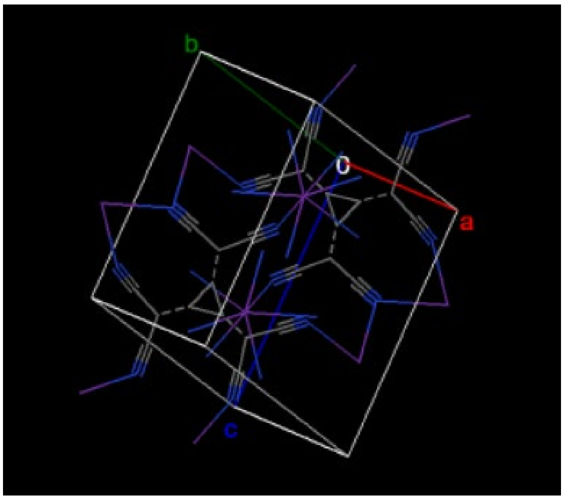
With PhanPol2 in the research, I refer to “Polymer 2” from [1] by Phan et al.
I needed to calculate the density of this material (as it is not in any section of the research).

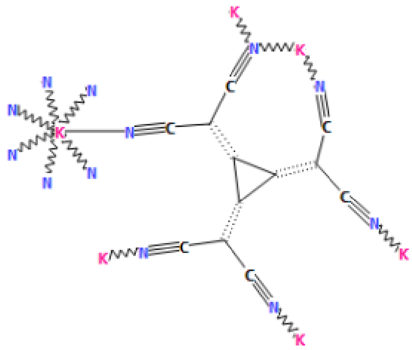
To calculate the density I used the crystallographic data of Polymer 1a (from which Polymer 2 depends on) as uploaded by Hoa Phan in the Cambridge Crystallographic Data Centre [2].
This gives the following data for the unit cell:

- a 6.585Å b 8.815Å c 11.172Å
- α 104.61° β 94.21° γ 107.21°

giving a unit cell volume of 591.71 $Å^3$ = 5.9171 * 10^{-22} cm^3 (calculated with [3]).

The first assumption is that the number of molecules per unit cells is 2. This assumption was made by the fact that in Figure S1a it is possible to see two chemical diagrams (as seen in Figure S1b) of the molecule.



(a)


(b)

Figure S1: (a) 3D Unit Cell Model, (b) Chemical Diagram [2]

The last problem was the absence of data useful to calculate the molecular weight. What was in the research is that for Polymer 1a the article referred to [CN6CP]K^+, and CN6CP in the article is also named as "*hexacyanotrimethylenecyclopropanide*", which according to another research by Miller et al. [4] has chemical formula $\{C_3[C(CN)_2]_3\}^-$. Then, counting the 6 potassium elements seen in Figure S1b, I assumed the chemical formula $\{C_3[C(CN)_2]_3\}K_6$, which weights 462.762 g/mol.

Using the equation suggested by Dutta in [5] to calculate the theoretical density, I got a density of 2.597334 g/cm^3. Considering then the total pore volume of 0.0681 cm^3/g, the final density results in 2.207 g/cm^3, which is the one used in SolidWorks and used to convert the magnetic data.

To use the material in EMS I need the BH magnetic data. However, it was available only the MH curve in a graph. I managed to get some valuable points to reconstruct a curve (shown in Figure S2 & Table S1).

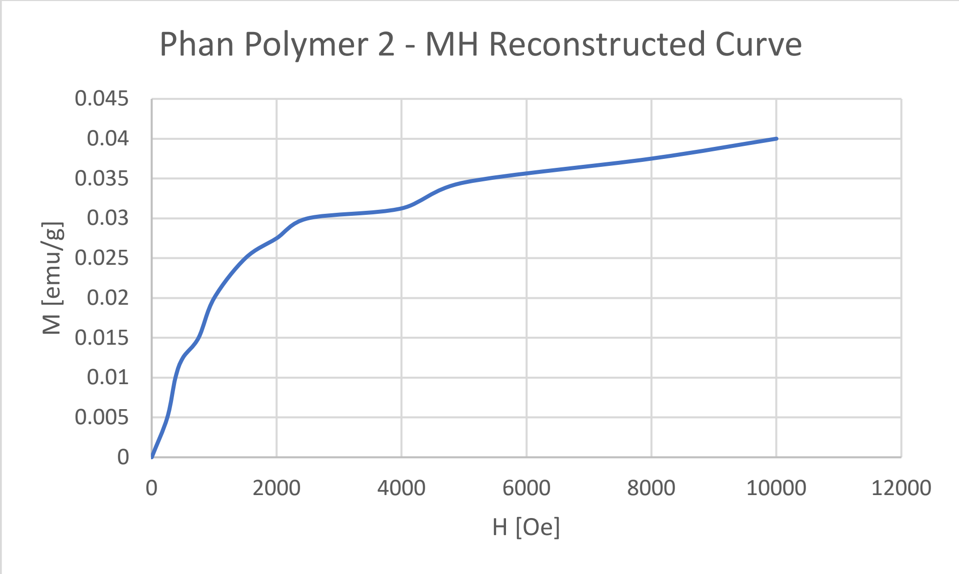


Figure S2: PhanPol2 - MH Reconstructed Data

This data was used to calculate the BH curve (shown in Table S1 & Figure S3), used then for the simulation.

Table S1: PhanPol2 data

Phan Polymer 2						
B [T]	H [A/m]	H [Oe]	M [A/m]	M [emu/cm^3]	M [emu/g]	D [g/cm^3]
0	0	0	0	0	0	2.207
0.025013867	19894.37	250	11.035	0.011035	0.005	
0.038027734	30239.44	380	22.07	0.02207	0.01	
0.050034667	39788.74	500	27.5875	0.0275875	0.0125	
0.075041601	59683.1	750	33.105	0.033105	0.015	
0.100055468	79577.47	1000	44.14	0.04414	0.02	
0.150069335	119366.2	1500	55.175	0.055175	0.025	
0.200076268	159154.9	2000	60.6925	0.0606925	0.0275	
0.250083202	198943.7	2500	66.21	0.06621	0.03	
0.400086669	318309.9	4000	68.96875	0.06896875	0.03125	
0.500095682	397887.4	5000	76.1415	0.0761415	0.0345	
0.800104002	636619.8	8000	82.7625	0.0827625	0.0375	
1.000110936	795774.7	10000	88.28	0.08828	0.04	
Permanent Magnetization						
Br [T]	Hc [A/m]	Hc [Oe]	Mr [A/m]	Mr [emu/cm^3]	Mr [emu/g]	D [g/cm^3]
0.030024961	23873.24	300	19.863	0.019863	0.009	2.207

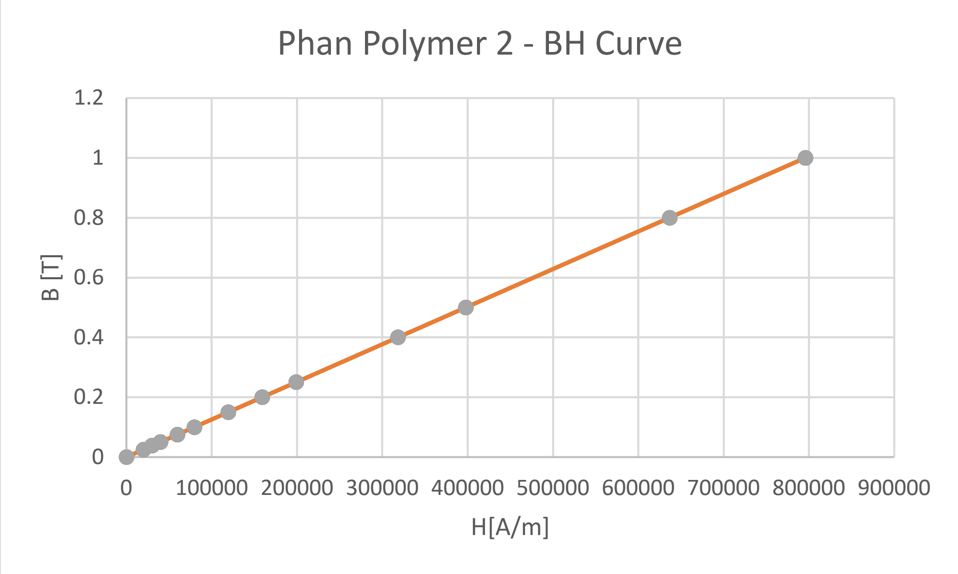


Figure S3: PhanPol2 - BH curve

Other Materials Data

For Electrical Steels M19 and M36, and CoFe Hiperco 50, the magnetization data was taken from the default EMS material. Their density was retrieved online [6].

For the SMC components, I decided to take three Höganäs AB compounds [7] [8] [9]. One from each family of their product, which relate as:

- 1P baseline
- 3P mechanical strength and permeability
- 5P lowest losses

For **1P** I took **Somaloy 110i** (to be an example of **Fine Particles #200**), it has the lowest density between all the offered SMC by this company.
For **3P** I took **Somaloy 700** (to be an example of **Large Particles #40**), it has the highest density between all the offered SMC by this company.
For **5P** I took **Somaloy 130i** (to be an example of **Medium Particles #100**).
The magnetization and density values were taken from their respective datasheet.
From Table S2 it is possible to see the density values used within SolidWorks for the simulations.

Table S2: Density of selected materials for the research [6] [7] [8] [9]

Material	Density value [g/cm^3]
Silicon Steel M19	7.402
Silicon Steel M36	7.018
CoFe Hiperco 50	7.845
Somaloy 110i 1P	7.260
Somaloy 700 3P	7.570
Somaloy 130i 5P	7.440
PhanPol2	2.207

1-Phase Tests

HSIC Factor

The 1-Phase test was more of a trial and error type. The coils of the full metallic motor were excited at only 0.4 A for 0.015 sec.

Then, in the hybrid (organic stator) version, starting from 4 A, different reasonable trials were performed until the peak displacement at 0.015 seconds was almost equal. From this current value, I would calculate the IC Factor.

From my trial and error data (Figure S4) it is visible that the curves tend to follow a non-linear increase in displacement from an increase in current indicating already that the IC Factor is not linear (for M19 there is more data available even if not visible in the graph as it was also tested at 0.4 and 7.1 A).

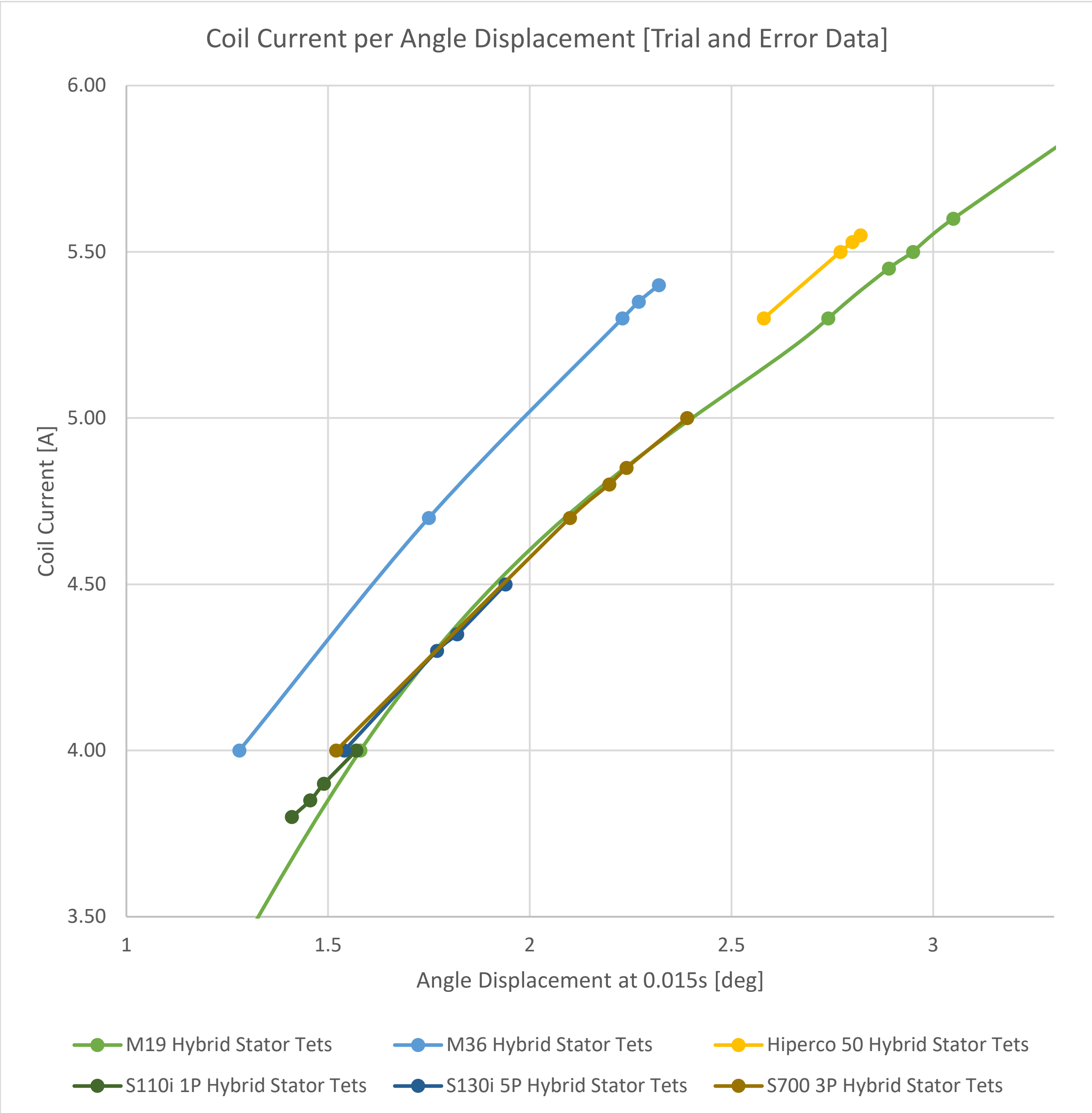
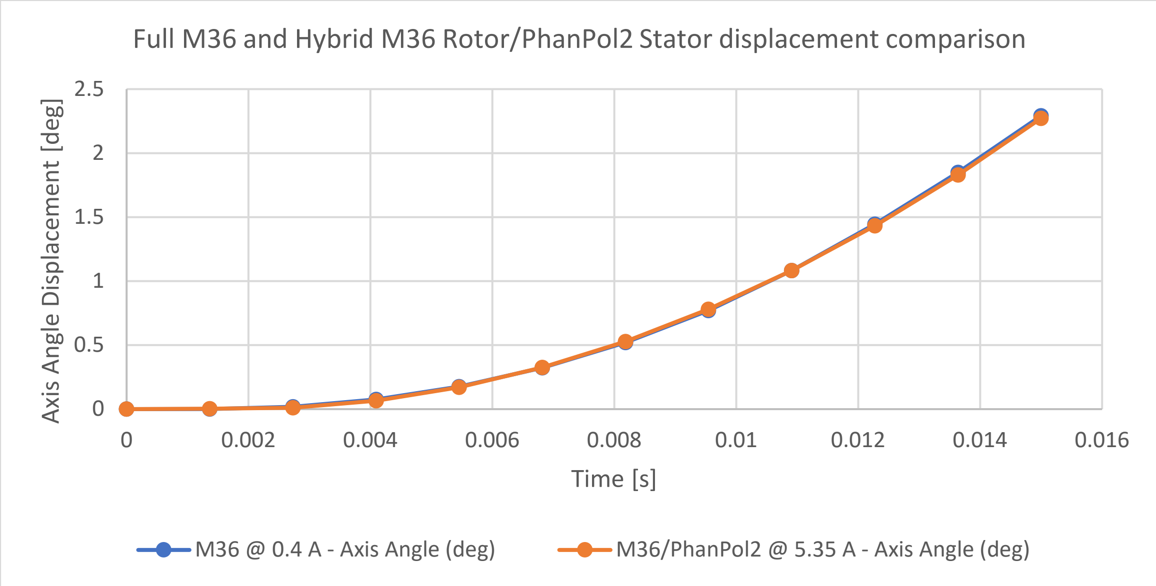
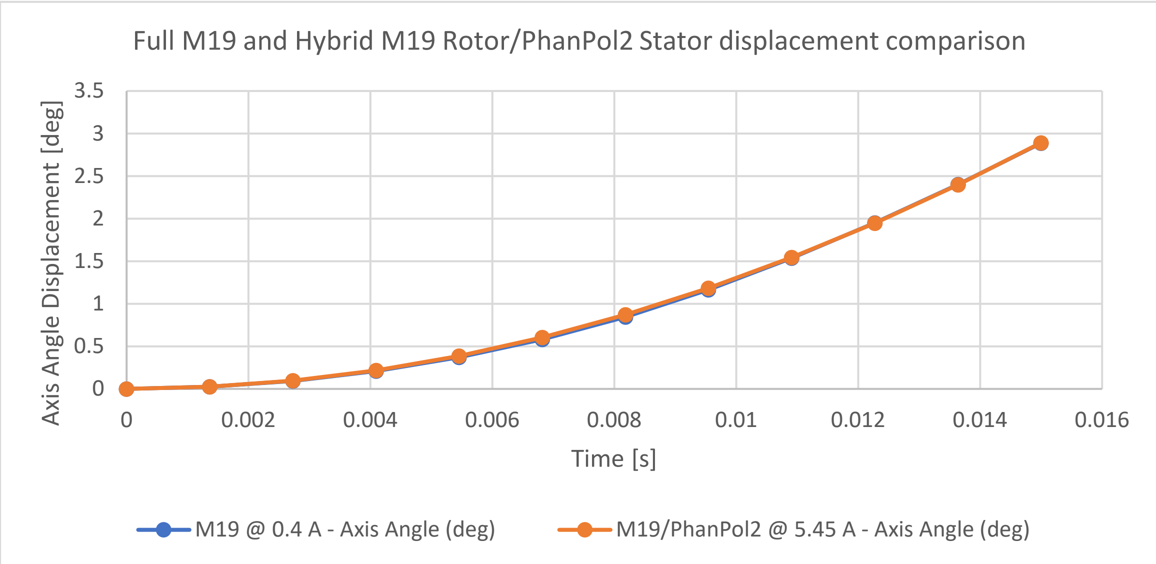


Figure S4: Trial and Error Curves

After the Peak Value at 0.015 seconds was compared, I compared all the 12 points I had from the FEM analysis (Figure S5 & Figure S6), to see if the curves had also a similar slope (and not only the final angle displacement). As it is possible to see the curves have an almost equal slope.



(a)



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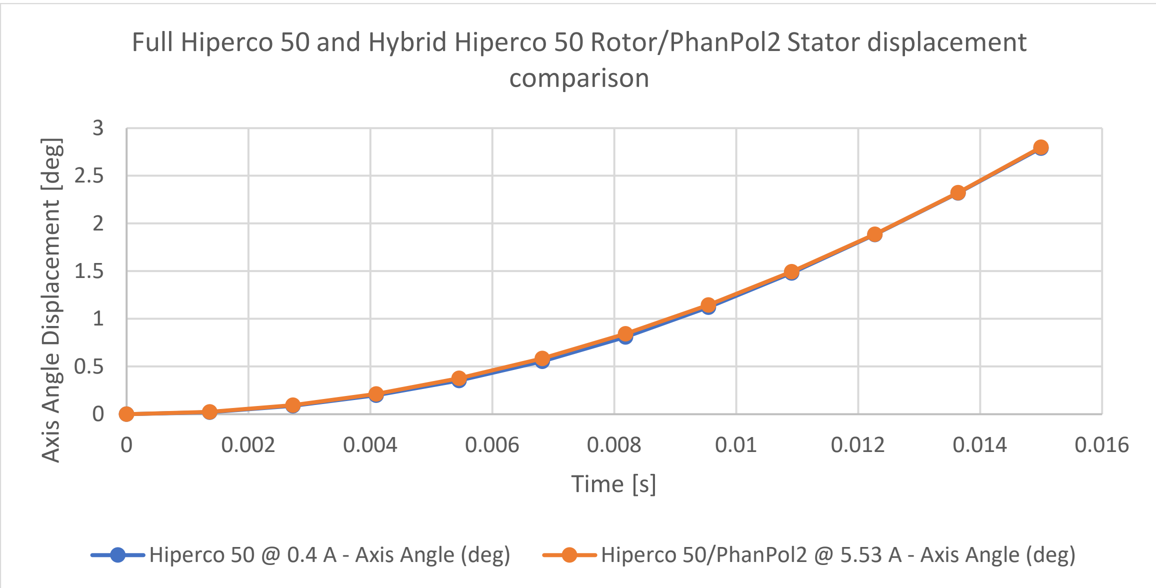

(c)

Figure S5: Displacement Comparison Data, Full Metallic/Hybrid Stator Organic

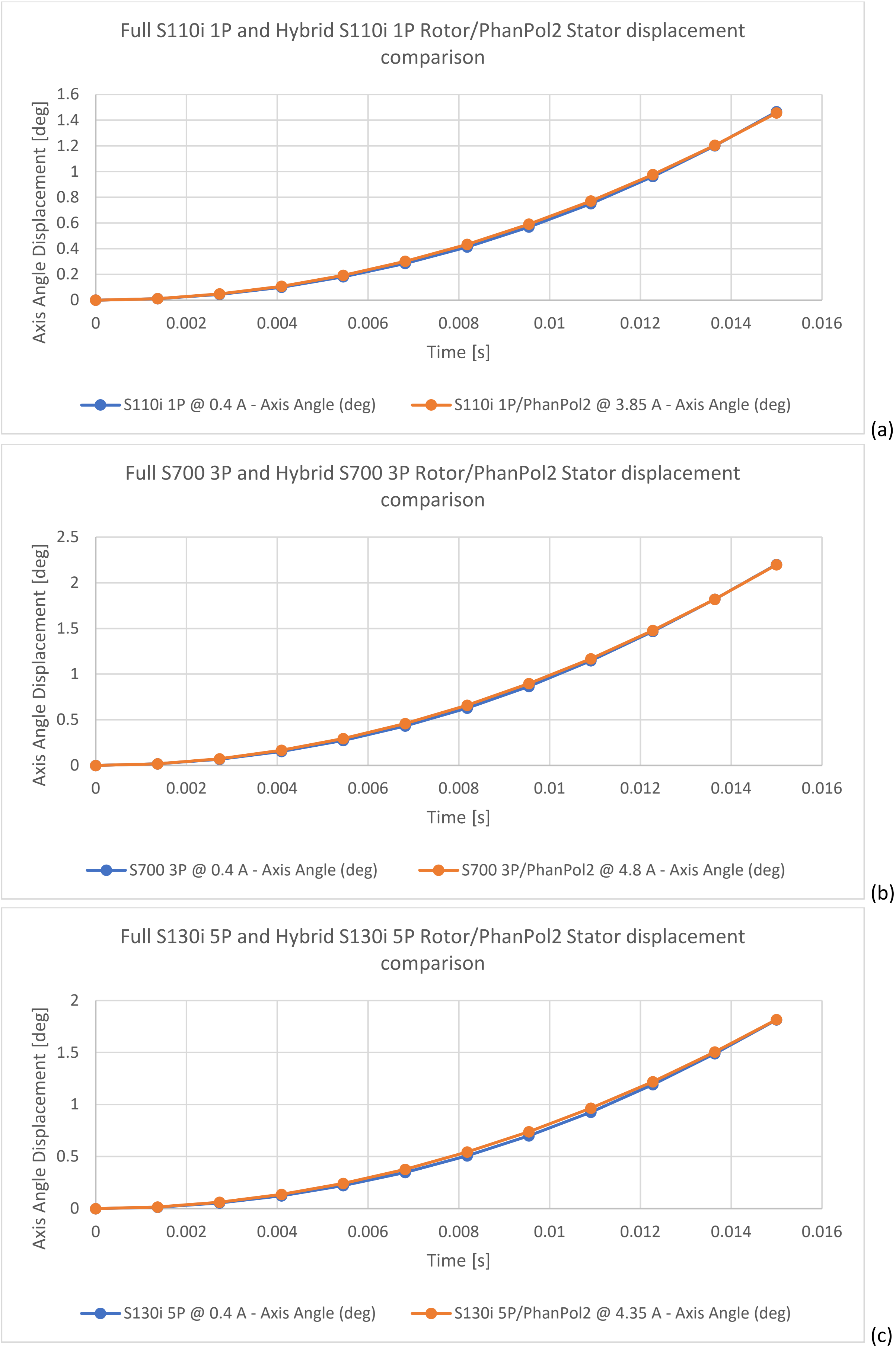

Figure S6: Displacement Comparison Data, Full SMC/Hybrid Stator Organic

Then I proceeded to calculate the HSICF (Figure S7).

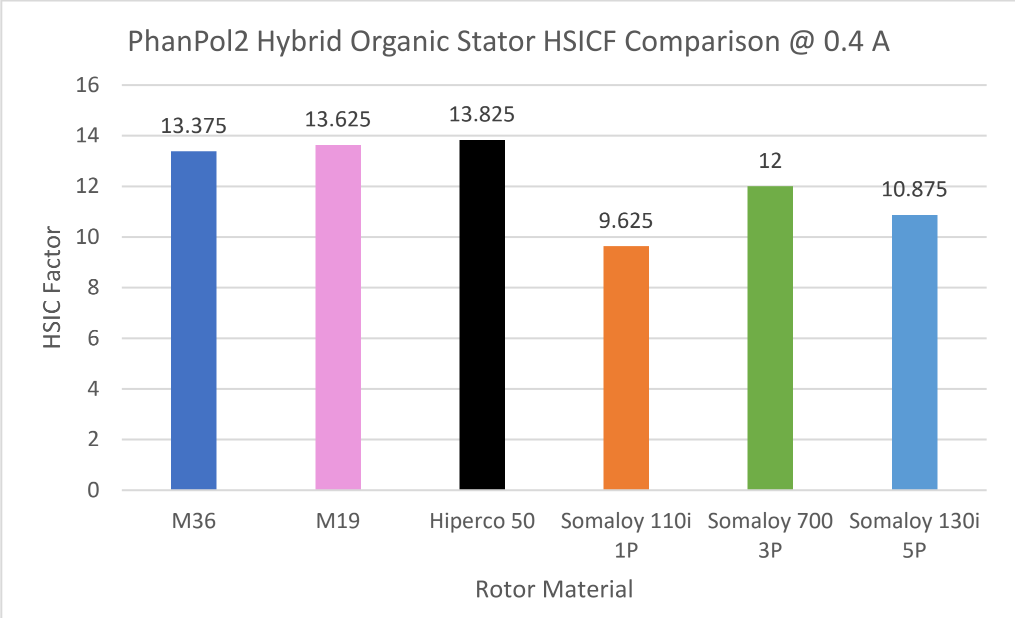

Figure S7: HSIC Factor Comparison

However as I said before, the difference in peak displacement was not linear, so only for M19 I run the second test, where the full M19 motor was excited by 1 A, and the Organic Stator Hybrid version was excited at 13.625 (following the HSICF). What I obtained (Figure S8) is that at these current values the HSICF is surely lower, as the hybrid displacement was higher.

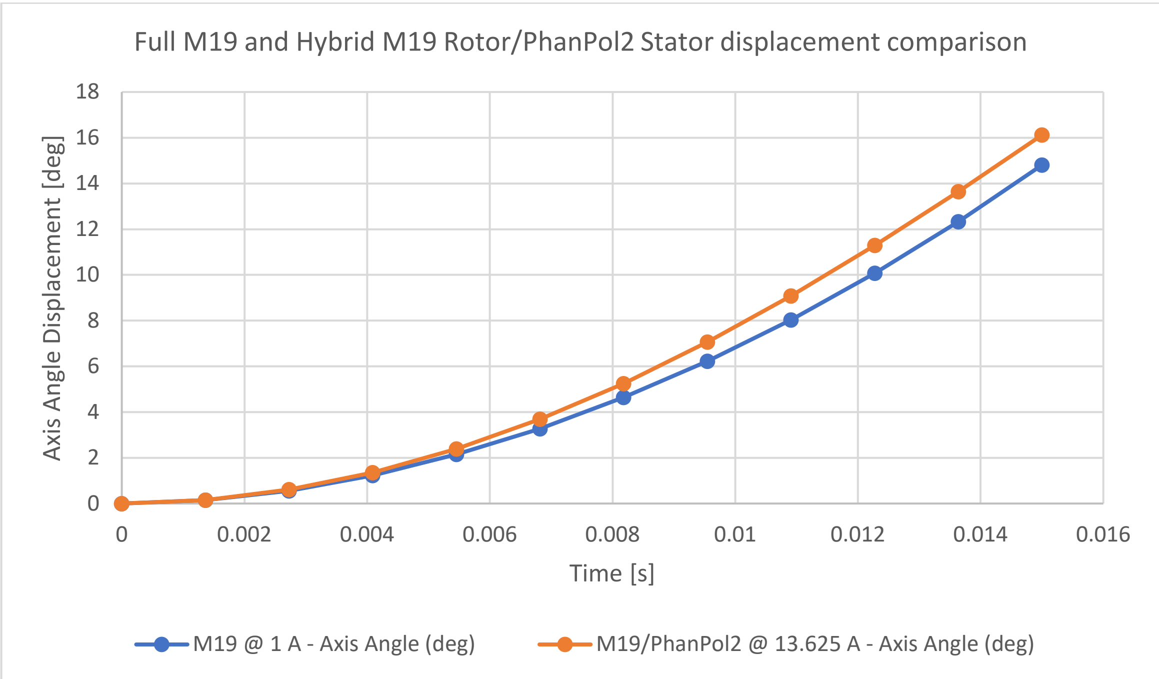

Figure S8: M19/Stator-Hybrid displacement comparison at higher current

However, the current here was getting high (as the motor is small and the turns per coil are 180). Thus, I decided that it is for the best interest to keep the IC Factor compared to a low current (0.4 A), as this represents the worst-case scenario, and keeps the hybrid motor current at a reasonable value. Hence, no other tests were performed for HSIC Factor.

HRIC Factor

The tests that I run for the HRIC Factor were similar to the ones used for the HSICF. However, the torque had odd behaviour. For my test at 7 A (Figure S9), at around 0.006 seconds the torque changes the magnitude, slowing down the motor at first and eventually turning it back at around 0.013 seconds (Figure S10). Since this displacement was not comparable to the full M19 motor displacement the HRICF at hodiern date is Not Defined. More research is needed based on torque behaviour.

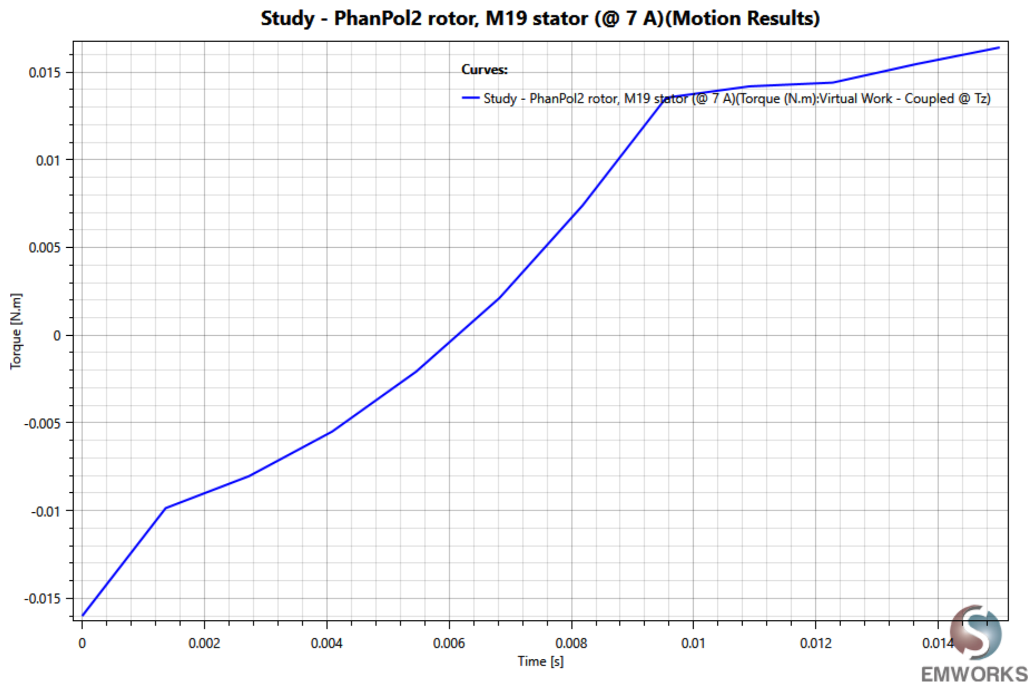

Figure S9: Torque in Organic Rotor Hybrid Test @ 7 A

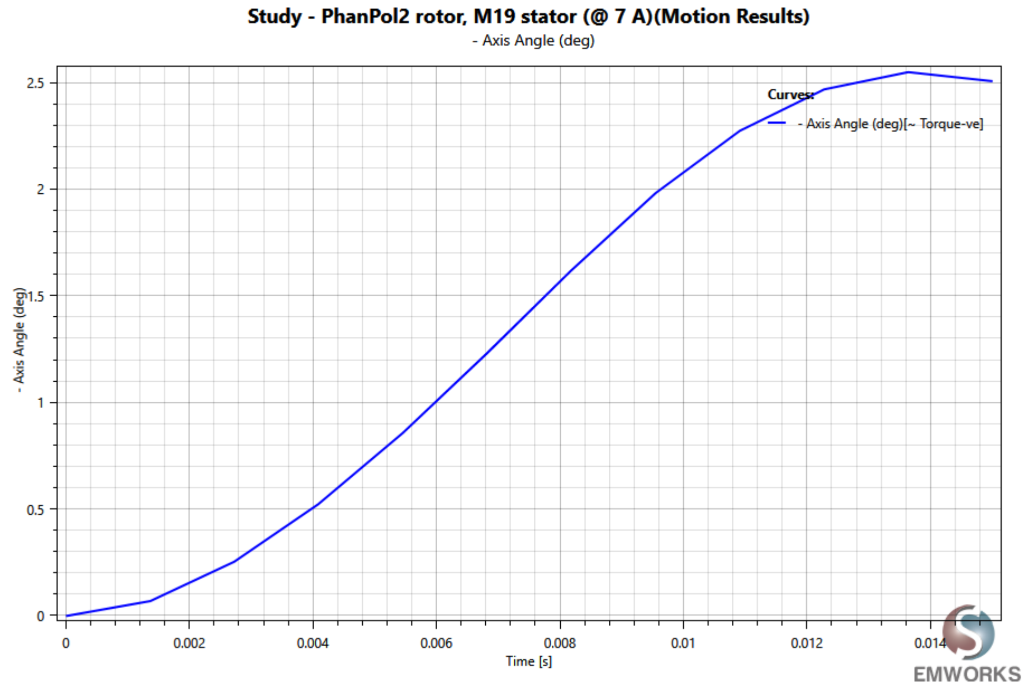

Figure S10: Angle Displacement in Organic Rotor Hybrid Test @ 7 A

OIC Factor

The tests that I run for the full organic motor were performed at 0.4, 4 and 40 A. However, even at 40 A the displacement was almost not visible (Figure S11), and the OICF greater than 100. Even here the torque had an odd behaviour (Figure S12), starting from positive, and the turning to negative at a really low value. I decided not to investigate this since 40 A is an already not feasible solution, and at lower current the displacement was not visible at all.

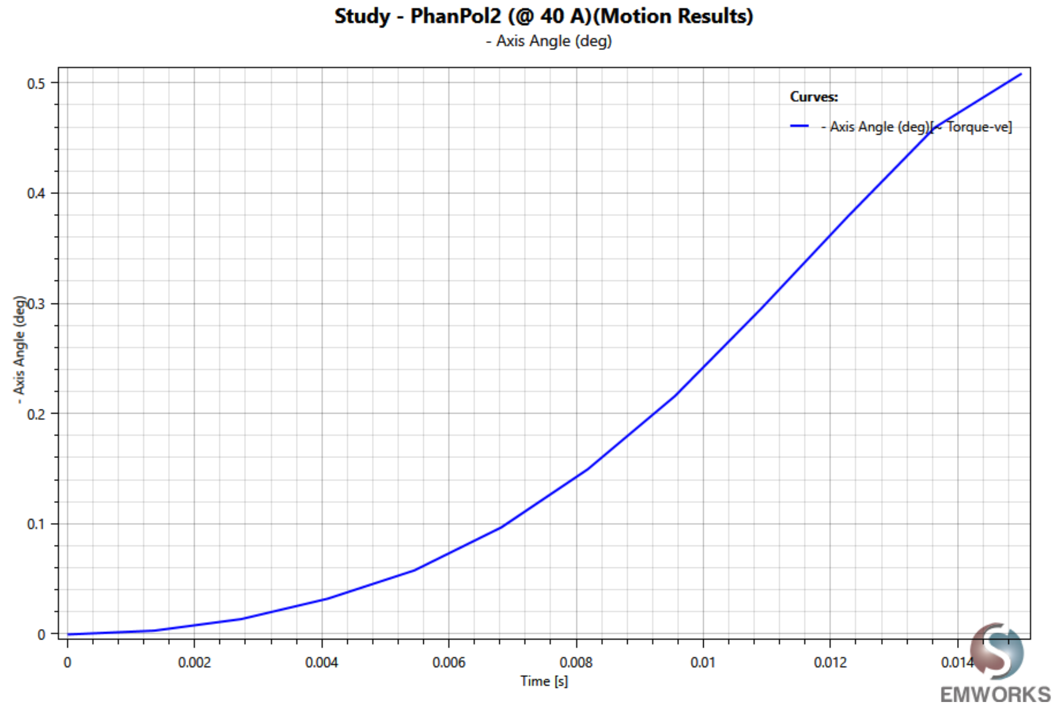

Figure S11: Angle Displacement in Organic Motor Test @ 40 A

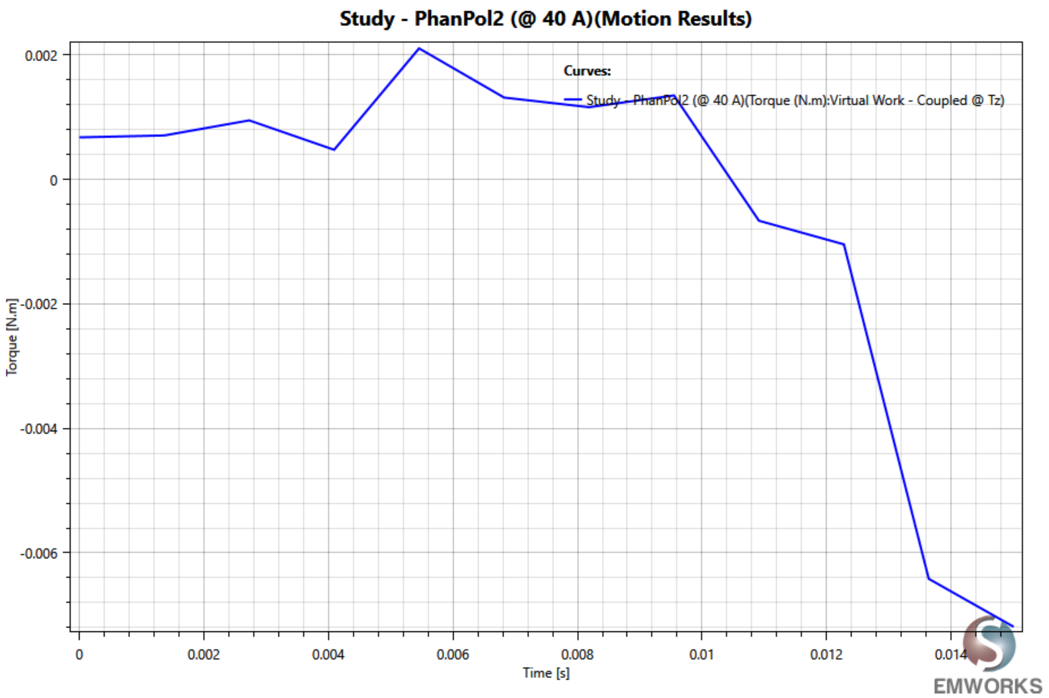

Figure S12: Torque in Organic Motor Test @ 40 A

3-Phases Tests

Even though the 1-Phase Tests gave me some insight about the start-up displacement, they were all about the working of 1-Phase for a short period, thus I had to do a longer test considering all the 3-Phases. However, since this kind of simulation is time consuming, it was performed only for motors containing silicon steel M19.

I run 4 tests. The first one is with only M19 in stator and rotor, with excitation of 0.4 A in the coils using a quadrature control system. The control system used by this first test can be seen in Figure S13.

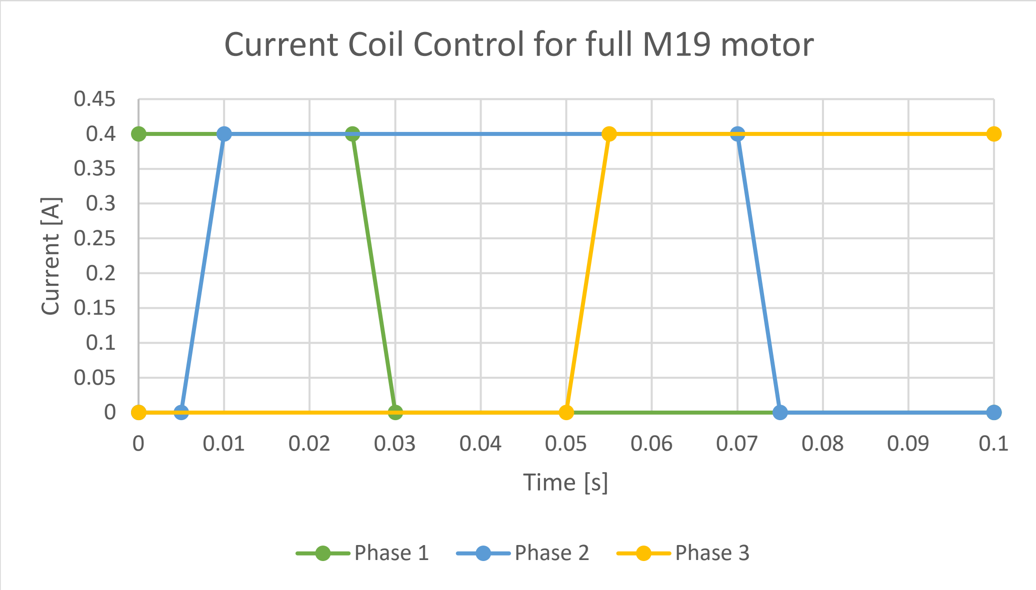

Figure S13: Current Coil Control for full M19 motor

Then a second test was performed at 5.3 A. Because of a miscalculation I thought that this was the current for evaluating the HSICF, so the first test was performed with this value. However, to achieve a similar displacement, the control pulses were slightly different. Phase 1 was 0.005 seconds longer, and the other two phases were delayed by 0.005 seconds, as it can be seen in Figure S14.

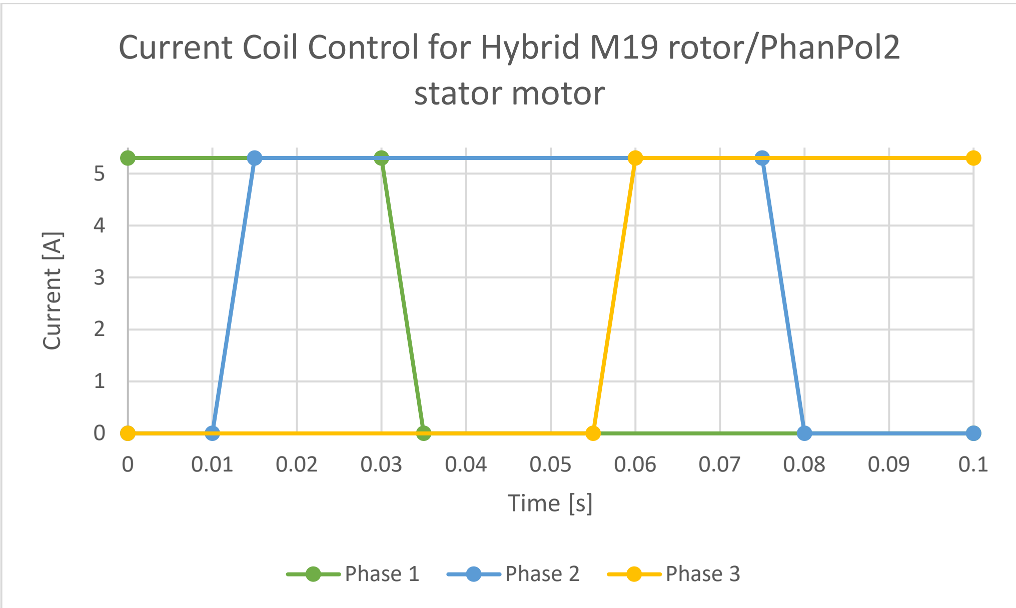

Figure S14: Current Coil Control for Hybrid M19 rotor/PhanPol2 stator motor

Then, when I checked again my calculations and I found out that 5.45 A was the correct value for the HSICF, I performed other two tests at 5.45 A; one with pulses length equal to Figure S13, one with pulses length equal to Figure S14, but in both cases with a current of 5.45 A. All the four tests' displacement were compared in Figure S15.

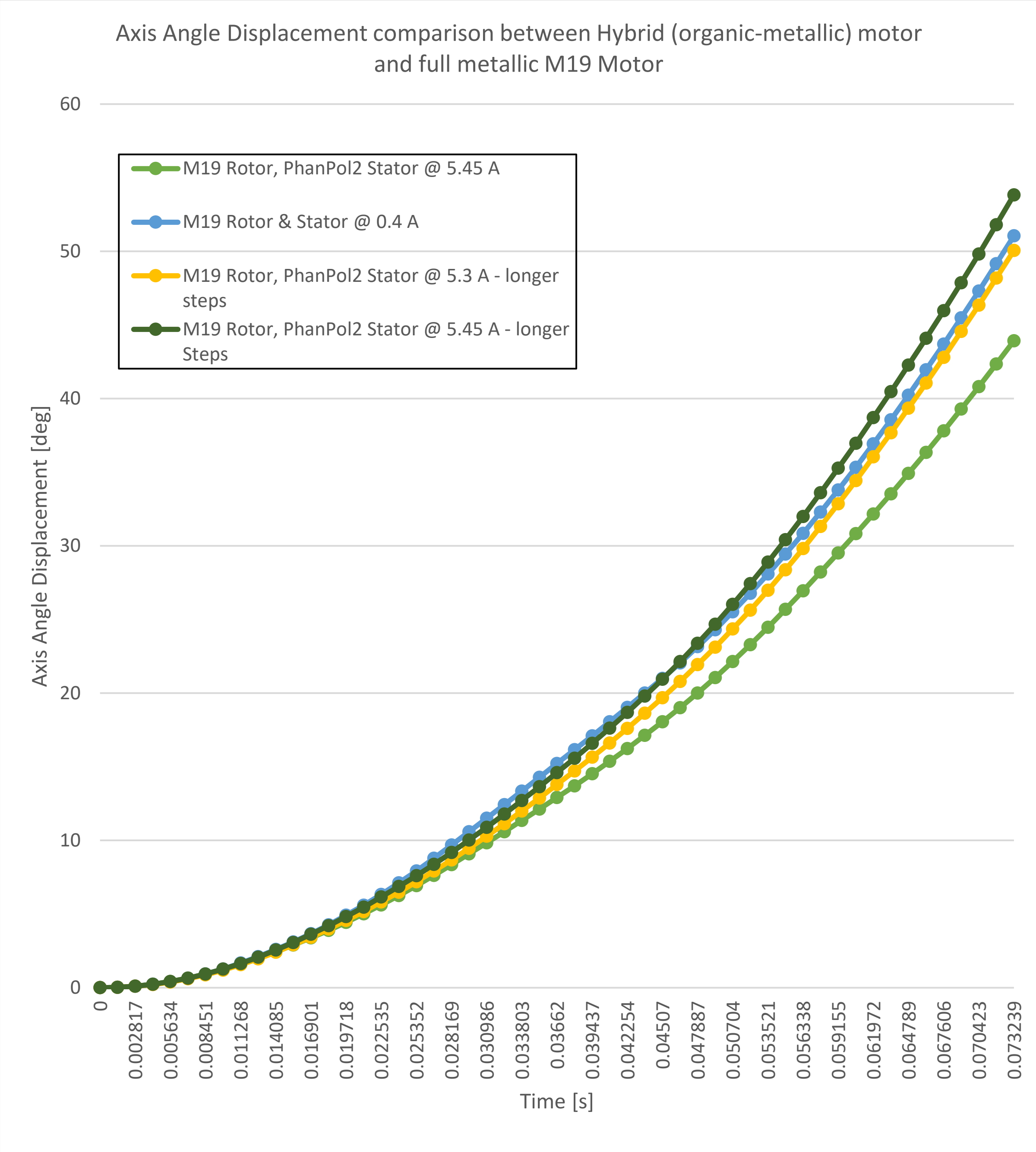

Figure S15: Axis Angle Displacement comparison between Hybrid (organic-metallic) motor and full metallic M19 Motor

The 3-phase test was supposed to run for 0.1 seconds (for a total of 71 time steps). However, each time I run the study, this would crash between time steps 55 and 60. Thus, in Figure S15 I only compared the displacement of the four tests, until the lowest time step (which occurred to be 0.073239 s), but for some of these tests displacement values after this time are available.

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