

1 A Magnetostatic analysis of magnetic saturation's impact on PMSM overall
2 efficiency and copper losses under varying load conditions.

3 **Abstract**

4 Currently, electric motors have a wide arrange of applications across industries and
5 a they are one of the pillars in the world's decarbonization, most notably the
6 permanent magnet synchronous motor (PMSM) due to its efficiency compared to
7 others. This paper's purpose is to analyze the impact of operating a saturated
8 PMSM, under load condition variations, on overall efficiency and copper losses
9 using a finite element analysis (FEA), for that a two-dimensional finite element
10 model was developed in Ansys Maxwell Student software. RMS current was
11 increased in order to simulate load variations; then, electrical power input and
12 mechanical power output were both measured in watts and evaluated to analyze
13 efficiency degradation and copper losses on saturated conditions. The simulation
14 output results showing that the increasing current supplied to a saturated system
15 does not proportionally equal to magnetic flux density gains, plateauing at a
16 specific point, stalling electromagnetic torque, as a result the mechanical power
17 output stagnated. Conversely, as the electrical power input continued to rise it was
18 dissipated as heat rather than mechanical output, hence reducing the overall
19 efficiency. Therefore, the results met the hypothesis, which established that more
20 current driven into the PMSM would not proportionally increase magnetic flux
21 density, gains in mechanical power output would diminish to the point it stagnates,
22 and excess current piles on copper losses, thence reducing overall efficiency. This
23 paper can be used to further understand the effects of magnetic saturation on a
24 PMSM's overall efficiency and copper losses to optimize electrical power usage.
25 Keywords: magnetic saturation, load variation, efficiency, permanent synchronous
26 magnet motors, copper losses.

27 **1. Introduction**

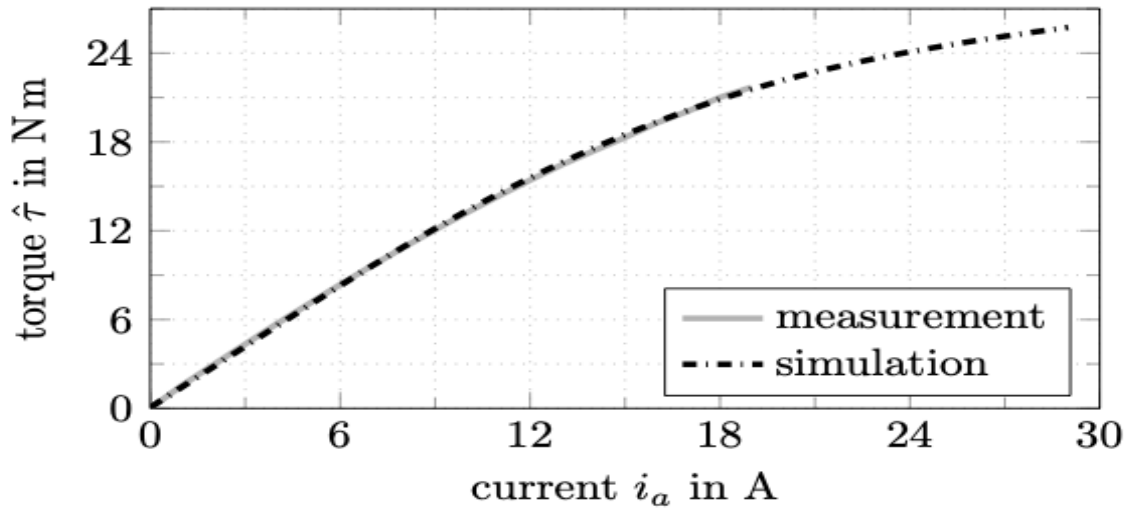
28 In the modern day, electric motors are used in a variety of utilities that range
29 from basic household appliances to heavy industrial machinery (Saidur, 2010). In
30 fact, they are one of the fundamental pillars in the context of global
31 decarbonization, since electric motors generate lower greenhouse gas (GHG)
32 emissions in comparison to internal combustion engines (ICEs) during their use
33 phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among
34 countries due to the difference between the energy source used for power
35 generation. Moreover, a comparative analysis on the overall efficiency between

36 electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded
37 that the efficiency from battery to wheels ranges from 50% to 80%, whereas the
38 most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it
39 is necessary to consider the energy source used and its efficiency to generate the
40 electricity to provide a more well-rounded analysis named: well to wheel. In this
41 perspective EVs' efficiency can drop to similar or lower levels than those found in
42 ICEVs (Albatayneh et al., 2020).

43 Despite the fact that electric motors are more efficient overall, they have a
44 fundamental restraint: magnetic saturation. Magnetic saturation is produced when
45 the magnetic field strength (H) continues to increase, but the magnetic flux density
46 (B) does not increase at the same rate, achieving a plateau (Pjevalica et al., 2015).
47 This circumstance arises in response to higher mechanical loads being applied to
48 the motor, requiring more current to strengthen the magnetic field within the core.
49 Nevertheless, the addition of more current into the system, beyond a certain point,
50 drives the core into saturation. For that reason, any further increases in current do
51 not provoke an equivalent gain in magnetic flux density, limiting torque production,
52 thus capping the mechanical power output (See in Figure 1). Additionally, providing
53 additional current into a saturated motor produces a disproportional gain in
54 mechanical power output, causing a large amount of the excess electrical power
55 input to be dissipated as heat—accounting for 55-60% of all losses. Specifically, they
56 are called I^2R losses, since they are derived after Joule's law; moreover, these losses
57 are the result of passing current through the stator's winding, hence, as more
58 current is driven into the system, the thermal losses increase as well (Saidur, 2010).

59 Figure 1

60 *Relationship between torque and electric current* (Faustner et al., 2015)



61

62 Previous work on magnetic saturation indicates that its primary cause of
 63 magnetic saturation is higher load conditions, which leads to an increase in current
 64 supplied to the stator windings. As a consequence, the magnetic field strength (H)
 65 increases, but the stator's magnetic flux density (B) stalls due to size and material
 66 strains. Thence, further increases in H would reduce flux gains following a
 67 nonlinear behavior.

68 Other studies that analyzed the consequences of saturation on the
 69 mechanical power output found a nonlinear relationship between current and
 70 torque production. Even though torque keeps increasing with a greater current, the
 71 rate at which torque grows reduces significantly under saturation situations,
 72 signing that any excess electrical input does not relate, proportionally, to the
 73 motor's mechanical output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015).

74 Similarly, research on PMSMs frequently states that higher current increases
 75 copper losses. These losses are dissipated in the stator's windings as heat,
 76 contributing to reduce energy conversion efficiency (Burt et al., 2008; Li et al.,
 77 2025; Liu et al., 2018; Atay, 2000).

78 The combination of the existing literature establishes that the operation of
 79 motors in overload leads motors to saturation, providing higher electrical power
 80 input, which increases disproportionately relative to the mechanical power output
 81 and escalates the percentage of power lost due to heating. However, there is a gap
 82 in present work, which mainly focuses on each of these effects separately and lacks
 83 an explicit graphical representation of the power converted into heat and
 84 mechanical output when the system is already saturated. Also, researchers do not

85 agree on a common behavior that efficiency suffers as the load varies when the
86 motor is subjected to saturation conditions.

87 This paper intends to establish a relationship between load variations on a
88 PMSM operating under saturation conditions and the energy converted into
89 mechanical output and copper losses. It is expected that a PMSM, in saturation,
90 with increasing load condition causes the PMSM to draw additional current into the
91 system, but the corresponding mechanical output experience gains increasingly
92 smaller; this disproportion between electrical power input and mechanical power
93 output reduces the motor's overall efficiency, rapidly increasing copper losses
94 within the stator. However, this has not been properly connected within the
95 existing literature; in this sense, the purpose of this paper is to establish the
96 relationship between those motor properties affected by magnetic saturation by
97 building upon the literature. This paper is organized as it follows: in first place,
98 section 2 expands the theoretical background with more context of how magnetic
99 saturation affects the properties of electric motors and the PMSM structure; in
100 section 3, the methods and the PMSM's specific configuration are described;
101 section 4 presents and analyzes the results of the 2D simulation on the impact of
102 operating a saturated PMSM on its magnetic flux density, average torque,
103 mechanical output, copper losses, and overall efficiency; section 5 discusses the
104 significance of the results, limitations, and how it compares to the literature
105 reviewed; and finally, section 6 concludes the paper with some suggestions on
106 future research.

107 **2. Context**

108 In this section, supplementary context is provided to understand more
109 deeply the relationship between magnetic flux density, electromagnetic torque,
110 mechanical power output, copper losses, and overall efficiency, and what these
111 equations show based on the hypothesis. Additionally, it is presented what a PMSM
112 is and what are its components.

113 **2.1 Mechanical output in saturation**

114 As forementioned in the literature review, magnetic saturation happens when
115 magnetic field strength (H), measured in amperes per meter, continues to increase,
116 but the magnetic flux density (B), measured in Tesla, does not increase
117 proportionally, following a nonlinear behavior known as the B-H curve, as shown in
118 Figure 2:

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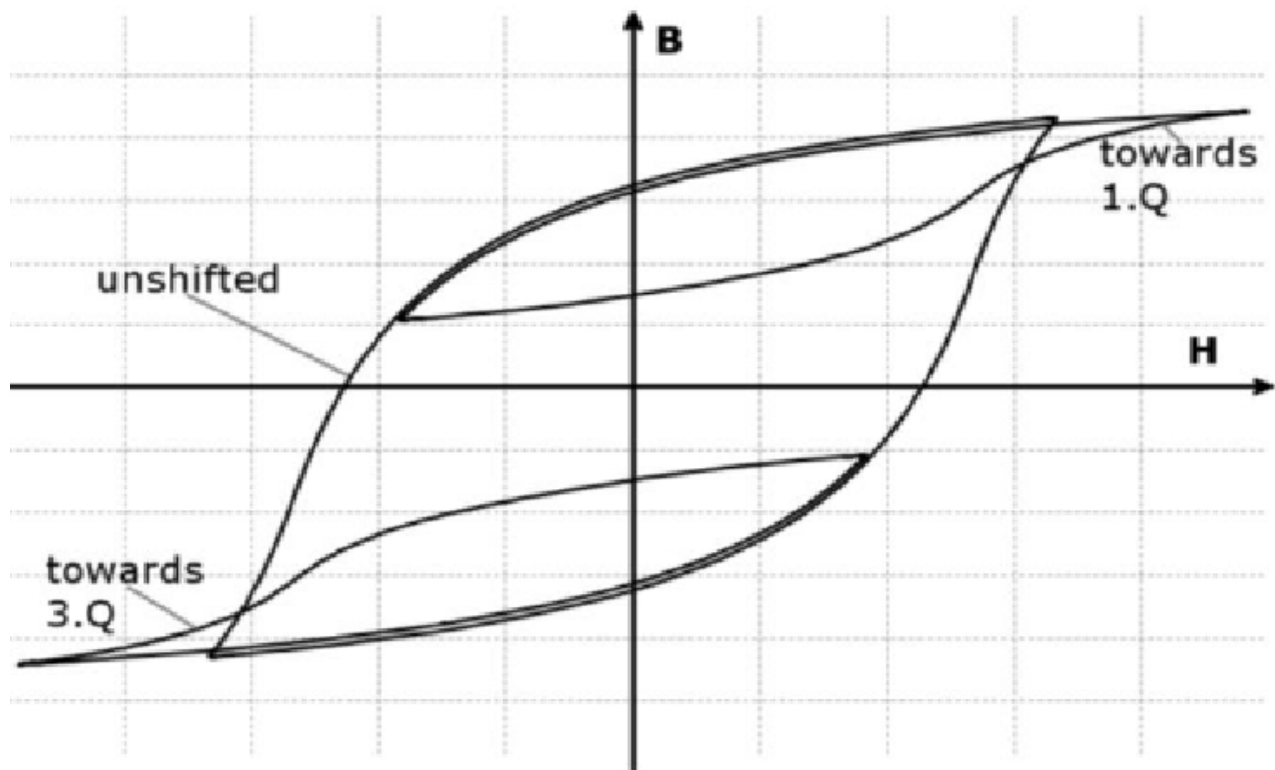
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129 Figure 2

130 B-H behavior of the stator core by the influence of the windings' induced magnetic
131 field (Pjevalica et al., 2015)



132

133 This behavior can be further understood when the equation that links B and H is
134 analyzed:

135

$$B = \mu_0(H + M(H)) \quad (1)$$

136 Where $\mu_0 = 4\pi \cdot 10^{-7} [T \cdot m \cdot A^{-1}]$ is the constant of vacuum's magnetic permeability,
 137 and M is the material magnetization, measured in A/m. At first, magnetization
 138 increases in proportion to H , but the material has a magnetization limit, causing M
 139 to plateau despite increases in H . As a consequence, increases in magnetic flux
 140 density diminish gradually, leading to saturation and making increases in flux
 141 density look almost insignificant as more current is driven into the system.

142 The direct relationship between torque and magnetic flux density explains
 143 the reason because the stagnation in magnetic flux density limits torque
 144 production. The formula used to calculate torque, in most 2D FEA models, is based
 145 on the Maxwell stress tensor surface integral that calculates the electromagnetic
 146 torque (T_e). The equation is displayed below: (Popescu, 2006; Shin et al., 2021)

147

$$T_e = \frac{1}{\mu_0} \int_0^{2\pi} r^2 B_r B_\theta d\theta \quad (2)$$

148 Where B_r , B_θ are the radial and tangential components of the flux density B , r is the
 149 radius of the circle limited by the outer diameter air gap. In 2D models, the surface
 150 integral from the Maxwell stress tensor is turned into a line integral along the air
 151 gap.

152 Likewise, when torque stagnates, the mechanical power output is also
 153 stalled, because it is proportional to the torque, as it is shown in the equation
 154 below:

155

$$P_{mech} = T_e \times \omega \quad (3)$$

156 Where P_{mech} is the mechanical power output, T_e is the electromagnetic torque used
 157 in FEA simulations, and ω is the PMSM's angular speed, measured in RPM. In most
 158 PMSM simulations, angular speed is assumed to be constant, since magnetic
 159 saturation does not directly relate to the angular speed formula. Additionally, the
 160 only situation that could impact the angular speed is in the case the load exceeds
 161 the saturated torque capability, meaning that the motor cannot sustain angular
 162 speed constant, as a result decreasing angular speed.

163 2.2 Overall efficiency

164 A motor's overall efficiency is calculated based on the ratio between
165 mechanical power output and electrical power input, illustrated in the formula
166 below:

$$167 \quad \eta = \frac{P_{mech}}{P_{elec}} \quad (4)$$

168 While electrical input soars, mechanical power output does not increase the same
169 amount when the motor is saturated, reducing overall efficiency. Furthermore, if
170 overall efficiency drops, the excess energy needs to be converted into another sort
171 of energy: thermal energy that it is possible to predict using Joule's law:

$$172 \quad P = n I^2 R(T) \quad (5)$$

173 Where the resistance (R) is dependent on the coil's temperature (T) and n is the
174 number of motor phases. Joule's law is used to calculate the power lost as heating
175 dissipation. Since the formula depends on current, it is expected that losses will
176 mount as more current is driven into the system. Therefore, copper losses have a
177 direct relation with the motor's saturation. (Tong et al., 2025)

178 **2.3 Permanent Magnet Synchronous Motor (PMSM)**

179 A PMSM is a type of AC electric motor that consists of two main parts: the
180 stator and the rotor (see Figure 3). The stator consists of two components: the
181 stator core and the stator windings. The core is composed of laminated silicon
182 sheets to house the stator windings and reduce energy loss; the stator windings are
183 sets of coils winded inside cages within the stator's core and are fed with electric
184 current to create a rotating magnetic field. Similarly, the rotor has two components:
185 the rotor core and permanent magnets. The rotor core serves almost the same
186 utility as the stator core, it is the structure that sustain the permanent magnets
187 that will rotate due to the induced rotating magnetic field, and in this case, it was a
188 surface-mounted rotor; the permanent magnets supply a constant magnetic field
189 that will make the rotor rotate when interacting with the stator's windings. In
190 addition, like any other AC motor, PMSMs have phases, in order to approach the
191 most to a real PMSM it was chosen to use the most common number of phases:
192 three (Mersha & Du, 2022).

193 **3 Methods**

194 In this section, a complete description of the PMSM configuration is shown
195 based on the details of the numerical model imported and modified. Additionally,

the methodology used to investigate the effects of operating a saturated PMSM on its overall efficiency and copper losses is presented.

3.1 Configuration

The surface-mounted PMSM model was imported from RMxpert's examples file, tool embedded in the Ansys Maxwell student version software. Tables 1, 2, and 3 show the motor's structural parameters, and Figure 3 shows a picture of the motor's design (Mersha & Du, 2022).

Table 1

Stator's specifications

Parameters	Values
Stator outer diameter	120 mm
Stator inner diameter	75 mm
Length of stator core	65 mm
Stacking factor	0.95
Steel type	M19-24G
Number of slots	24
Slot type	2
Skew width	0

Table 2

Rotor's specifications

Parameters	Values
Rotor outer diameter	74 mm
Rotor inner diameter	26 mm
Length of the rotor core	65 mm
Steel type	M19-24G
Stacking factor of rotor core	0.95
Number of poles	4

Pole type	1
Air gap	1 mm

208

209 Table 3

210 *Permanent magnet's specifications*

Parameters	Value
Embrace	0.7
Offset	0 mm
Magnet type	Ceramic8D
Magnet thickness	3.5 mm

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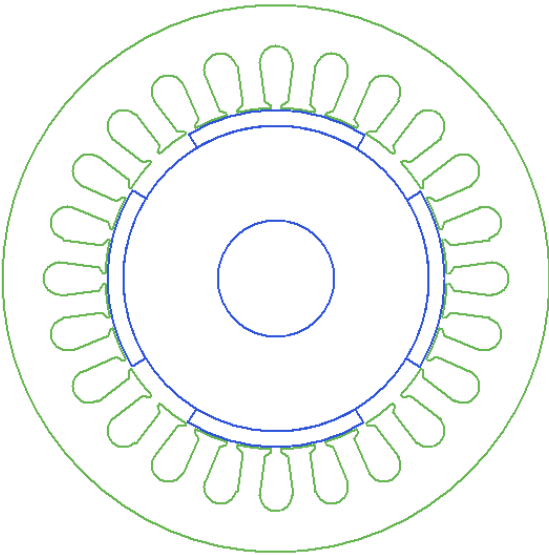
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215 Figure 3

216 *RMxpvt modified model*



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218 A two-dimensional model was chosen, since the differences to a three-dimensional
219 model are minimal and demands less computational capacity in order to simulate
220 the parameters.

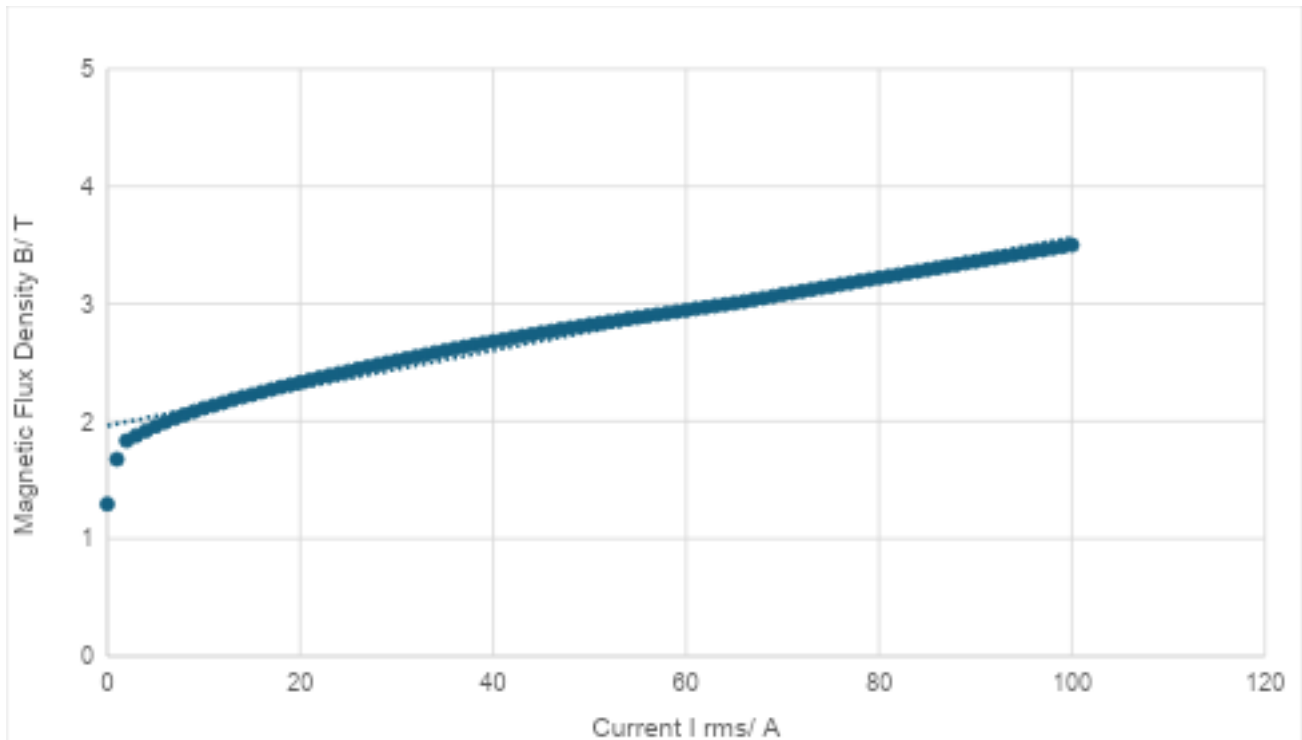
221 3.2 Numerical model

222 The solution type used for the simulation was magnetostatic. Moreover, the
223 constant variables were angular speed fixed at 2000 rpm to represent steady state,
224 and resistance was fixed at a temperature of 75°C. There were two different
225 parametric sweeps: root mean square (RMS) current and mechanical angle. RMS
226 current was the variable modified to emulate load variations, using the parametric
227 sweep tool. In addition, its parametric sweep was introduced to find at which
228 current value magnetic saturation occurs, which was found by identifying the point
229 where the ratio between the difference in B and the difference in current drops
230 significantly. Secondly, electric current was increased beyond the saturation point
231 and evaluated how it influences mechanical power output. Then, the mechanical
232 angle sweep was made at some punctual electric current values to find the average
233 torque output as current increases. After, using the result found for average torque,
234 the mechanical power output was calculated by plugging the values into the
235 mechanical power formula. Subsequently, overall efficiency was calculated using
236 the ratio between mechanical power output at specific current values over
237 electrical power input, which was estimated by summing copper losses and
238 mechanical output, since copper losses account for more than half of total losses in
239 electric motors (Saidur, 2010).

240 4. Results

241 Figure 4

242 *Magnetic flux density vs. I RMS graph*

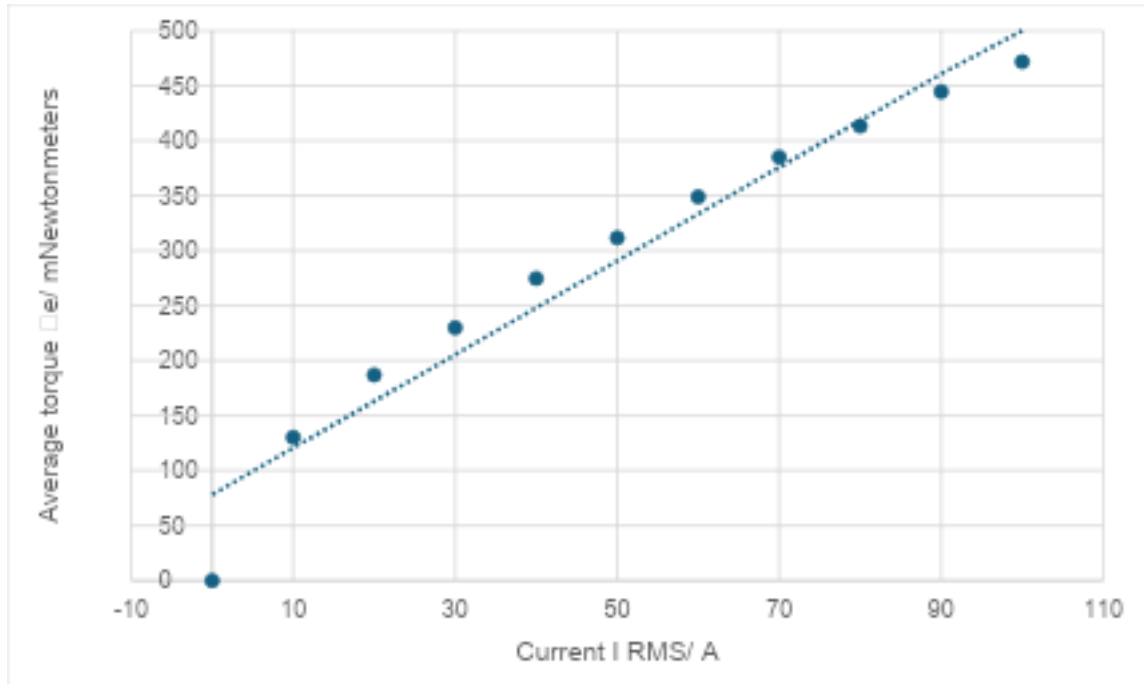


243

244 In Figure 4, a graph is shown between RMS current and the maximum
 245 magnetic flux density identified within the stator, each point is the correspondent
 246 value of magnetic flux density to current, from zero to 100 ampere. Although
 247 magnetic flux density continues to increase, it follows a nonlinear path that reduces
 248 the pace at which B increases as current becomes greater. For instance, to increase
 249 one T in flux density, initially, it takes about a 15 A increase, but the next increase of
 250 one T demands 63 more amperes than the last increase. That means that the
 251 magnetic flux density produced by the current starts to stabilize, since it takes
 252 more than four times the current to increase it by the same amount. Thence, the
 253 saturation point is around 15 A, since the gains get significantly smaller when
 254 compared to previous values. Further increases in current will generate less and
 255 less further increases in magnetic flux density, which indicates a saturation
 256 behavior. Consequently, as reviewed previously, more current input saturates
 257 magnetic flux density, torque production will be limited and, thus, mechanical
 258 output.

259 Figure 5

260 Average torque vs. RMS current graph



261

262 Figure 5 shows how average torque changes as a result of increases in
 263 current, the values of average torque shown are apart by 10 A of current input. The
 264 trend followed by the average torque is nonlinear, almost logarithmical. It
 265 showcases signs that average torque started to stabilize after a sequence of
 266 increases in current, reducing the rate of gains in torque. For example, the increase
 267 produced by the first 10 A is of 130 mNm, whereas the increase from 10 A to 90
 268 A to 100 A is of 27 mNm, showing a reduction of 79.3% on the ratio of increments in
 269 average torque, aligning with the disproportionality showed previously on magnetic
 270 flux density, since it caps torque production. Since torque is one of the components
 271 of mechanical power, its stabilization stalls mechanical power values and impacts
 272 negatively overall efficiency.

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275 Figure 6

276 Copper losses vs. I RMS graph

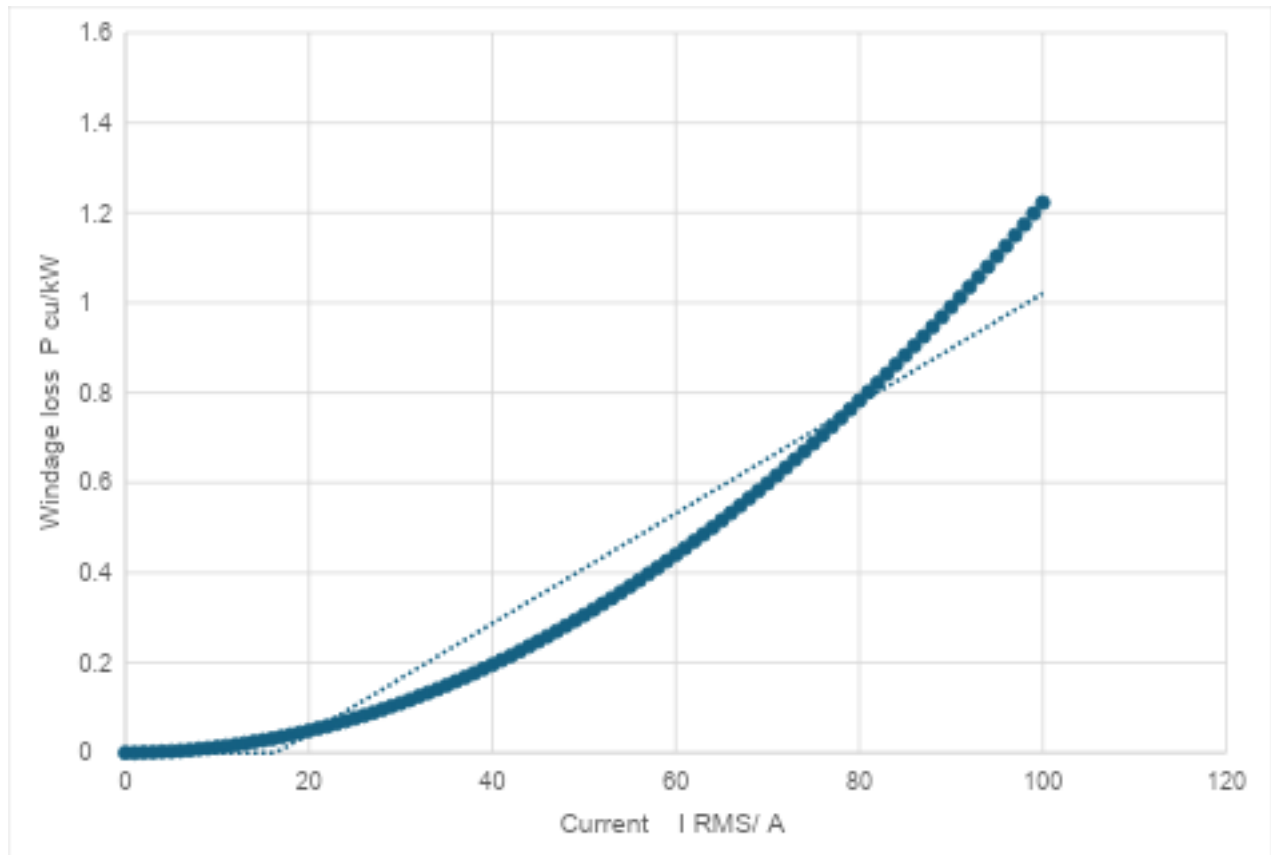


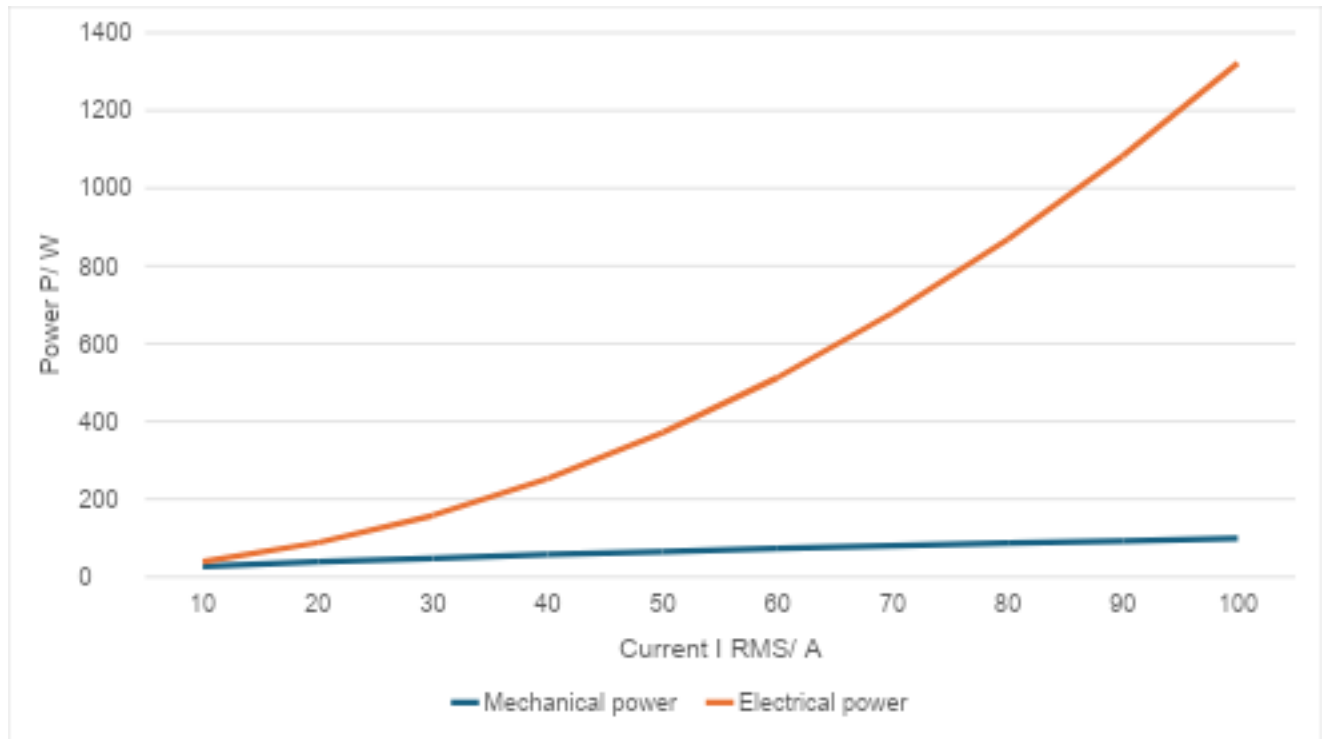
Fig. 6: Copper losses vs. I RMS graph

The graph shown in Figure 6 illustrates the relationship between copper losses and RMS current, each value of power lost due to heat is spaced by 1 A from 0 to 100 A. The behavior illustrated in this figure is close to an exponential growth, since the rate copper losses increase grows steeply at every step exemplified in the final values as the separation among the points become more prominent. Up to 40 A copper losses comprise approximately 200 watts, but as current increases to 60 A, losses are more than twice the value registered at 40, and at 100 A, copper losses are responsible for more than 1,200 watts lost to heating. This behavior is assigned to Joule's law, since copper losses increase with the square of the RMS current. The PMSM would increase electrical power input trying to make up for increasing load conditions, but this behavior of driving more power leads the PMSM into saturation. Therefore, as shown in Fig. 6, operating a PMSM beyond the saturation point can massively impact the amount of electrical power dissipated as heating, highlighting its impact on efficiency.

Figure 7

294 Electrical and mechanical output vs. RMS current graph

295



296

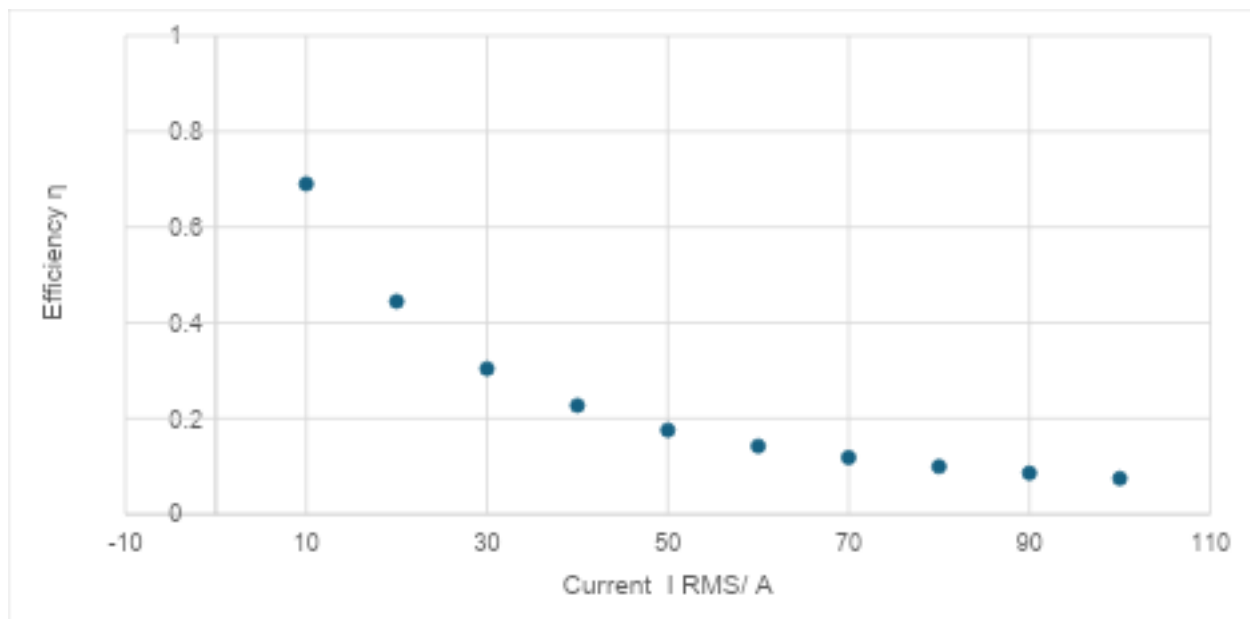
297 Electrical input was calculated by summing windage losses with
298 mechanical power output. Despite that it underestimates electrical input, since iron
299 core and eddy current losses were not taken into consideration due to copper
300 losses being a variable type of loss that takes up to 60% of all the losses in an
301 electric motor (Saidur, 2010). Furthermore, the mechanical output due to software's
302 limitations and angular speed not being directly related to magnetic field density,
303 the value of angular speed was chosen as 2000 rpm, which converting into rad/s, is
304 approximately 209. Nonetheless, because it is a magnetostatic analysis angular
305 speed needed to be fixed.

306 In Figure 7, it is illustrated how mechanical output gets outgrown by
307 electrical input when taken saturation into consideration and comparing on a
308 graph. In lower electrical power input values, the mechanical output is almost
309 equivalent to it, but as the current increases beyond the saturation point the
310 mechanical output starts to stall. Since increasing current causes greater copper
311 losses, the electrical power input skyrockets, whereas the mechanical power output
312 does not follow up, rather it stabilizes and achieves a plateau at 98 watts. This

313 difference between electrical power input and mechanical power output is
314 staggering to the point it is more than 1,119 W. The stagnation of torque and the
315 steep increase of copper losses cause such disparity between them, making it
316 reasonable to understand why overall efficiency drops when operating a PMSM in
317 saturation.

318 Figure 8

319 *Efficiency vs. RMS current graph*



320
321 Lastly, Figure 8, a scatterplot of the RMS current and the overall
322 efficiency calculated is shown. This scatterplot exposes how efficiency plummets as
323 more current runs into the system, and it starts to converge towards 0, despite it
324 not being possible unless the motor is stopped. At 10 A, efficiency is decently high
325 with approximately 70%, but after trespassing saturation point at 20 A is already
326 lower than 50 %, which continues to decline at a fast pace, achieving 7.47%
327 efficiency when current reaches 100 A. Due to magnetic saturation, mechanical
328 power output stalls, whereas the electrical power input continues to increase
329 rapidly.

330 5. Discussion

331 As stated in the hypothesis, it was expected that when load conditions are
332 increased, the saturated PMSM would draw additional current into the system.
333 However, the additional current would not be directly converted into mechanical

output gains, but rather diminish gains as current increases. This nonlinear relation between electrical power input and mechanical power output was a result of the rapid increase in copper losses, causing overall efficiency to drop.

In this sense, as shown in the analysis, this behavior is followed. Figure 4 shows that more current does not equal proportional gains in magnetic flux density. Next, since magnetic flux density held back around the saturation point, average torque follows the same path, but the gains flatten less as current increases. Since torque is affected, mechanical power growth was also impacted negatively, whereas copper losses rose sharply. Consequently, the disproportion between electrical power input and mechanical power output grows massively to the point that overall efficiency plummets, falling from around 70% at 10A to 7.5% at 100 A.

Nonetheless, this simulation and analysis have some limitations. In spite of using Ansys Student Maxwell for free and it being one of the most detailed, largely used software, it brought some limitations. In first place, a magnetostatic simulation was done, which is not the most realistic, since it assumes the motor is fixed at a given position and it does not move from that point, meaning that to have the average torque, a mechanical angle sweep was needed, and there was no angular speed output to have a more realistic simulation. Secondly, in magnetostatic simulations, it was not possible to change the load, rather the whole analysis was done in respect to electrical current, since it is directly related to load condition increases (Liu et al., 2018). In terms of losses, due to software limitations, temperature was fixed, in turn meaning resistance remains invariable, which results in an underestimation of losses even further, since that is not a realistic situation. Finally, efficiency was calculated by estimating electrical input as mechanical output plus copper losses, overestimating efficiency, since the other types of losses were not considered.

In comparison to previous research, this work connects the impact of increasing loads in causing magnetic saturation and the result of magnetic saturation in torque, efficiency, and thermal losses, which was the gap found in the literature. However, some of the papers reviewed had different materials, purposes, specifications, and approaches, meaning results may differ between different studies. Furthermore, this work only comprises PMSMs, meaning the results cannot be generalized to other motor types. Nonetheless, the results are consistent to prior work: the nonlinear behavior of the B-H curve, the relationship between

increasingly higher electric current and torque (Faustner et al., 2015), the disproportion between increases in electric power input relative to mechanical power output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015), fast rise of copper losses (Burt et al., 2008; Li et al., 2025; Liu et al., 2018; Atay, 2000), and the decline in overall efficiency.

This research is of extreme relevance in the current world scenario focused on sustainability, as world's decarbonization efforts rely heavily on EVs and clean energy production. Therefore, understanding the behavior of magnetic saturation and its implications on the electrical power efficiency of PMSMs can aid manufacturers in designing their motors to maximize efficiency and minimize losses, especially copper losses that increase under higher load conditions. Reducing these losses mean that EVs can avoid unnecessary power consumption and diminish the number of recharges. Hence, the reduction in energy demand decreases the need for additional power generation and reduces GHG emissions of EVs, depending on the energy source used for electricity generation (Tagliaferri et al., 2016).

On the other hand, copper losses damage central pieces of PMSMs, implying more material is used to replace the damaged pieces. When temperature increases within the windings, copper heats up and the excessive heat damages its insulation leading to short circuits that interrupts the motors functioning (Tong et al., 2025). Moreover, permanent magnets can be demagnetized permanently if their temperature surpasses a certain level, causing inevitable losses of rare-earth magnets (Guo et al., 2020). Therefore, copper losses can make PMSMs more harmful to the environment than beneficial as those damages demand the extraction of more minerals, which is a highly polluting industry (Moghimidehkordi et al., 2024).

6. Conclusion

In this paper, the causes and consequences of magnetic saturation in an electric motor were discussed. A two-dimensional FEA simulation was set to further understand the impacts of magnetic saturation on a PMSM's efficiency and copper losses. The results confirmed that more current causes the magnetic flux density to stall, which is the primary sign of saturation. Then, it was demonstrated that the mechanical power output is flattened by the limited torque production. In contrast, electrical power input escalates at a faster rate than mechanical output

403 due to the dramatic increase in copper losses this disproportion results in a sharp
404 decline of overall efficiency.

405 This work was applied to a PMSM motor, though one of the most widely
406 used, there are many different types of electric motors built with different
407 materials and arrangements. Furthermore, size is a factor that can affect the
408 saturation point of different motors. Other possible variations include a more
409 realistic resistance behavior and rpm.

410 Future work should focus on redoing the experiment following different
411 approaches: three-dimensional FEA transient simulation, physical experimentation,
412 and a combination with MATLAB and Simulink. A three-dimensional transient
413 simulation provides a better insight into the real dynamics of a PMSM, since the
414 simulation takes into consideration the motor's functioning over time and
415 comprises a complete version of the motor. In comparison, a physical experiment is
416 the most realistic way to understand the impacts of magnetic saturation. Finally,
417 software like MATLAB and Simulink can be combined with the FEA simulation for a
418 more complete analysis of the circuit.

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459 machines through Maxwell stress harmonic filter (HFT) method. *Electrical*
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462 *Renewable and Sustainable Energy Reviews*, 14(3), 877–898.
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474 Tong, N., Zhang, C., Li, Y., Chen, Y., Yang, W., Li, J., Yu, P., & Li, K. (2025). Research on

475 temperature rise characteristics of built in permanent magnet synchronous

476 motor coupled with magnetic thermal flow field. *Case Studies in Thermal*

477 *Engineering*, 75, 107030. <https://doi.org/10.1016/j.csite.2025.107030>

478

Decision: **Forward to peer review.**

Review: This paper is well-structured and demonstrates a solid understanding of the research topic. The abstract clearly outlines the purpose, methodology, and key findings. The introduction provides a relevant literature review and identifies a clear research gap. The methodology is appropriately detailed for a 2D FEA simulation, and the results are presented logically with supporting figures. The discussion effectively connects the findings back to the hypothesis and existing literature while acknowledging limitations.

For our journal, this paper presents a coherent and well-executed study that merits consideration for peer review.

The manuscript investigates the impact of magnetic saturation on the efficiency and copper losses of a permanent magnet synchronous motor (PMSM). The author used a 2D finite element analysis (FEA) model developed in Ansys Maxwell. By varying the RMS current to emulate load conditions, the study evaluates the relationships between magnetic flux density, torque, mechanical output power, copper losses, and overall efficiency. The results indicate that increasing current leads to a flattening of the mechanical power output and a decrease in overall efficiency. The topic is important and interesting, and the work demonstrates a solid understanding of the basic physical principles. The structure of the paper is generally clear, and the figures support the main conclusions. However, several issues need to be addressed. I would recommend this manuscript for publication after major revision.

1. The author assumes that increasing current is equivalent to increasing load. Please justify this assumption more clearly, since in practical motor operation load and current are not strictly interchangeable.
2. Is there any other reason that causes efficiency drop in addition to copper losses? Other loss mechanisms, such as core losses and mechanical losses, may also play a role. Please either discuss it and explain why they can be neglected in this paper.
3. On page 10, the author declares that “the saturation point is around 15 A, since the gains get significantly smaller when compared to previous values.” This statement is qualitative. Please provide a quantitative analysis to define what “significantly smaller” means and how the saturation point is determined.
4. The electrical input power is simplified as the sum of mechanical output and copper losses. Please explain why other losses are neglected and discuss how this simplification may affect the results.

5. Some explanations are repetitive, especially for magnetic saturation and copper losses. Please avoid repeating the same concepts.
6. Please keep units consistent throughout the manuscript, for example “mNewtonmeters” and “mN m”.
7. Typos:
 - a. Abstract Page 1 line 4 “a wide arrange”
 - b. Abstract Page 1 line 4 to 5 “and a they are”
 - c. Abstract Page 1 line 12 “results showing that”

Decision

Accept with major revisions

I appreciate with immense gratitude the attention and time dedicated to review my paper.

I am glad that the reviewer has found this paper to be accessible and useful for future optimization of electrical systems. The referee has raised many important concerns to be addressed about the absence of captions following figures, the accessibility of references, and data analysis of the saturation point in figure 4.

In contrast, I believe there might be a confusion in which category my paper fits in. I wrote this paper as an empirical paper, so I tried to make it more explicit by explaining how the effects were going to be investigated in line 109.

Technical points made and how I addressed:

1. *Figure 4: The supposed asymptotic behavior is not completely clear here, or rather, after the first two points it is somewhat (as most of the gains in current occur within the first few non-zero values of amperes, though the magnetic flux density never quite plateaus). Is there a way to focus/zoom in on the left side of the plot to emphasize that the most rapid gains of B are found within the first few amperes of current? The explanation in the text seems acceptable, but the figure could be improved.*
As an enhanced panel, would it be useful to include perhaps a second panel demonstrating the decrease in the rate of increase of B as a function of I? This might be a bit more compelling and illustrative of the points desired to be made.

Response: In figure 4, I do not think the best way to show that most gains are concentrated within the first few non-zero values of amperes. Nonetheless, I introduced a new methodology to identify where saturation occurs through incremental slope. In the manuscript it compares the average gain made from 1-15 A with 16-30 A and 16-30 A with 31-45 A finding it a quantitative way to represent that gains experiment a reduction after surpassing the range between 10-20 A in the paragraph between lines 283-291.

2. *Reminder for all figures: It is standard to have a title (as the author does) and a caption, the latter which is missing from most of the figures. The figures should be sufficiently standalone such that a reader can understand what is presented without significant need to read the main manuscript text.*

Response: I introduced captions for all figures and shortened redundant sentences that are now explicit or implicit stated within the captions.

3. *Several of these references are paywalled, which means that they cannot be easily accessed. Some can be accessed through various institutional licenses, but not readily all of them. I think that the best practice is to make sure that the articles are more accessible to a general audience. For example, I was not able to access the Popescu (2006) paper, even though it was published more than 20 years ago. The Burt et al. (2008) paper is also restricted.*

Response: In my research process, I have picked only sources with their full document available on google scholar. However, as mentioned in the feedback most of them are paywalled in their original publication websites. I used Zotero in order to cite my references and save them if there is any other way I can cite them with the URL or any different way, I will do it, but I am unaware of how. I respectfully ask to provide any suggestion to cite them, since all of the references are available for free on google scholar.

Typos/Minor Grammatical Suggestions

- 1) *Line 4: Change “arrange” to “range”.*

Response: In line 4 “arrange” has been changed to “range”.

- 2) *Line 9: Suggest changing “for that” to “for which”.*

Response: In line 9 “for that” has been changed to “for which”.

- 3) *Line 13: Change “showing” to “show”.*

Response: In line 13 “showing” has been changed to “show”.

- 4) *Line 15: Consider changing “equal” to “equate”.*

Response: In line 14 “equal” has been changed to “equate”.

- 5) *Line 40: Change “named” to “namely”; also include a comma after “analysis”.*

Response: In line 40 “named” has been changed to “namely”.

- 6) *Line 52: “disproportionate” rather than “disproportional” is the preferred word.*

Response: In line 52 “disproportional” has been changed to “disproportionate”.

6) Line 71: Change “signing” to “signaling”.

Response: In line 85 “signing” has been changed to “signaling”.

7) Line 79: Change “disproportionately” to “disproportionally”.

Response: In line 93 “disproportionately” has been changed to “disproportionally”.

9) Line 96: Some consolidation and reduction of words would help readability: Change “This paper is organized as it follows: in first place ...” to “This paper is organized as follows:” (remove “it” and “in first place”).

Response: In line 110 “This paper is organized as it follows: in first place” has been changed to “This paper is organized as follows:”. Moreover, I tried to reduce redundancy and unessential information.

10) Lines 109-110: This sentence is awkward as written now. Please consider changing to: “Additionally, this paper characterizes PMSMs and their components.”

Response: In line 122 “Additionally, it is presented what a PMSM is and what are its components.” has been changed to “Additionally, this paper characterizes PMSMs and their components.”

11) Lines 160-161: Awkward phrase: Change “angular speed constant” to “constant angular speed.”

Response: In line 168-169 “angular speed constant” has been changed to “constant angular speed”.

12) Line 182: Change “winded” to “wound”.

Response: In line 197 “winded” has been changed to “wounded”, it is a typo I meant “wound”

13) Line 185: Change “sustain” to “sustains”

Response: In line 200 “sustain” has been changed to “sustains”

14) Line 189: Change “in order to approach the most to a real PMSM” to “in order to most closely emulate a real PMSM ...”

Response: In line 204 “in order to approach the most to a real PMSM” has been changed to “in order to most closely emulate a real PMSM”

15) Line 216: Change “differences to” to “differences with”

Response: In line 232 “differences to” has been changed to “differences with”.

16) Line 217: For clarity, add “a 2-D model” before “demands” to make clear that the subject is a “2-D model” and not “differences.”

Response: In line 232 I added “a 2-D model” to make clear it is the subject.

17) Line 231: Change “After” to “Afterwards.”

Response: In line 251 “After” has been changed to “Afterwards”.

18) Line 244: “ampere” should be plural, as in “amperes”

Response: I have standardized the use of A instead of amperes.

19) Line 253: Change “less and less further increases” to “smaller increases”

Response: I eliminated the sentence with this structure, replacing it by the sentences in the lines 282-287 that retains the idea.

20) Line 254: Remove “a” before “saturation”

Response: I eliminated the sentence with the redundant “a”, replacing it by the sentences in the lines 282-287 that retains the idea.

21) Lines 254-256: This sentence is awkward as written and should be revised.

Response: I rephrased it in lines 289-290.

22) Line 261: Change “apart” to “binned”

Response: It is now found in the caption for figure 5 in line 294. There, “apart” has been replaced by “binned”.

23) Line 265: remove “from” before “10 A”; also remove “of” before “130 mNm” and before “27 mNm”.

Response: All suggested words were removed, now found in lines 299-300.

24) Lines 269-270: change “impacts negatively overall efficiency” to “reduces overall efficiency”

Response: I eliminated this part of the sentence finding it to be redundant.

25) Line 279: Remove “an” before “exponential”.

Response: I have removed “an” before “exponential, which can now be found in line 313.

26) Line 301: Change “converting” to “converted”

Response: In line 336, converting has been changed to “converted”

27) Line 302: Remove “because”. Also, consider writing this sentence in a more active form rather than a passive form.

Response: In lines 336-337, I removed “because” from it and wrote in active form.

28) Line 305: Change “taken” to “taking”

Response: The word was eliminated as the sentence was moved and rephrased to become the caption for figure 7 (lines 327-329).

29) The portion of the sentence from lines 322-324 needs an overhaul: Consider this instead: “but after surpassing a saturation point of 20 A, efficiency is below 50%, which continues to decline at a fast pace, only at 7.47% when the current reaches 100 A.”

Response: Since, the approach taken to identify magnetic saturation has changed I eliminated “a saturation point of ” from the new sentence, which can be found between lines 355-356.

30) Line 344: Change “In first place” to “In the first place”

Response: I replaced “In first place” for “In the first place” in line 374.

31) Line 382: Change “interrupt” to “interrupts” and add a possessive at the end of motors, e.g. motors’

Response: In line 412, “interrupt” was changed into “interrupts” and the possessive was added to motors.

32) Line 396: Change “the dramatic increase in copper losses this disproportion results in a sharp decline” to “the dramatic increase in copper losses causes a sharp decline ...”

Response: In lines 425-426, “the dramatic increase in copper losses this disproportion results in a sharp decline” was changed to “the dramatic increase in copper losses causes a sharp decline”.

33) Line 402: Remove “a” before “more realistic”

Response: In lines 430-431, “a” was removed before “more realistic”.

1 A Magnetostatic Analysis of Magnetic Saturation's Impact on PMSM Overall 2 Efficiency and Copper Losses Under Varying Load Conditions.

3 **Abstract**

4 Currently, electric motors have a wide range of applications across industries and
5 they are one of the pillars in the world's decarbonization, most notably the
6 permanent magnet synchronous motor (PMSM) due to its efficiency compared to
7 others. This paper's purpose is to analyze the impact of operating a saturated
8 PMSM, under load condition variations, on overall efficiency and copper losses
9 using a finite element analysis (FEA), for which a two-dimensional finite element
10 model was developed in Ansys Maxwell Student software. RMS current was
11 increased in order to simulate load variations; then, electrical power input and
12 mechanical power output were both measured in watts and evaluated to analyze
13 efficiency degradation and copper losses on saturated conditions. The simulation
14 results show that the increasing current supplied to a saturated system does not
15 proportionally equate to magnetic flux density gains, plateauing after increasing
16 beyond the range of values saturation starts, stalling electromagnetic torque, as a
17 result the mechanical power output stagnated. Conversely, as the electrical power
18 input continued to rise it was dissipated as heat rather than mechanical output,
19 hence reducing the overall efficiency. Therefore, the results met the hypothesis,
20 which established that more current driven into the PMSM would not
21 proportionally increase magnetic flux density, gains in mechanical power output
22 would diminish to the point it stagnates, and excess current piles on copper losses,
23 thence reducing overall efficiency. This paper can be used to further understand
24 the effects of magnetic saturation on a PMSM's overall efficiency and copper losses
25 to optimize electrical power usage.

26 Keywords: magnetic saturation, load variation, efficiency, permanent synchronous
27 magnet motors, copper losses.

28 **1. Introduction**

29 In the modern day, electric motors are used in a variety of utilities that range
30 from basic household appliances to heavy industrial machinery (Saidur, 2010). In
31 fact, they are one of the fundamental pillars in the context of global
32 decarbonization, since electric motors generate lower greenhouse gas (GHG)
33 emissions in comparison to internal combustion engines (ICEs) during their use
34 phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among
35 countries due to the difference between the energy source used for power

36 generation. Moreover, a comparative analysis on the overall efficiency between
37 electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded
38 that the efficiency from battery to wheels ranges from 50% to 80%, whereas the
39 most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it
40 is necessary to consider the energy source used and its efficiency to generate the
41 electricity to provide a more well-rounded analysis, namely: well to wheel. In this
42 perspective EVs' efficiency can drop to similar or lower levels than those found in
43 ICEVs (Albatayneh et al., 2020).

44 Despite the fact that electric motors are more efficient overall, they have a
45 fundamental restraint: magnetic saturation. Magnetic saturation is produced when
46 the magnetic field strength (H) continues to increase, but the magnetic flux density
47 (B) does not increase at the same rate, achieving a plateau (Pjevalica et al., 2015).
48 This circumstance arises in response to higher mechanical loads being applied to
49 the motor, requiring more current to strengthen the magnetic field within the core.
50 Nevertheless, the addition of more current into the system, beyond a certain range
51 of values, drives the core into saturation. For that reason, any further increases in
52 current do not provoke an equivalent gain in magnetic flux density, limiting torque
53 production, thus capping the mechanical power output (See in Figure 1).
54 Additionally, providing additional current into a saturated motor produces a
55 disproportionate gain in mechanical power output, causing a large amount of the
56 excess electrical power input to be dissipated as heat—accounting for 55-60% of all
57 losses in efficiency. Specifically, they are called I^2R losses, since they are derived
58 after Joule's law; hence, as more current is driven into the system, the thermal
59 losses increase as well (Saidur, 2010).

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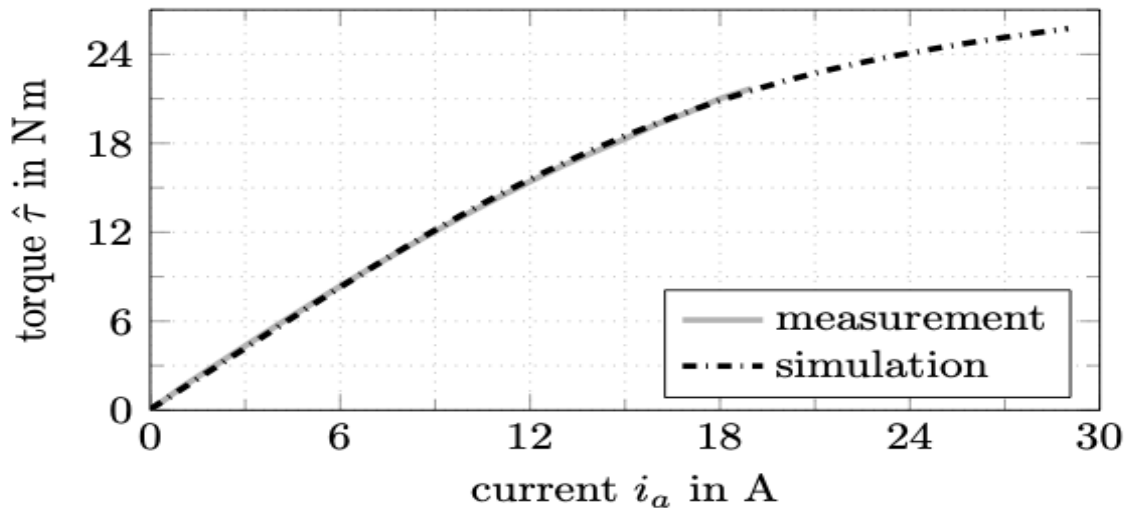
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74 Figure 1

75 Relationship between torque and electric current (Faustner et al., 2015)

76 Graph shows torque versus current of a simulated PMSM, showing a nonlinear behavior at higher
77 current levels.



78

79 Previous work on magnetic saturation indicates that its primary cause of
80 magnetic saturation is higher load conditions, which leads to an increase in current
81 supplied to the stator windings. As a consequence, the magnetic field strength (H)
82 increases, but the stator's magnetic flux density (B) does not compound as much
83 due to size and material strains.

84 Other studies that analyzed the consequences of saturation on the
85 mechanical power output found a nonlinear relationship between current and
86 torque production. Even though torque keeps increasing with a greater current, the
87 rate at which torque grows reduces significantly under saturation situations,
88 signaling that any excess electrical input does not relate, proportionally, to the
89 motor's mechanical output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015).

90 Similarly, research on PMSMs frequently states that higher current increases
91 copper losses. These losses contribute in reducing energy conversion efficiency
92 (Burt et al., 2008; Li et al., 2025; Liu et al., 2018; Atay, 2000).

93 The combination of the existing literature establishes that the operation of
94 motors in overload leads motors to saturation, providing higher electrical power
95 input, which increases disproportionately relative to the mechanical power output
96 and escalates the percentage of power lost due to heating. However, there is a gap

97 in present work, which mainly focuses on each of these effects separately and lacks
98 an explicit graphical representation of the power converted into heat and
99 mechanical output when the system is already saturated. Also, researchers do not
100 agree on a common behavior that efficiency suffers as the load varies when the
101 motor is subjected to saturation conditions.

102 This paper intends to establish a relationship between load variations on a
103 PMSM operating under saturation conditions and the energy converted into
104 mechanical output and copper losses. It is expected that a PMSM, in saturation,
105 with increasing load condition causes the PMSM to draw additional current into the
106 system, but the corresponding mechanical output experience gains increasingly
107 smaller; this disproportion between electrical power input and mechanical power
108 output reduces the motor's overall efficiency. However, this has not been properly
109 connected within the existing literature; in this sense, the purpose of this paper is
110 to establish the relationship between those motor properties affected by magnetic
111 saturation by conducting a PMSM's magnetostatic simulation and building upon the
112 literature. This paper is organized as follows: section 2 expands the theoretical
113 background with more context of magnetic saturation effects and the PMSM
114 structure; in section 3, the methods and the PMSM's specific configuration are
115 described; section 4 presents and analyzes the results of the 2D simulation on the
116 impact of operating a saturated PMSM on its properties; section 5 discusses the
117 significance of the results, limitations, and a comparison to the literature reviewed
118 to guide the simulation and paper; and finally, section 6 concludes the paper with
119 some suggestions on future research.

120 **2. Context**

121 In this section, supplementary context is provided to understand more
122 deeply the relationship between magnetic flux density, electromagnetic torque,
123 mechanical power output, copper losses, and overall efficiency, and what these
124 equations show based on the hypothesis. Additionally, this paper characterizes
125 PMSMs and their components.

126 **2.1 Mechanical output in saturation**

127 As forementioned in the literature review, magnetic saturation happens when
128 magnetic field strength (H), measured in amperes per meter, continues to increase,
129 but the magnetic flux density (B), measured in Tesla, does not increase
130 proportionally.

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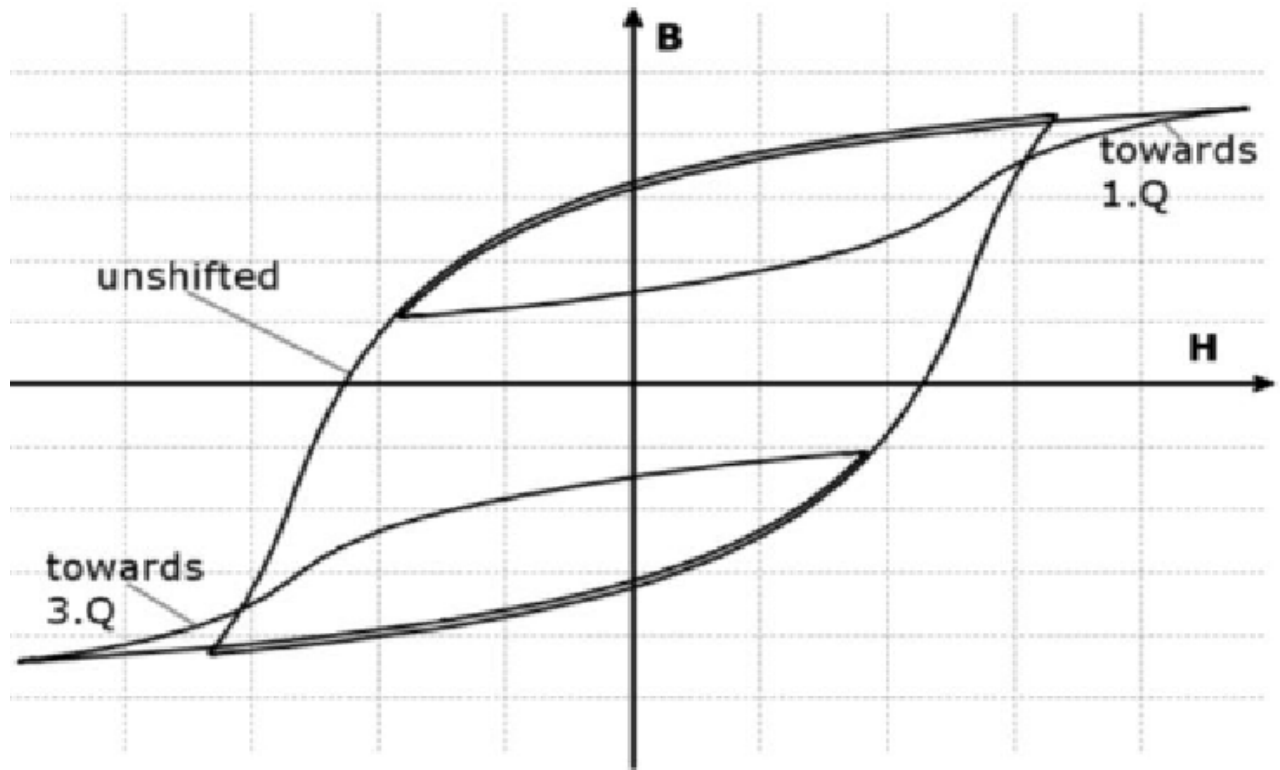
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134 Figure 2

135 B-H behavior of the stator core by the influence of the windings' induced magnetic
136 field (Pjevalica et al., 2015)

137 This figure exhibits the B-H curve that follows a nonlinear behavior as magnetic field strength
138 increases due to higher current levels.



139

140 This behavior can be further understood when the equation that links B and H is
141 analyzed:

142

$$B = \mu_0(H + M(H)) \quad (1)$$

143 Where $\mu_0 = 4\pi \cdot 10^{-7} [T \cdot m \cdot A^{-1}]$ is the constant of vacuum's magnetic permeability,
144 and M is the material magnetization, measured in A/m. At first, magnetization
145 increases in proportion to H, but the material has a magnetization limit, causing M
146 to plateau despite increases in H.

147 In this sense, the range of values in which saturation starts can be identified
148 based on the reduction of incremental slope. This method consists in comparing in
149 a ratio the local slope of certain values in low current and at higher current, setting
150 a measurable bar to compare increases, in which 1 means they are the same and
151 they become smaller as saturation is achieved (Zhu et al., 2021).

152 The direct relationship between torque and magnetic flux density explains
153 the reason why the stagnation in magnetic flux density limits torque production.
154 The formula used to calculate torque, in most 2D FEA models, is based on the
155 Maxwell stress tensor surface integral that calculates the electromagnetic torque (T_e). The equation is displayed below: (Popescu, 2006; Shin et al., 2021)

157
$$T_e = \frac{1}{\mu_0} \int_0^{2\pi} r^2 B_r B_\theta d\theta \quad (2)$$

158 Where B_r B_θ are the radial and tangential components of the flux density B, r is the
159 radius of the circle limited by the outer diameter air gap. In 2D models, the surface
160 integral from the Maxwell stress tensor is turned into a line integral along the air
161 gap.

162 Likewise, when torque stagnates, the mechanical power output is also
163 stalled, because it is proportional to the torque, as it is shown in the equation
164 below:

165
$$P_{mech} = T_e \times \omega \quad (3)$$

166 Where P_{mech} is the mechanical power output, T_e is the electromagnetic torque used
167 in FEA simulations, and ω is the PMSM's angular speed, measured in RPM. In most
168 PMSM simulations, angular speed is assumed to be constant, since magnetic
169 saturation does not directly relate to the angular speed formula. Additionally, the
170 only situation that could impact the angular speed is in the case the load exceeds
171 the saturated torque capability, meaning that the motor cannot sustain constant
172 angular speed, as a result decreasing angular speed.

173 2.2 Overall efficiency

174 A motor's overall efficiency is calculated based on the ratio between
175 mechanical power output and electrical power input, illustrated in the formula
176 below:

177

$$\eta = \frac{P_{mech}}{P_{elec}} \quad (4)$$

178 While electrical input soars, mechanical power output does not increase the same
 179 amount when the motor is saturated, reducing overall efficiency. Furthermore, if
 180 overall efficiency drops, the excess energy needs to be converted into another sort
 181 of energy: thermal energy that it is possible to predict using Joule's law:

182

$$P = n I^2 R(T) \quad (5)$$

183 Where the resistance (R) is dependent on the coil's temperature (T) and n is the
 184 number of motor phases. Since the formula depends on current, it is expected that
 185 losses will mount as more current is driven into the system. (Tong et al., 2025)

186 However, it is important to acknowledge that there are more types of losses:
 187 iron, friction and windage, and stray losses. Iron and friction and windage losses are
 188 considered independent to the load, meaning that more current will not increase
 189 these types of losses; also, they make up around 26% of losses, which is small
 190 compared to almost 60% that copper losses achieve as load is increased. Although
 191 the stray losses are generally proportional to the square of the current in the stator,
 192 it only comprises 15% of all losses. In this sense, copper losses were the only taken
 193 into consideration due to its significance compared to the other losses and its
 194 relationship with electric current.

195 2.3 Permanent Magnet Synchronous Motor (PMSM)

196 A PMSM is a type of AC electric motor that consists of two main parts: the
 197 stator and the rotor (see Figure 3). The stator consists of two components: the
 198 stator core and the stator windings. The core is composed of laminated silicon
 199 sheets to house the stator windings and reduce energy loss; the stator windings are
 200 sets of coils wound inside cages within the stator's core and are fed with electric
 201 current to create a rotating magnetic field. Similarly, the rotor has two components:
 202 the rotor core and permanent magnets. The rotor core serves almost the same
 203 utility as the stator core, it is the structure that sustains the permanent magnets
 204 that will rotate due to the induced rotating magnetic field, and in this case, it was a
 205 surface-mounted rotor; the permanent magnets supply a constant magnetic field
 206 that will make the rotor rotate when interacting with the stator's windings. In
 207 addition, like any other AC motor, PMSMs have phases, in order to most closely
 208 emulate a real PMSM it was chosen to use the most common number of phases:
 209 three (Mersha & Du, 2022).

210 3 Methods

211 In this section, a complete description of the PMSM configuration is shown
212 based on the details of the numerical model imported and modified. Additionally,
213 the methodology used to investigate the effects of operating a saturated PMSM on
214 its overall efficiency and copper losses is presented.

215 3.1 Configuration

216 The surface-mounted PMSM model was imported from RMxpert's examples
217 file, tool embedded in the Ansys Maxwell student version software. Tables 1, 2, and
218 3 show the motor's structural parameters, and Figure 3 shows a picture of the
219 motor's design (Mersha & Du, 2022).

220 Table 1

221 *Stator's specifications*

Parameters	Values
Stator outer diameter	120 mm
Stator inner diameter	75 mm
Length of stator core	65 mm
Stacking factor	0.95
Steel type	M19-24G
Number of slots	24
Slot type	2
Skew width	0

222

223 Table 2

224 *Rotor's specifications*

Parameters	Values
Rotor outer diameter	74 mm
Rotor inner diameter	26 mm
Length of the rotor core	65 mm
Steel type	M19-24G

Stacking factor of rotor core	0.95
Number of poles	4
Pole type	1
Air gap	1 mm

225

226 Table 3

227 *Permanent magnet's specifications*

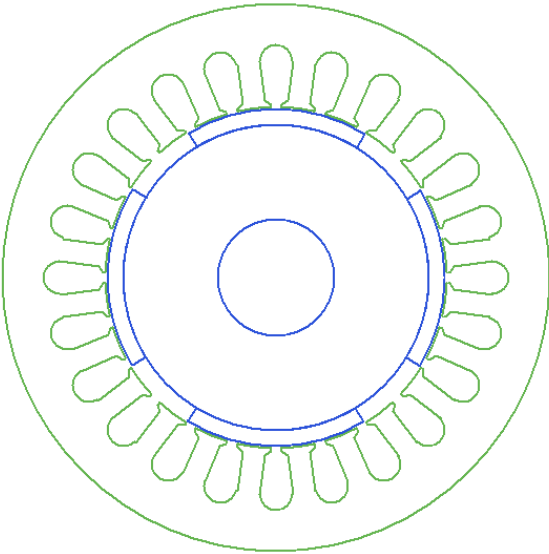
Parameters	Value
Embrace	0.7
Offset	0 mm
Magnet type	Ceramic8D
Magnet thickness	3.5 mm

228

229 Figure 3

230 *RMxpvt modified model*

231 The cross-sectional view of the 2-D PMSM model setup, with the stator and rotor highlighted in
232 green and blue, respectively. Image obtained from the researcher's experimental setup in Ansys
233 Maxwell.



234

235 A two-dimensional model was chosen, since the differences with a
236 three-dimensional model are minimal and a 2-D model demands less computational
237 capacity in order to simulate the parameters.

238 **3.2 Numerical model**

239 The solution type used for the simulation was magnetostatic. Moreover, the
240 constant variables were angular speed fixed at 2000 rpm to represent steady state,
241 and resistance was fixed at a temperature of 75°C. There were two different
242 parametric sweeps: root mean square (RMS) current and mechanical angle. RMS
243 current was the variable modified to emulate load variations, using the parametric
244 sweep tool. Nonetheless, it is important to consider that even though mechanical
245 load and RMS current are related it is a simplification of a far more complex
246 relationship involving only the q-axis current component of the RMS current;
247 Nevertheless, at normal operating conditions, the d-axis component is
248 approximately 0, meaning RMS current is similar to the q-axis magnitude
249 (Gundogan & Bakan, 2026). In addition, its parametric sweep was introduced to find
250 at which range of current values saturation occurs by comparing different increases
251 experimented in magnetic flux density in distinct current values. Secondly, electric
252 current was increased beyond the range at which saturation begins and evaluated
253 how it influences mechanical power output. Then, the mechanical angle sweep was
254 made at some punctual electric current values to find the average torque output as
255 current increases. Afterwards, using the result found for average torque, the
256 mechanical power output was calculated by plugging the values into the mechanical
257 power formula. Subsequently, overall efficiency was calculated using the ratio
258 between mechanical power output at specific current values over electrical power
259 input, which was estimated by adding copper losses and mechanical output, since
260 copper losses account for more than half of total losses in electric motors (Saidur,
261 2010).

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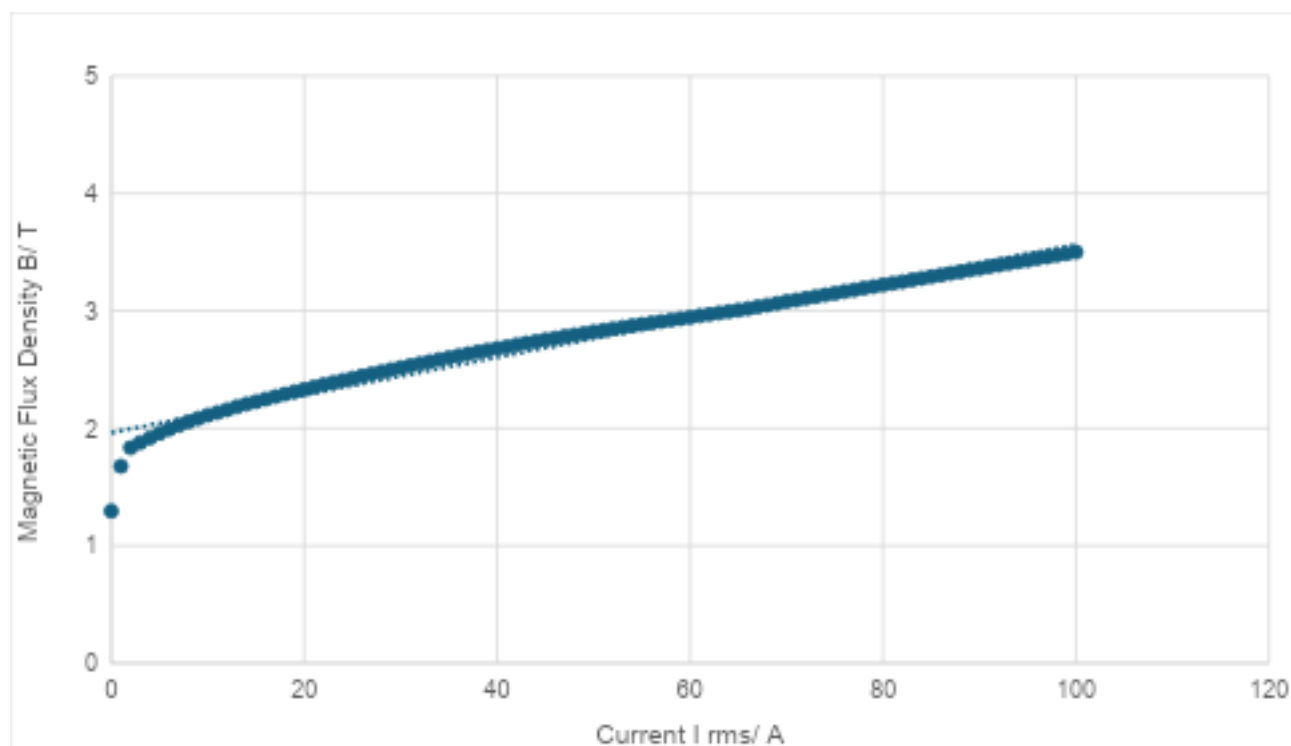
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274 4. Results

275 Figure 4

276 *Magnetic flux density vs. I RMS graph*

277 The graph shows the relationship between RMS current and the maximum magnetic flux within the
278 stator. Each point corresponds to a value of magnetic flux density for currents from zero to 100 A.



279

280 Although magnetic flux density continues to increase, it follows a nonlinear
281 path that reduces the pace at which B increases as current becomes greater. For
282 instance, to increase one T in flux density, initially, it takes about a 15 A increase,
283 but the next increase of one T demands 63 more A than the last increase. That

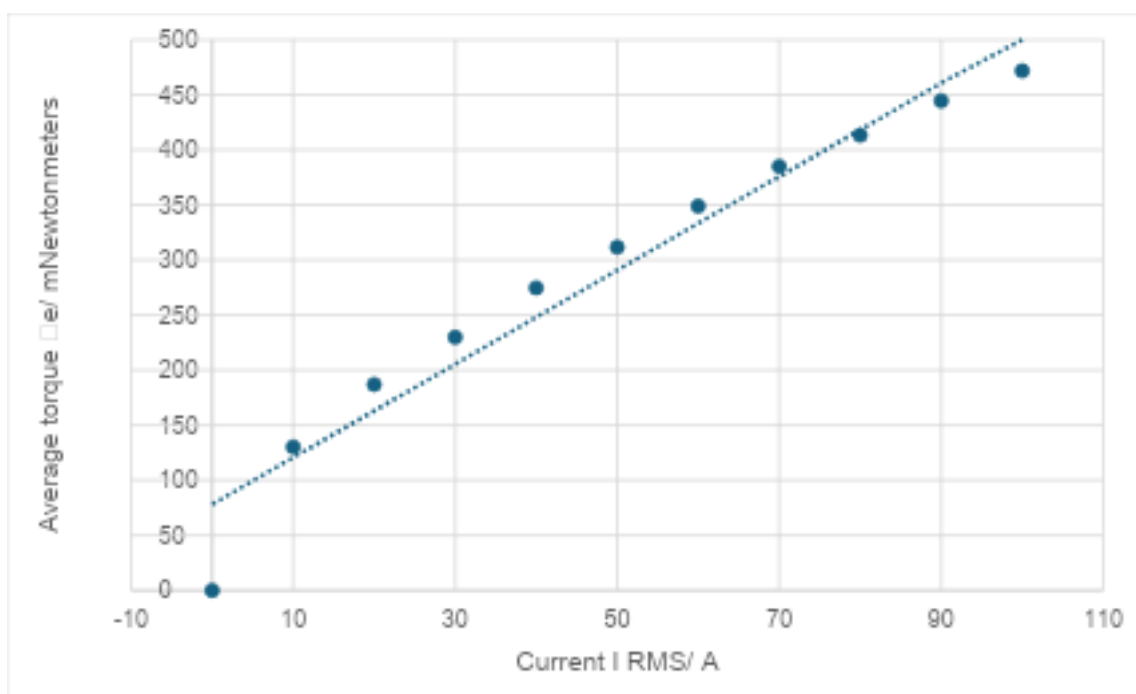
284 means that the magnetic flux density produced by the current starts to stabilize,
285 since it takes more than four times the current to increase it by the same amount.

286 Moreover, the incremental slope between the increase experimented from 1
287 to 15 A, where most prominent gains seem to be concentrated is approximately 0.55
288 T, whereas the increase experimented from 16 to 30 A, the next 15 A of current is
289 nearly 0.27 T. The ratio between those two slopes is 0.49 that means that although
290 only 15 A apart the second slope is already 49% of the first, showing that saturation
291 possibly starts within 10 to 20 where increases get significantly smaller. Conversely,
292 if compared the increases from 16-30 A and 31-45 A the ratio becomes 0.82,
293 indicating magnetic flux density is stabilizing. Consequently, increasing current
294 input saturates magnetic flux density which in turn limits torque production.

295 Figure 5

296 *Average torque vs. RMS current graph*

297 This graph presents the variation of average torque with increasing current. Average torque values
298 are binned by 10 A of current input. The trend followed by the average torque is nonlinear, almost
299 logarithmic.



300

301 Figure 5 showcases signs that average torque started to stabilize after a
302 sequence of increases in current, reducing the rate of gains in torque. For example,
303 the increase produced by the first 10 A is 130 mNewtonmeters, whereas the

304 increase of 10 A from 90 A to 100 A is 27 mNewtonmeters, showing a reduction of
305 79.3% on the ratio of increments in average torque, aligning with the
306 disproportionality showed previously on magnetic flux density, since it caps torque
307 production. Since torque is one of the components of mechanical power, its
308 stabilization stalls mechanical power values.

309

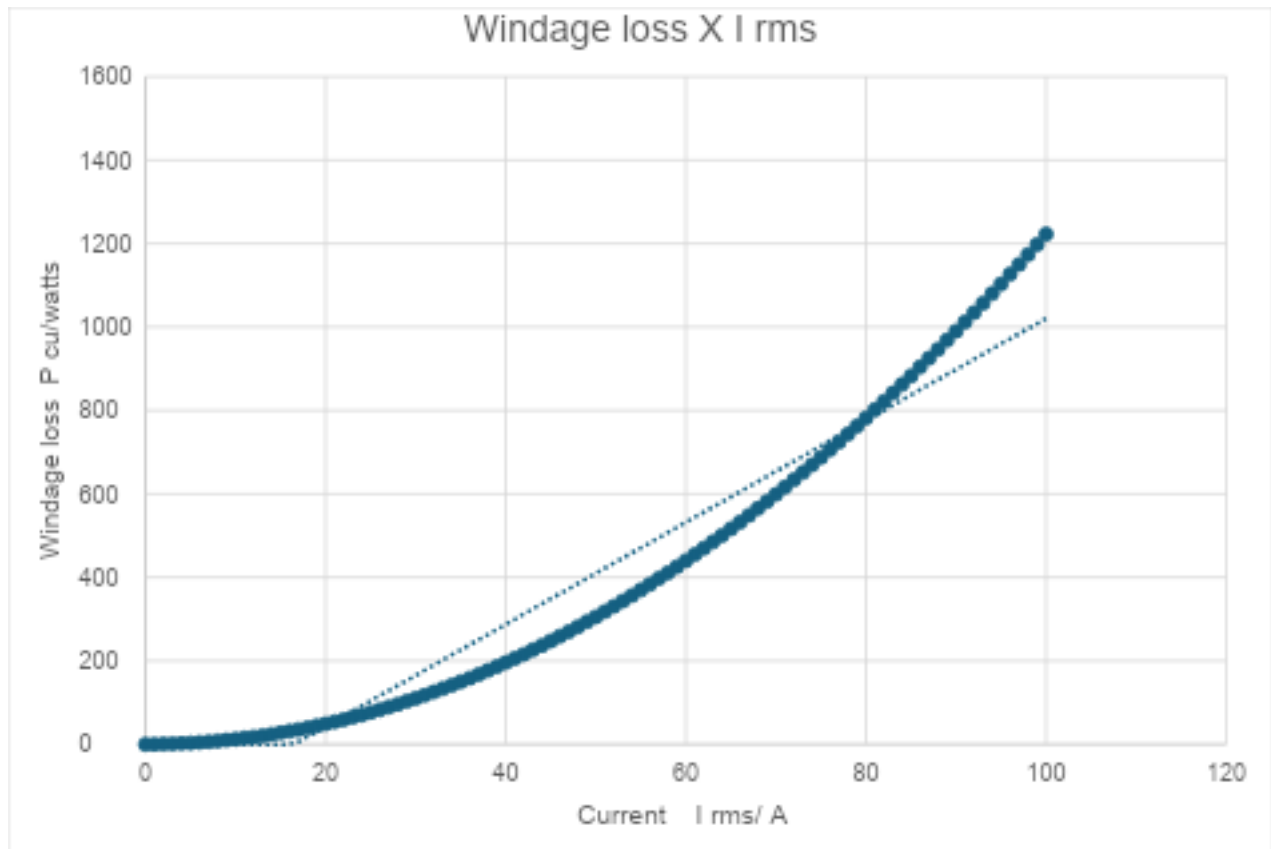
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311

312 Figure 6

313 *Copper losses vs. I RMS graph*

314 The graph of Figure 6 illustrates copper losses in function of RMS current, each value of power lost
315 due to heat is spaced by 1 A from 0 to 100 A, exhibiting a behavior close to exponential growth.



316

317 The behavior illustrated in this figure is close to exponential growth, since
318 the rate copper losses increase grows steeply at every step exemplified in the final
319 values as the separation among the points becomes more prominent. Up to 40 A

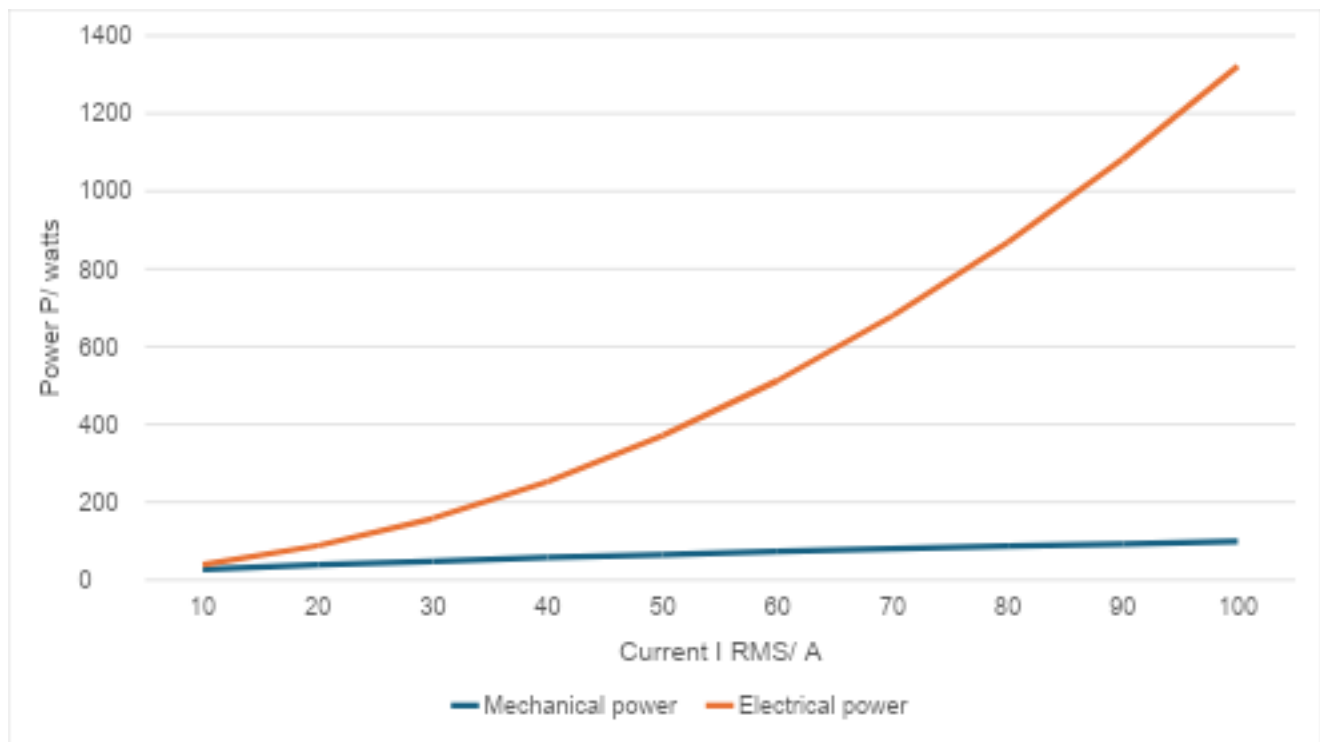
copper losses comprise approximately 200 watts, but as current increases to 60 A, losses are more than twice the value registered at 40, and at 100 A, copper losses are responsible for more than 1,200 watts. This scenario is one that the PMSM increases electrical power input trying to make up for increasing load conditions, but this behavior causes magnetic saturation and compounds copper losses. Therefore, as shown in Fig. 6, operating a PMSM beyond the start of saturation can massively impact the amount of electrical power dissipated as heating, highlighting its impact on efficiency.

328

329 Figure 7

330 *Electrical input and mechanical output vs. RMS current graph*

331 Figure 7, portrays a comparison between electrical power input, represented by the orange line, and
332 mechanical power output, represented by the blue line, both as a function of RMS current. It
333 highlights how mechanical output is outgrown by electrical input when factoring saturation.



334

335 Electrical input was calculated by adding windage losses with mechanical
336 power output. Despite that, electrical input is underestimated, since iron core and
337 eddy current losses were not taken into consideration (Saidur, 2010). Furthermore,
338 the mechanical output due to software's limitations and angular speed not being

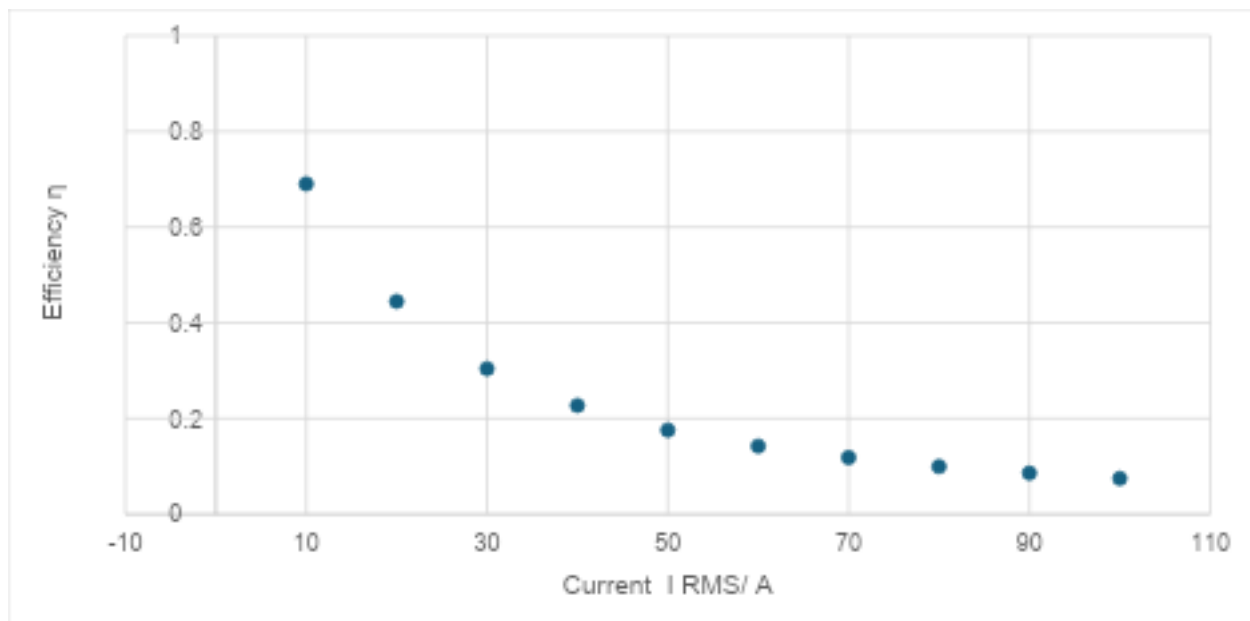
339 directly related to magnetic field density, the value of angular speed was chosen as
340 2000 rpm, which converted into rad/s, is approximately 209. Nonetheless, the
341 angular speed is fixed since it is a magnetostatic analysis.

342 In lower electrical power input values, the mechanical output is almost
343 equivalent to it, but as the current increases beyond where saturation starts the
344 mechanical output starts to stall. The electrical power input skyrockets, whereas
345 the mechanical power output does not follow up, rather it stabilizes and achieves a
346 plateau at 98 watts. This difference between electrical power input and mechanical
347 power output is staggering to the point it is more than 1,119 watts. The stagnation of
348 torque and the steep increase of copper losses cause such disparity between them,
349 making it reasonable to understand why overall efficiency drops when operating a
350 PMSM in saturation.

351 Figure 8

352 *Efficiency vs. RMS current graph*

353 Figure 8 is a scatterplot of the RMS current and the overall efficiency calculated spaced by 10 A. This
354 scatterplot presents the decline in efficiency as a consequence of the previous results.



355

356 This scatterplot exposes how efficiency plummets as more current runs
357 into the system, and it starts to converge towards 0, despite it not being possible
358 unless the motor is stopped. At 10 A, efficiency is decently high with approximately

359 70%, but after surpassing 20 A, the efficiency is below 50 %, which continues to
360 decline at a fast pace, only at 7.47% efficiency when the current reaches 100 A.

361 5. Discussion

362 As stated in the hypothesis, it was expected that when load conditions are
363 increased, the saturated PMSM would draw additional current into the system.
364 However, the additional current would not be directly converted into mechanical
365 output gains, but rather diminish gains as current increases. This nonlinear relation
366 between electrical power input and mechanical power output was a result of the
367 rapid increase in copper losses, causing overall efficiency to drop.

368 In this sense, as shown in the analysis, this behavior is followed. Figure 4
369 shows that more current does not equal proportional gains in magnetic flux
370 density. Next, since the rate of gains in magnetic flux density was held back around
371 10-20 A, average torque follows the same path. Since torque is affected, mechanical
372 power growth was also impacted negatively, whereas copper losses rose sharply.
373 Consequently, the disproportion between electrical power input and mechanical
374 power output grows massively to the point that overall efficiency plummets, falling
375 from around 70% at 10A to 7.5% at 100 A.

376 Nonetheless, this simulation and analysis have some limitations. In spite of
377 using Ansys Student Maxwell for free and it being one of the most detailed, largely
378 used software, it brought some limitations. In the first place, a magnetostatic
379 simulation was done, which is not the most realistic, since it assumes the motor is
380 fixed at a given position and it does not move from that point, meaning that to have
381 the average torque, a mechanical angle sweep was needed, and there was no
382 angular speed output to have more realistic simulation. Secondly, in magnetostatic
383 simulations, it was not possible to change the load, rather the whole analysis was
384 done in respect to electrical current, since it is directly related to load condition
385 increases (Liu et al., 2018). In terms of losses, due to software limitations,
386 temperature was fixed, in turn meaning resistance remains invariable, which results
387 in an underestimation of losses even further, since that is not a realistic situation.
388 Finally, efficiency was calculated by estimating electrical input as mechanical
389 output plus copper losses, overestimating efficiency, since the other types of losses
390 were neglected.

391 In comparison to previous research, this work connects the impact of
392 increasing loads in causing magnetic saturation and the result of magnetic

saturation in torque, efficiency, and thermal losses, which was the gap found in the literature. However, some of the papers reviewed had different materials, purposes, specifications, and approaches, meaning results may differ between different studies. Furthermore, this work only comprises PMSMs, meaning the results cannot be generalized to other motor types. Nonetheless, the results are consistent to prior work: the nonlinear behavior of the B-H curve, the relationship between increasingly higher electric current and torque (Faustner et al., 2015), the disproportion between increases in electric power input relative to mechanical power output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015), fast rise of copper losses (Burt et al., 2008; Li et al., 2025; Liu et al., 2018; Atay, 2000), and the decline in overall efficiency.

This research is of extreme relevance in the current world scenario, as world's decarbonization efforts rely heavily on EVs and clean energy production. Therefore, understanding the behavior of magnetic saturation and its implications on the electrical power efficiency of PMSMs can aid manufacturers in designing their motors to maximize efficiency and minimize losses, especially copper losses. Reducing these losses mean that EVs can avoid unnecessary power consumption and diminish the number of recharges. Hence, the reduction in energy demand decreases the need for additional power generation and reduces GHG emissions of EVs, depending on the energy source used for electricity generation (Tagliaferri et al., 2016).

On the other hand, copper losses damage central pieces of PMSMs, implying more material is used to replace the damaged pieces. When temperature increases within the windings, copper heats up and the excessive heat damages its insulation leading to short circuits that interrupts the motors' functioning (Tong et al., 2025). Moreover, permanent magnets can be demagnetized permanently if their temperature surpasses a certain level, causing inevitable losses of rare-earth magnets (Guo et al., 2020). Therefore, copper losses can make PMSMs more harmful than beneficial to the environment as those damages demand the extraction of more minerals, which is a highly polluting industry (Moghimidehkordi et al., 2024).

6. Conclusion

In this paper, the causes and consequences of magnetic saturation in an electric motor were discussed. A two-dimensional FEA simulation was set to further understand the impacts of magnetic saturation on a PMSM's efficiency and

428 copper losses. The results confirmed that more current causes the magnetic flux
429 density to stall, which is the primary sign of saturation. Then, it was demonstrated
430 that the mechanical power output is flattened by the limited torque production. In
431 contrast, electrical power input escalates at a faster rate than mechanical output
432 due to the dramatic increase in copper losses causes a sharp decline in overall
433 efficiency.

434 This work was applied to a PMSM motor, though one of the most widely
435 used, there are many different types of electric motors built with different
436 materials and arrangements. Furthermore, size is a factor that can affect the range
437 of values at which saturation starts in different motors. Other possible variations
438 include more realistic resistance behavior and rpm.

439 Future work should focus on redoing the experiment following different
440 approaches: three-dimensional FEA transient simulation, physical experimentation,
441 and a combination with MATLAB and Simulink. A three-dimensional transient
442 simulation provides a better insight into the real dynamics of a PMSM, since the
443 simulation takes into consideration the motor's functioning over time and
444 comprises a complete version of the motor. In comparison, a physical experiment is
445 the most realistic way to understand the impacts of magnetic saturation. Finally,
446 software like MATLAB and Simulink can be combined with the FEA simulation for a
447 more complete analysis of the circuit.

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513

1 A Magnetostatic Analysis of Magnetic Saturation's Impact on PMSM Overall 2 Efficiency and Copper Losses Under Varying Load Conditions.

3 Abstract

4 Currently, electric motors have a wide range of applications across industries and a
5 they are one of the pillars in the world's decarbonization, most notably the
6 permanent magnet synchronous motor (PMSM) due to its efficiency compared to
7 others. This paper's purpose is to analyze the impact of operating a saturated
8 PMSM, under load condition variations, on overall efficiency and copper losses
9 using a finite element analysis (FEA), for which a two-dimensional finite element
10 model was developed in Ansys Maxwell Student software. RMS current was
11 increased in order to simulate load variations; then, electrical power input and
12 mechanical power output were both measured in watts and evaluated to analyze
13 efficiency degradation and copper losses on saturated conditions. The simulation
14 results show that the increasing current supplied to a saturated system does not
15 proportionally equate to magnetic flux density gains, plateauing after increasing
16 beyond the range of values saturation starts, stalling electromagnetic torque, as a
17 result the mechanical power output stagnated. Conversely, as the electrical power
18 input continued to rise it was dissipated as heat rather than mechanical output,
19 hence reducing the overall efficiency. Therefore, the results met the hypothesis,
20 which established that more current driven into the PMSM would not
21 proportionally increase magnetic flux density, gains in mechanical power output
22 would diminish to the point it stagnates, and excess current piles on copper losses,
23 thence reducing overall efficiency. This paper can be used to further understand
24 the effects of magnetic saturation on a PMSM's overall efficiency and copper losses
25 to optimize electrical power usage.

26 Keywords: magnetic saturation, load variation, efficiency, permanent synchronous
27 magnet motors, copper losses.

28 1. Introduction

29 In the modern day, electric motors are used in a variety of utilities that range
30 from basic household appliances to heavy industrial machinery (Saidur, 2010). In
31 fact, they are one of the fundamental pillars in the context of global
32 decarbonization, since electric motors generate lower greenhouse gas (GHG)
33 emissions in comparison to internal combustion engines (ICEs) during their use
34 phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among
35 countries due to the difference between the energy source used for power

36 generation. Moreover, a comparative analysis on the overall efficiency between
37 electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded
38 that the efficiency from battery to wheels ranges from 50% to 80%, whereas the
39 most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it
40 is necessary to consider the energy source used and its efficiency to generate the
41 electricity to provide a more well-rounded analysis, namely: well to wheel. In this
42 perspective EVs' efficiency can drop to similar or lower levels than those found in
43 ICEVs (Albatayneh et al., 2020).

44 Despite the fact that electric motors are more efficient overall, they have a
45 fundamental restraint: magnetic saturation. Magnetic saturation is produced when
46 the magnetic field strength (H) continues to increase, but the magnetic flux density
47 (B) does not increase at the same rate, achieving a plateau (Pjevalica et al., 2015).
48 This circumstance arises in response to higher mechanical loads being applied to
49 the motor, requiring more current to strengthen the magnetic field within the core.
50 Nevertheless, the addition of more current into the system, beyond a certain range
51 of values, drives the core into saturation. For that reason, any further increases in
52 current do not provoke an equivalent gain in magnetic flux density, limiting torque
53 production, thus capping the mechanical power output (See in Figure 1).
54 Additionally, providing additional current into a saturated motor produces a
55 disproportionate gain in mechanical power output, causing a large amount of the
56 excess electrical power input to be dissipated as heat—accounting for 55-60% of all
57 losses in efficiency. Specifically, they are called I^2R losses, since they are derived
58 after Joule's law; hence, as more current is driven into the system, the thermal
59 losses increase as well (Saidur, 2010).

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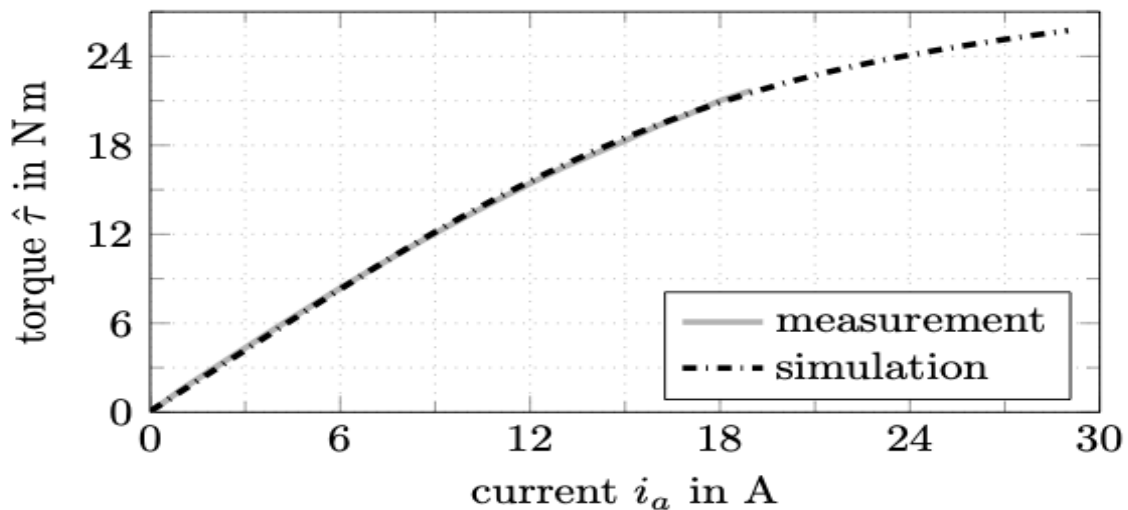
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73

74 Figure 1

75 Relationship between torque and electric current (Faustner et al., 2015)

76 Graph shows torque versus current of a simulated PMSM, showing a nonlinear behavior at higher
77 current levels.



78

79 Previous work on magnetic saturation indicates that its primary cause of
80 magnetic saturation is higher load conditions, which leads to an increase in current
81 supplied to the stator windings. As a consequence, the magnetic field strength (H)
82 increases, but the stator's magnetic flux density (B) does not compound as much
83 due to size and material strains. ~~Thence, further increases in H would reduce flux~~
84 ~~gains following a nonlinear behavior.~~

85 Other studies that analyzed the consequences of saturation on the
86 mechanical power output found a nonlinear relationship between current and
87 torque production. Even though torque keeps increasing with a greater current, the
88 rate at which torque grows reduces significantly under saturation situations,
89 signaling that any excess electrical input does not relate, proportionally, to the
90 motor's mechanical output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015).

91 Similarly, research on PMSMs frequently states that higher current increases
92 copper losses. These losses are dissipated in the stator's windings as heat
93 contribute in reducing energy conversion efficiency (Burt et al., 2008; Li et al., 2025;
94 Liu et al., 2018; Atay, 2000).

95 The combination of the existing literature establishes that the operation of
96 motors in overload leads motors to saturation, providing higher electrical power

input, which increases disproportionately relative to the mechanical power output and escalates the percentage of power lost due to heating. However, there is a gap in present work, which mainly focuses on each of these effects separately and lacks an explicit graphical representation of the power converted into heat and mechanical output when the system is already saturated. Also, researchers do not agree on a common behavior that efficiency suffers as the load varies when the motor is subjected to saturation conditions.

This paper intends to establish a relationship between load variations on a PMSM operating under saturation conditions and the energy converted into mechanical output and copper losses. It is expected that a PMSM, in saturation, with increasing load condition causes the PMSM to draw additional current into the system, but the corresponding mechanical output experience gains increasingly smaller; this disproportion between electrical power input and mechanical power output reduces the motor's overall efficiency, ~~rapidly increasing copper losses within the stator~~. However, this has not been properly connected within the existing literature; in this sense, the purpose of this paper is to establish the relationship between those motor properties affected by magnetic saturation **by conducting a PMSM's magnetostatic simulation** and building upon the literature. This paper is organized as it follows: ~~in first place~~, section 2 expands the theoretical background with more context of **magnetic saturation effects** and the PMSM structure; in section 3, the methods and the PMSM's specific configuration are described; section 4 presents and analyzes the results of the 2D simulation on the impact of operating a saturated PMSM on its **properties**; section 5 discusses the significance of the results, limitations, **and a comparison to the literature reviewed to guide the simulation and paper**; and finally, section 6 concludes the paper with some suggestions on future research.

2. Context

In this section, supplementary context is provided to understand more deeply the relationship between magnetic flux density, electromagnetic torque, mechanical power output, copper losses, and overall efficiency, and what these equations show based on the hypothesis. Additionally, **this paper characterizes PMSMs and their components.**

2.1 Mechanical output in saturation

As forementioned in the literature review, magnetic saturation happens when magnetic field strength (H), measured in amperes per meter, continues to increase, but the magnetic flux density (B), measured in Tesla, does not increase

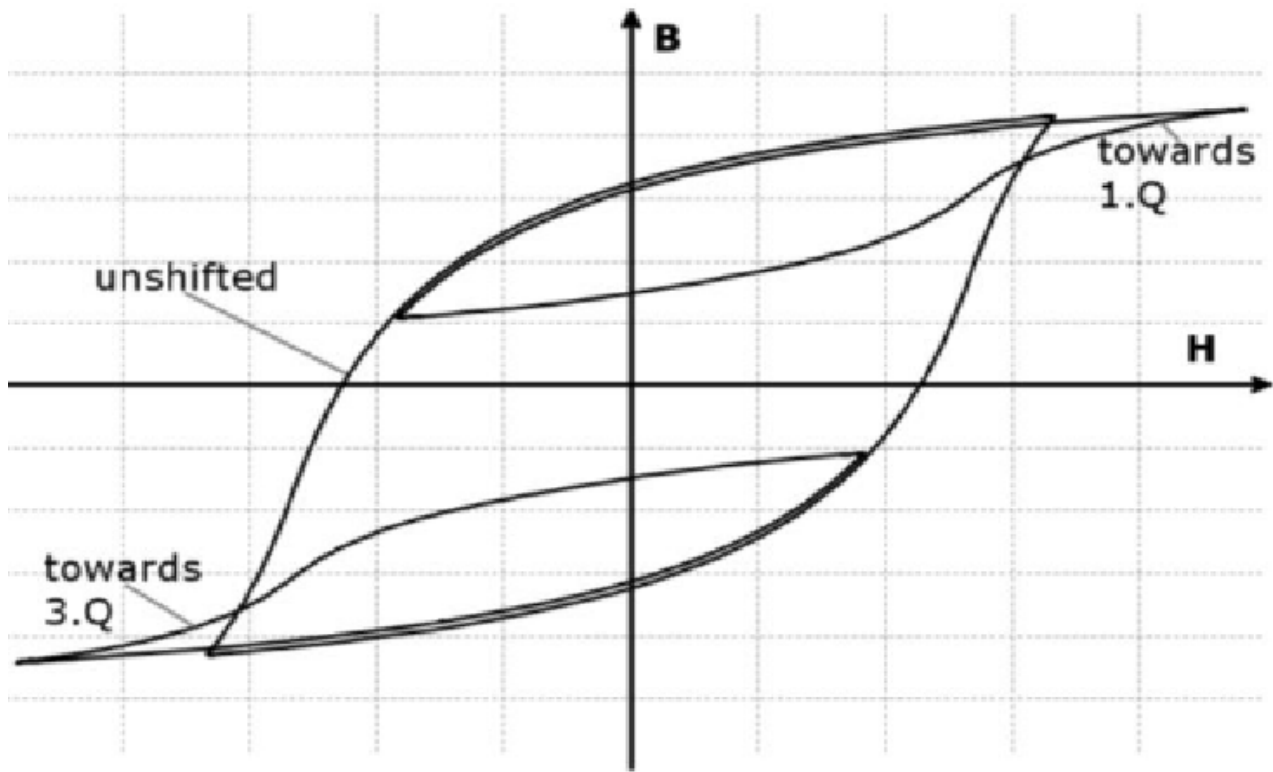
proportionally. , following a nonlinear behavior known as the B-H curve, as shown in Figure 2:

135

Figure 2

B-H behavior of the stator core by the influence of the windings' induced magnetic field (Pjevalica et al., 2015)

This figure exhibits the B-H curve that follows a nonlinear behavior as magnetic field strength increases due to higher current levels.



141

This behavior can be further understood when the equation that links B and H is analyzed:

144

$$B = \mu_0(H + M(H)) \quad (1)$$

Where $\mu_0 = 4\pi \cdot 10^{-7} [T \cdot m \cdot A^{-1}]$ is the constant of vacuum's magnetic permeability, and M is the material magnetization, measured in A/m. At first, magnetization increases in proportion to H, but the material has a magnetization limit, causing M to plateau despite increases in H. As a consequence, increases in magnetic flux

density diminish gradually, leading to saturation and making increases in flux density look almost insignificant as more current is driven into the system.

In this sense, the range of values in which saturation starts can be identified based on the reduction of incremental slope. This method consists in comparing in a ratio the local slope of certain values in low current and at higher current, setting a measurable bar to compare increases, in which 1 means they are the same and they become smaller as saturation is achieved (Zhu et al., 2021).

The direct relationship between torque and magnetic flux density explains the reason why the stagnation in magnetic flux density limits torque production. The formula used to calculate torque, in most 2D FEA models, is based on the Maxwell stress tensor surface integral that calculates the electromagnetic torque (T_e). The equation is displayed below: (Popescu, 2006; Shin et al., 2021)

$$T_e = \frac{1}{\mu_0} \int_0^{2\pi} r^2 B_r B_\theta d\theta \quad (2)$$

Where B_r B_θ are the radial and tangential components of the flux density B, r is the radius of the circle limited by the outer diameter air gap. In 2D models, the surface integral from the Maxwell stress tensor is turned into a line integral along the air gap.

Likewise, when torque stagnates, the mechanical power output is also stalled, because it is proportional to the torque, as it is shown in the equation below:

$$P_{mech} = T_e \times \omega \quad (3)$$

Where P_{mech} is the mechanical power output, T_e is the electromagnetic torque used in FEA simulations, and ω is the PMSM's angular speed, measured in RPM. In most PMSM simulations, angular speed is assumed to be constant, since magnetic saturation does not directly relate to the angular speed formula. Additionally, the only situation that could impact the angular speed is in the case the load exceeds the saturated torque capability, meaning that the motor cannot sustain constant angular speed, as a result decreasing angular speed.

2.2 Overall efficiency

178 A motor's overall efficiency is calculated based on the ratio between
179 mechanical power output and electrical power input, illustrated in the formula
180 below:

$$181 \quad \eta = \frac{P_{mech}}{P_{elec}} \quad (4)$$

182 While electrical input soars, mechanical power output does not increase the same
183 amount when the motor is saturated, reducing overall efficiency. Furthermore, if
184 overall efficiency drops, the excess energy needs to be converted into another sort
185 of energy: thermal energy that it is possible to predict using Joule's law:

$$186 \quad P = n I^2 R(T) \quad (5)$$

187 Where the resistance (R) is dependent on the coil's temperature (T) and n is the
188 number of motor phases. ~~Joule's law is used to calculate the power lost.~~ Since the
189 formula depends on current, it is expected that losses will mount as more current is
190 driven into the system. (Tong et al., 2025) ~~Therefore, copper losses have a direct~~
191 ~~relation with the motor's saturation.~~

192 However, it is important to acknowledge that there are more types of losses:
193 iron, friction and windage, and stray losses. Iron and friction and windage losses are
194 considered independent to the load, meaning that more current will not increase
195 these types of losses; also, they make up around 26% of losses, which is small
196 compared to almost 60% that copper losses achieve as load is increased. Although
197 the stray losses are generally proportional to the square of the current in the stator,
198 it only comprises 15% of all losses. In this sense, copper losses were the only taken
199 into consideration due to its significance compared to the other losses and its
200 relationship with electric current.

201 2.3 Permanent Magnet Synchronous Motor (PMSM)

202 A PMSM is a type of AC electric motor that consists of two main parts: the
203 stator and the rotor (see Figure 3). The stator consists of two components: the
204 stator core and the stator windings. The core is composed of laminated silicon
205 sheets to house the stator windings and reduce energy loss; the stator windings are
206 sets of coils wound inside cages within the stator's core and are fed with electric
207 current to create a rotating magnetic field. Similarly, the rotor has two components:
208 the rotor core and permanent magnets. The rotor core serves almost the same
209 utility as the stator core, it is the structure that sustains the permanent magnets

that will rotate due to the induced rotating magnetic field, and in this case, it was a surface-mounted rotor; the permanent magnets supply a constant magnetic field that will make the rotor rotate when interacting with the stator's windings. In addition, like any other AC motor, PMSMs have phases, in order to most closely emulate a real PMSM it was chosen to use the most common number of phases: three (Mersha & Du, 2022).

3 Methods

In this section, a complete description of the PMSM configuration is shown based on the details of the numerical model imported and modified. Additionally, the methodology used to investigate the effects of operating a saturated PMSM on its overall efficiency and copper losses is presented.

3.1 Configuration

The surface-mounted PMSM model was imported from RMxpert's examples file, tool embedded in the Ansys Maxwell student version software. Tables 1, 2, and 3 show the motor's structural parameters, and Figure 3 shows a picture of the motor's design (Mersha & Du, 2022).

Table 1

Stator's specifications

Parameters	Values
Stator outer diameter	120 mm
Stator inner diameter	75 mm
Length of stator core	65 mm
Stacking factor	0.95
Steel type	M19-24G
Number of slots	24
Slot type	2
Skew width	0

Table 2

Rotor's specifications

Parameters	Values
------------	--------

Rotor outer diameter	74 mm
Rotor inner diameter	26 mm
Length of the rotor core	65 mm
Steel type	M19-24G
Stacking factor of rotor core	0.95
Number of poles	4
Pole type	1
Air gap	1 mm

231

232 Table 3

233 *Permanent magnet's specifications*

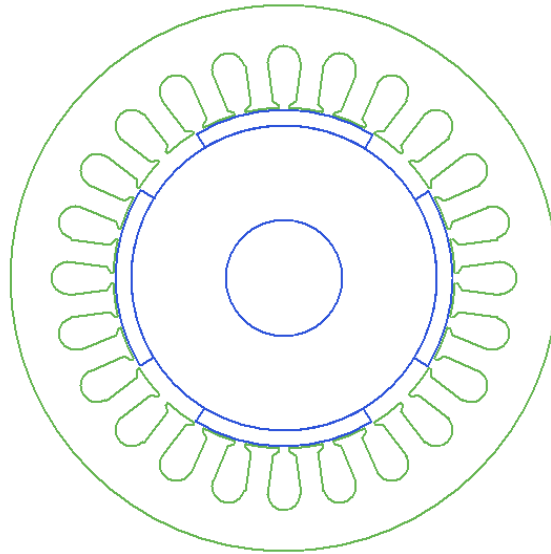
Parameters	Value
Embrace	0.7
Offset	0 mm
Magnet type	Ceramic8D
Magnet thickness	3.5 mm

234

235 Figure 3

236 *RMxpvt modified model*

237 The cross-sectional view of the 2-D PMSM model setup, with the stator and rotor highlighted in
238 green and blue, respectively. Image obtained from the researcher's experimental setup in Ansys
239 Maxwell.



240

241 A two-dimensional model was chosen, since the differences with a
 242 three-dimensional model are minimal and a 2-D model demands less computational
 243 capacity in order to simulate the parameters.

244 3.2 Numerical model

245 The solution type used for the simulation was magnetostatic. Moreover, the
 246 constant variables were angular speed fixed at 2000 rpm to represent steady state,
 247 and resistance was fixed at a temperature of 75°C. There were two different
 248 parametric sweeps: root mean square (RMS) current and mechanical angle. RMS
 249 current was the variable modified to emulate load variations, using the parametric
 250 sweep tool. Nonetheless, it is important to consider that even though mechanical
 251 load and RMS current are related it is a simplification of a far more complex
 252 relationship involving only the q-axis current component of the RMS current;
 253 Nevertheless, at normal operating conditions, the d-axis component is
 254 approximately 0, meaning RMS current is similar to the q-axis magnitude
 255 (Gundogan & Bakan, 2026). In addition, its parametric sweep was introduced to find
 256 at which range of current values saturation occurs by comparing different increases
 257 experimented in magnetic flux density in distinct current values. Secondly, electric
 258 current was increased beyond the range at which saturation begins and evaluated
 259 how it influences mechanical power output. Then, the mechanical angle sweep was
 260 made at some punctual electric current values to find the average torque output as
 261 current increases. Afterwards, using the result found for average torque, the
 262 mechanical power output was calculated by plugging the values into the mechanical
 263 power formula. Subsequently, overall efficiency was calculated using the ratio

264 between mechanical power output at specific current values over electrical power
265 input, which was estimated by adding copper losses and mechanical output, since
266 copper losses account for more than half of total losses in electric motors (Saidur,
267 2010).

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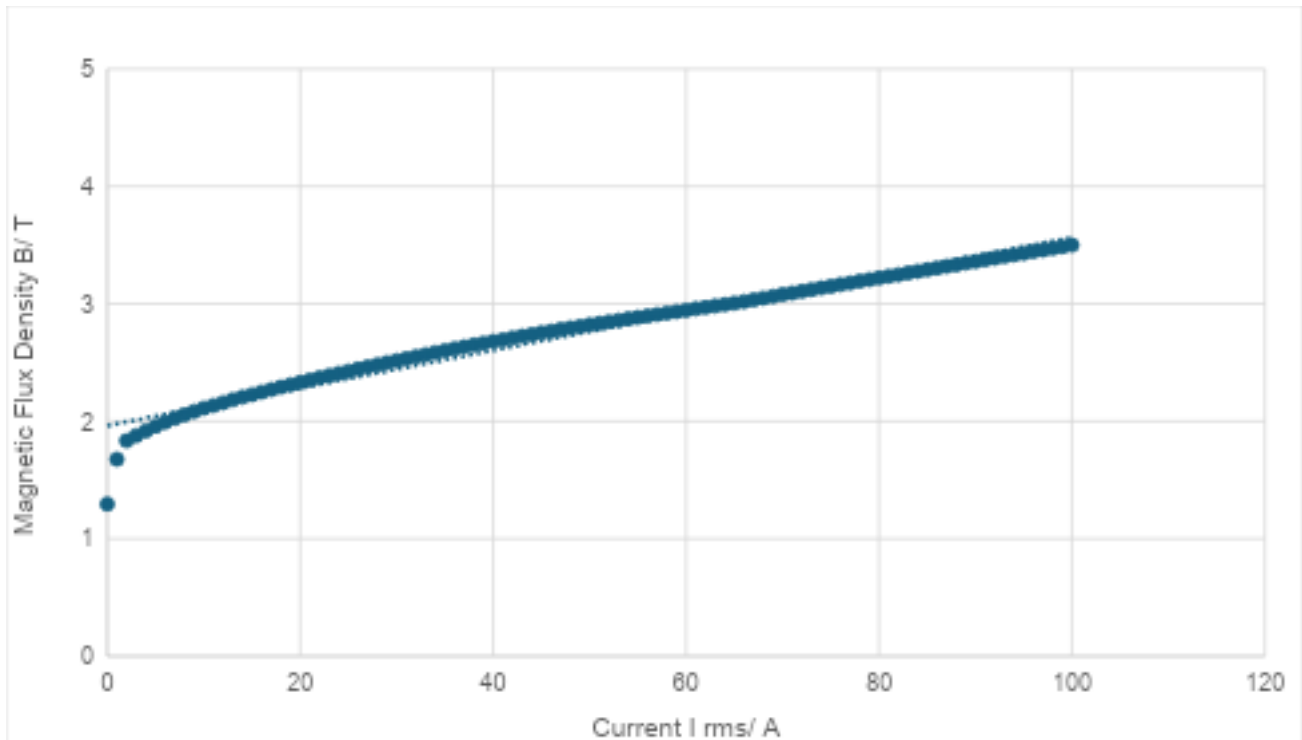
279

280 **4. Results**

281 Figure 4

282 *Magnetic flux density vs. I RMS graph*

283 The graph shows the relationship between RMS current and the maximum magnetic flux within the
284 stator. Each point corresponds to a value of magnetic flux density for currents from zero to 100 A.



285

286 In Figure 4, a graph is shown between RMS current and the maximum
 287 magnetic flux density identified within the stator, each point is the correspondent
 288 value of magnetic flux density to current, from zero to 100 ampere. Although
 289 magnetic flux density continues to increase, it follows a nonlinear path that reduces
 290 the pace at which B increases as current becomes greater. For instance, to increase
 291 one T in flux density, initially, it takes about a 15 A increase, but the next increase of
 292 one T demands 63 more A than the last increase. That means that the magnetic flux
 293 density produced by the current starts to stabilize, since it takes more than four
 294 times the current to increase it by the same amount. Thence, the saturation point is
 295 around 15 A, since the gains get significantly smaller when compared to previous
 296 values. Further increases in current will generate less and less further increases in
 297 magnetic flux density, which indicates a saturation behavior.

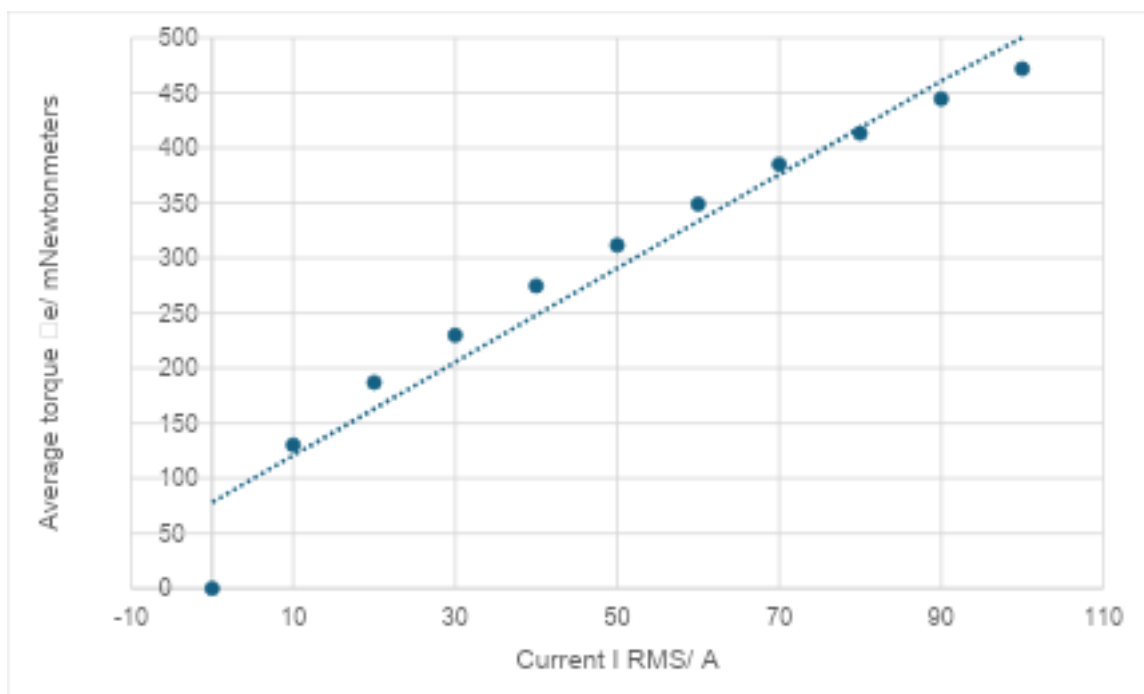
298 Moreover, the incremental slope between the increase experimented from 1
 299 to 15 A, where most prominent gains seem to be concentrated is approximately 0.55
 300 T, whereas the increase experimented from 16 to 30 A, the next 15 A of current is
 301 nearly 0.27 T. The ratio between those two slopes is 0.49 that means that although
 302 only 15 A apart the second slope is already 49% of the first, showing that saturation
 303 possibly starts within 10 to 20 where increases get significantly smaller. Conversely,
 304 if compared the increases from 16-30 A and 31-45 A the ratio becomes 0.82,

305 indicating magnetic flux density is stabilizing. Consequently, increasing current
306 input saturates magnetic flux density which in turn limits torque production.

307 Figure 5

308 Average torque vs. RMS current graph

309 This graph presents the variation of average torque with increasing current. Average torque values
310 are binned by 10 A of current input. The trend followed by the average torque is nonlinear, almost
311 logarithmic.



312
313 ~~Figure 5 shows how average torque changes as a result of increases in~~
314 ~~current, the values of average torque shown are apart by 10 A of current input. The~~
315 ~~trend followed by the average torque is nonlinear, almost logarithmic.~~ Figure 5
316 showcases signs that average torque started to stabilize after a sequence of
317 increases in current, reducing the rate of gains in torque. For example, the increase
318 produced by the first 10 A is 130 mNewtonmeters, whereas the increase of 10 A
319 from 90 A to 100 A is 27 mNewtonmeters, showing a reduction of 79.3% on the ratio
320 of increments in average torque, aligning with the disproportionality showed
321 previously on magnetic flux density, since it caps torque production. Since torque is
322 one of the components of mechanical power, its stabilization stalls mechanical
323 power values. and impacts negatively overall efficiency.

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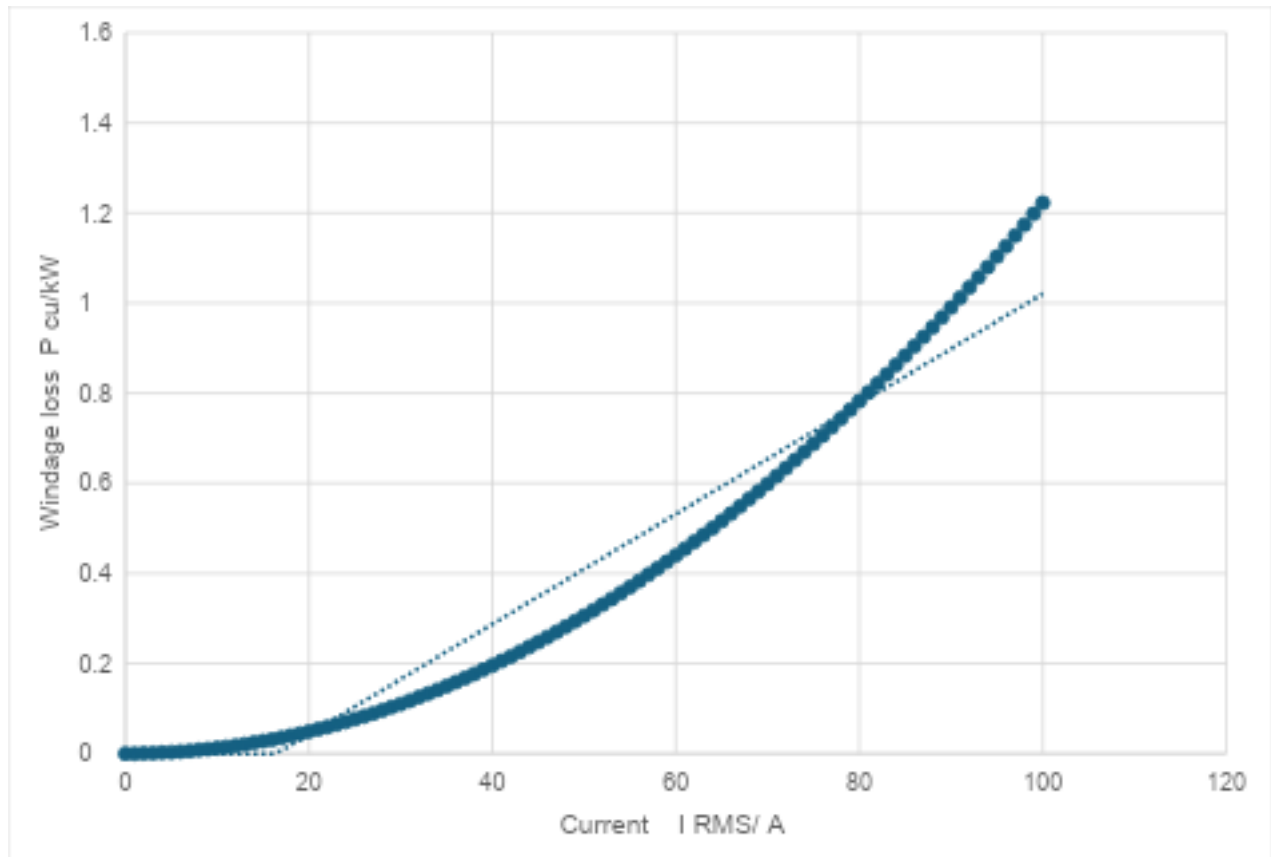
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328 Figure 6

329 Copper losses vs. I RMS graph

330 The graph of Figure 6 illustrates copper losses in function of RMS current, each value of power lost
331 due to heat is spaced by 1 A from 0 to 100 A, exhibiting a behavior close to exponential growth.



332

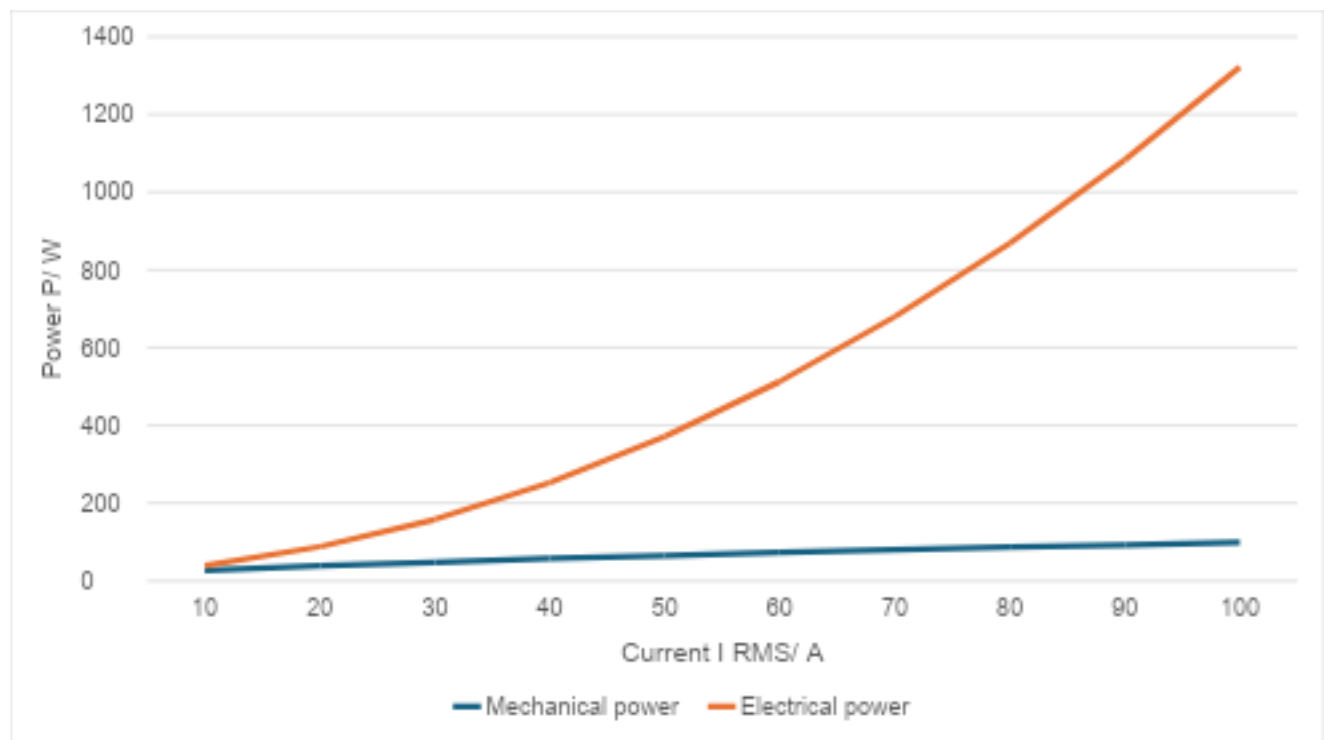
333 The graph shown in Figure 6 illustrates the relationship between copper
334 losses and RMS current, each value of power lost due to heat is spaced by 1 A from 0
335 to 100 A. The behavior illustrated in this figure is close to exponential growth, since
336 the rate copper losses increase grows steeply at every step exemplified in the final
337 values as the separation among the points becomes more prominent. Up to 40 A
338 copper losses comprise approximately 200 watts, but as current increases to 60 A,
339 losses are more than twice the value registered at 40, and at 100 A, copper losses
340 are responsible for more than 1,200 watts lost to heating. This behavior is assigned
341 to Joule's law, since copper losses increase with the square of the RMS current. This

scenario is one that the PMSM increases electrical power input trying to make up for increasing load conditions, but this behavior causes magnetic saturation and compounds copper losses. Therefore, as shown in Fig. 6, operating a PMSM beyond the start of saturation can massively impact the amount of electrical power dissipated as heating, highlighting its impact on efficiency.

Figure 7

Electrical input and mechanical output vs. RMS current graph

Figure 7, portrays a comparison between electrical power input, represented by the orange line, and mechanical power output, represented by the blue line, both as a function of RMS current. It highlights how mechanical output is outgrown by electrical input when factoring saturation.



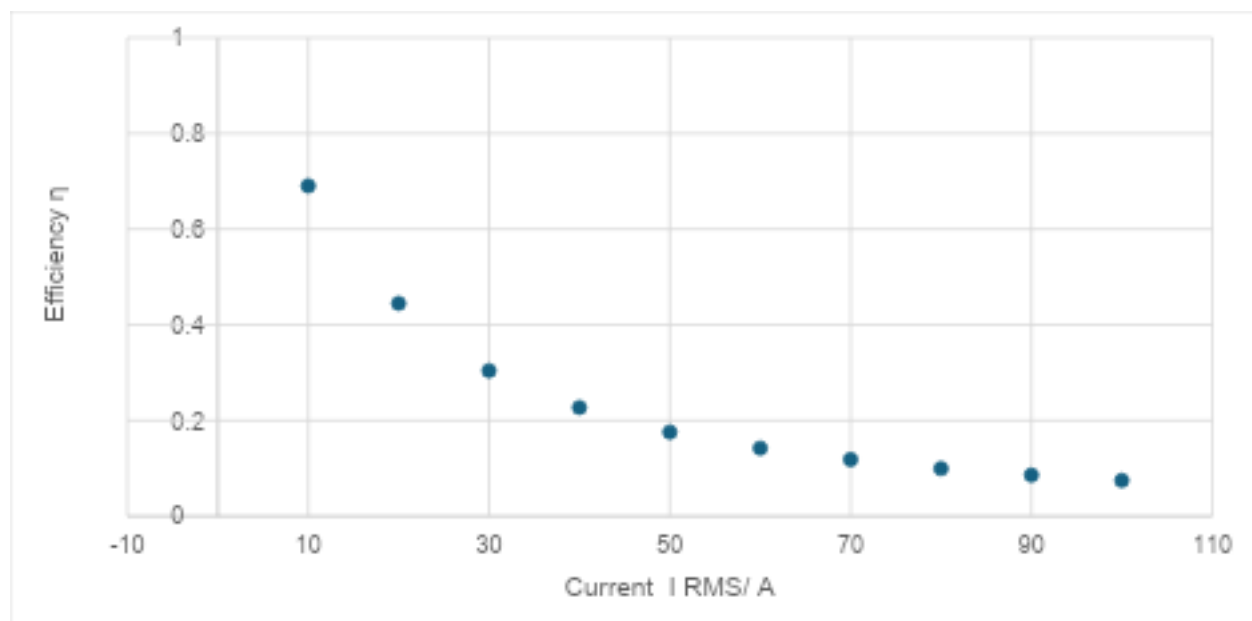
Electrical input was calculated by adding windage losses with mechanical power output. Despite that, electrical input is underestimated, since iron core and eddy current losses were not taken into consideration due to copper losses being a variable type of loss that takes up to 60% of all the losses in an electric motor (Saidur, 2010). Furthermore, the mechanical output due to software's limitations and angular speed not being directly related to magnetic field density, the value of angular speed was chosen as 2000 rpm, which converted into rad/s, is approximately 209. Nonetheless, the angular speed is fixed since it is a magnetostatic analysis.

362 In Figure 7, it is illustrated how mechanical output gets outgrown by
363 electrical input when taken saturation into consideration and comparing on a
364 graph. In lower electrical power input values, the mechanical output is almost
365 equivalent to it, but as the current increases beyond where saturation starts the
366 mechanical output starts to stall. Since increasing current causes greater copper
367 losses, The electrical power input skyrockets, whereas the mechanical power
368 output does not follow up, rather it stabilizes and achieves a plateau at 98 watts.
369 This difference between electrical power input and mechanical power output is
370 staggering to the point it is more than 1,119 watts. The stagnation of torque and the
371 steep increase of copper losses cause such disparity between them, making it
372 reasonable to understand why overall efficiency drops when operating a PMSM in
373 saturation.

374 Figure 8

375 *Efficiency vs. RMS current graph*

376 Figure 8 is a scatterplot of the RMS current and the overall efficiency calculated spaced by 10 A. This
377 scatterplot presents the decline in efficiency as a consequence of the previous results.



379 Lastly, Figure 8, a scatterplot of the RMS current and the overall
380 efficiency calculated is shown. This scatterplot exposes how efficiency plummets as
381 more current runs into the system, and it starts to converge towards 0, despite it
382 not being possible unless the motor is stopped. At 10 A, efficiency is decently high
383 with approximately 70%, but after surpassing 20 A, the efficiency is below 50 %,

384 which continues to decline at a fast pace, only at 7.47% efficiency when the current
385 reaches 100 A. ~~Due to magnetic saturation, mechanical power output stalls,~~
386 ~~whereas the electrical power input continues to increase rapidly.~~

387 5. Discussion

388 As stated in the hypothesis, it was expected that when load conditions are
389 increased, the saturated PMSM would draw additional current into the system.
390 However, the additional current would not be directly converted into mechanical
391 output gains, but rather diminish gains as current increases. This nonlinear relation
392 between electrical power input and mechanical power output was a result of the
393 rapid increase in copper losses, causing overall efficiency to drop.

394 In this sense, as shown in the analysis, this behavior is followed. Figure 4
395 shows that more current does not equal proportional gains in magnetic flux
396 density. Next, since the rate of gains in magnetic flux density was held back **around**
397 **10-20 A**, average torque follows the same path. Since torque is affected, mechanical
398 power growth was also impacted negatively, whereas copper losses rose sharply.
399 Consequently, the disproportion between electrical power input and mechanical
400 power output grows massively to the point that overall efficiency plummets, falling
401 from around 70% at 10A to 7.5% at 100 A.

402 Nonetheless, this simulation and analysis have some limitations. In spite of
403 using Ansys Student Maxwell for free and it being one of the most detailed, largely
404 used software, it brought some limitations. In the first place, a magnetostatic
405 simulation was done, which is not the most realistic, since it assumes the motor is
406 fixed at a given position and it does not move from that point, meaning that to have
407 the average torque, a mechanical angle sweep was needed, and there was no
408 angular speed output to have a more realistic simulation. Secondly, in
409 magnetostatic simulations, it was not possible to change the load, rather the whole
410 analysis was done in respect to electrical current, since it is directly related to load
411 condition increases (Liu et al., 2018). In terms of losses, due to software limitations,
412 temperature was fixed, in turn meaning resistance remains invariable, which results
413 in an underestimation of losses even further, since that is not a realistic situation.
414 Finally, efficiency was calculated by estimating electrical input as mechanical
415 output plus copper losses, overestimating efficiency, since the other types of losses
416 were **neglected**.

417 In comparison to previous research, this work connects the impact of
418 increasing loads in causing magnetic saturation and the result of magnetic
419 saturation in torque, efficiency, and thermal losses, which was the gap found in the
420 literature. However, some of the papers reviewed had different materials, purposes,
421 specifications, and approaches, meaning results may differ between different
422 studies. Furthermore, this work only comprises PMSMs, meaning the results cannot
423 be generalized to other motor types. Nonetheless, the results are consistent to
424 prior work: the nonlinear behavior of the B-H curve, the relationship between
425 increasingly higher electric current and torque (Faustner et al., 2015), the
426 disproportion between increases in electric power input relative to mechanical
427 power output (Chen et al., 2016; Liu et al., 2018; Faustner et al., 2015), fast rise of
428 copper losses (Burt et al., 2008; Li et al., 2025; Liu et al., 2018; Atay, 2000), and the
429 decline in overall efficiency.

430 This research is of extreme relevance in the current world scenario ~~focused~~
431 ~~on sustainability~~, as world's decarbonization efforts rely heavily on EVs and clean
432 energy production. Therefore, understanding the behavior of magnetic saturation
433 and its implications on the electrical power efficiency of PMSMs can aid
434 manufacturers in designing their motors to maximize efficiency and minimize
435 losses, especially copper losses ~~that increase under higher load conditions~~.
436 Reducing these losses mean that EVs can avoid unnecessary power consumption
437 and diminish the number of recharges. Hence, the reduction in energy demand
438 decreases the need for additional power generation and reduces GHG emissions of
439 EVs, depending on the energy source used for electricity generation (Tagliaferri et
440 al., 2016).

441 On the other hand, copper losses damage central pieces of PMSMs, implying
442 more material is used to replace the damaged pieces. When temperature increases
443 within the windings, copper heats up and the excessive heat damages its insulation
444 leading to short circuits that interrupts the **motors'** functioning (Tong et al., 2025).
445 Moreover, permanent magnets can be demagnetized permanently if their
446 temperature surpasses a certain level, causing inevitable losses of rare-earth
447 magnets (Guo et al., 2020). Therefore, copper losses can make **PMSMs more**
448 **harmful than beneficial to the environment** as those damages demand the
449 extraction of more minerals, which is a highly polluting industry (Moghim
450 Dehkordi et al., 2024).

451 6. Conclusion

452 In this paper, the causes and consequences of magnetic saturation in an
453 electric motor were discussed. A two-dimensional FEA simulation was set to
454 further understand the impacts of magnetic saturation on a PMSM's efficiency and
455 copper losses. The results confirmed that more current causes the magnetic flux
456 density to stall, which is the primary sign of saturation. Then, it was demonstrated
457 that the mechanical power output is flattened by the limited torque production. In
458 contrast, electrical power input escalates at a faster rate than mechanical output
459 due to the dramatic increase in copper losses causes a sharp decline in overall
460 efficiency.

461 This work was applied to a PMSM motor, though one of the most widely
462 used, there are many different types of electric motors built with different
463 materials and arrangements. Furthermore, size is a factor that can affect the range
464 of values at which saturation starts in different motors. Other possible variations
465 include more realistic resistance behavior and rpm.

466 Future work should focus on redoing the experiment following different
467 approaches: three-dimensional FEA transient simulation, physical experimentation,
468 and a combination with MATLAB and Simulink. A three-dimensional transient
469 simulation provides a better insight into the real dynamics of a PMSM, since the
470 simulation takes into consideration the motor's functioning over time and
471 comprises a complete version of the motor. In comparison, a physical experiment is
472 the most realistic way to understand the impacts of magnetic saturation. Finally,
473 software like MATLAB and Simulink can be combined with the FEA simulation for a
474 more complete analysis of the circuit.

475 7. Acknowledgements

476 This paper was mentored by Professor Andrea Giusti from Imperial College
477 London at the IRIS Winter program. Dr Giusti advised on how to build an academic
478 paper and provided feedback during the production of the paper.

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540

I appreciate with immense gratitude the attention and time dedicated to review my paper. And, I am thrilled that the reviewer has found my research interesting and clear.

How I addressed major revision points:

1. I have justified and clarified why I assumed increasing current is equivalent to increasing load while also explaining that they are not interchangeable in lines 240-245.
2. I have included more justification for the exclusion of the other type of losses in section 2.2 between lines 183-191.
3. I have complemented the qualitative explanation and replaced it with an incremental slope approach with the average slope of 1-15 A and 16-30 A, and also between 16-30 A and 31-45. Moreover, I have added in lines 145-149 an explanation of how this method works to find quantitatively where saturation happens.
4. I have included an explanation in section 2.2 in lines 183-191 justifying why it was only taken into consideration copper losses. Furthermore, in lines 332 and 333 it was already mentioning the underestimation of the electrical input only considering copper losses. In section 5 there is a discussion of the limitations explaining that the neglect of certain losses lead to an overestimation of the overall efficiency, this is between lines 384-387.
5. I tried to remove all the explanation that I found redundant after a thorough revision of the whole manuscript trying to keep the most concise and objective.
6. I standardized the measure units for current, torque, and power into A, mNewtonmeters, and watts in lines 274, 279, 299, 300, 316, and 318.
7. I fixed all the typos pointed out.

I appreciate with immense gratitude the attention and time dedicated to review my paper.

I am glad that the reviewer has found this paper to be accessible and useful for future optimization of electrical systems. However, I believe there might be a confusion in which category my paper fits in. I wrote this paper as an empirical paper, so I tried to make it more explicit by explaining how the effects were going to be investigated in line 109.

Technical points made and how I addressed:

1. In figure 4, I do not think the best way to show that most gains are concentrated within the first few non-zero values of amperes. Nonetheless, I introduced a new methodology to identify where saturation occurs through incremental slope. In the manuscript it compares the average gain made from 1-15 A with 16-30 A and 16-30 A with 31-45 A finding it a quantitative way to represent that gains experiment a reduction after surpassing the range between 10-20 A in the paragraph between lines 283-291.
2. I introduced captions for all figures and shortened redundant sentences that are now explicit or implicit stated within the captions.
3. In my research process, I have picked only sources with their full document available on google scholar. However, as mentioned in the feedback most of them are paywalled in their original publication websites. I used Zotero in order to cite my references and save them if there is any other way I can cite them with the URL or any different way, I will do it, but I am unaware of how. I respectfully ask to provide any suggestion to cite them, since all of the references are available for free on google scholar.

Typos/Minor Grammatical Suggestions

I have complied with all the reviewer's suggestions, unless I have either eliminated the sentence or paragraph or changed it completely that the word was found not necessary anymore.

The authors have addressed most of the comments from the previous review. The overall structure and clarity of the manuscript have improved significantly, and it now reads much more clearly. I recommend accepting the paper for publication.

Review of “A Magnetostatic Analysis of Magnetic Saturation’s Impact on PMSM Overall Efficiency and Copper Losses Under Varying Load Conditions”

As this review is of the revised version of this manuscript, this is a much more concise document, and I appreciate the efforts taken by the author to address the original questions, comments, and concerns. There remain a few minor items, including an alternative way of presenting the concept more effectively, which I describe below (which was requested for consideration in the original review). Additionally, the original concerns about some of the paywalled references have been rectified as I was able to locate some publicly available URLs through various academic or research-oriented repositories, and these may be considered in the final draft. Finally, typically captions appear below the figure, unless otherwise instructed by the journal – I would suggest inquiring directly with the editor to see if this is required; otherwise the typesetter may work with you directly.

All-in-all, given the improvements made, though with the need for potentially a few more amendments, I recommend this be considered for publication after some additional *minor revision*.

Finally, thank you for re-submitting your responses in a point-by-point format with the reviewers’ comments shown as well; moving forward, this is standard for most scholarly journals.

Specific Technical Points/Suggestions:

- 1) I do not see any visible difference in the new Fig. 4 versus the original version. I also think it might be useful to shrink the y-axis somewhat to perhaps better see the semi-saturation of magnetic flux density.

Also, I suggested in my first review a potential second plot of $\partial B/\partial I$ versus I , which I did not see addressed and which I would still be interested in seeing, even if it doesn’t end up in the final version.

- 2) Publicly available references: In terms of the Pjevalica et al. (2015) reference, I was only able to access it through my institution, and this is thus more limited for a general reader. I did locate this URL, which does not appear to be paywalled: https://www.researchgate.net/publication/282012182_Magnetic_Saturation_of_Permanent_Magnet_Motor_Coil_as_Key_Effect_for_Initial_Rotor_Position_Detection

For the Burt et al. (2008) reference, I was able to locate this non-paywalled version:
https://digitalcommons.calpoly.edu/eeng_fac/178/ - consider using this URL instead!

Minor Grammatical Comments/Typos:

- 1) Lines 90-91: Verbose – consider changing “contribute in reducing energy conversion efficiency” to “reduce energy conversion efficiency.”
- 2) Line 128: While “forementioned” is still valid, it is largely considered archaic and the preferred word here is “aforementioned.”
- 3) Line 182: I believe the author intended to state “thermal energy that is possible to predict ...” not “thermal energy that it is possible to predict ...”, correct?
- 4) Line 193: Add “the” before “load”.
- 5) Lines 193-197 need to be rewritten as it is unclear what the “it” refers to in line 195; furthermore, “its” in line 196 is inconsistent with the plural “copper losses”. I think that in line 196 it should instead read as “their significance” rather than “its significance”. (And, if that’s the case, change “its” at the end of line 196 to “their”.)
- 6) Line 203: Change “wounded” to “wound”
- 7) Paragraph from lines 294-302: I don’t quite understand the use of “experimented” (on lines 294 and 296) here and believe this needs to be revised.
- 8) Line 326: Change “copper losses in function of RMS current” to “copper losses as a function of RMS current.”
- 9) Line 347: Change “factoring saturation” to “factoring in saturation”
- 10) Line 377: Change “decently high with” to “decently high at”
- 11) Line 424: Add “the” before “world’s”
- 12) Line 450: Change “copper losses causes” to “copper losses causing”