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

Abstract

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

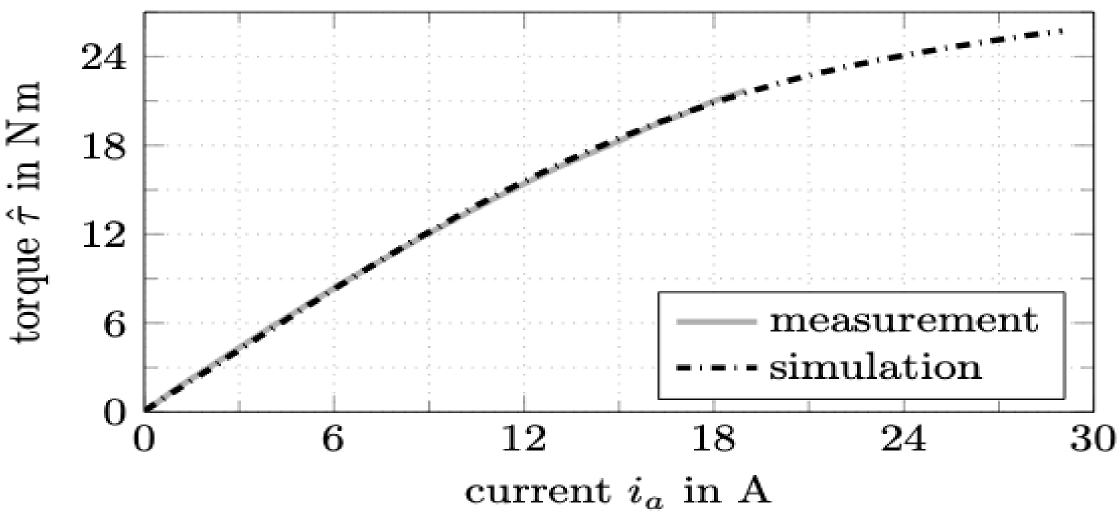
1. Introduction

In the modern day, electric motors are used in a variety of utilities that range from basic household appliances to heavy industrial machinery (Saidur, 2010). In fact, they are one of the fundamental pillars in the context of global decarbonization, since electric motors generate lower greenhouse gas (GHG) emissions in comparison to internal combustion engines (ICEs) during their use phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among countries due to the difference between the energy source used for power generation. Moreover, a comparative analysis on the overall efficiency between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded that the efficiency from battery to wheels ranges from 50% to 80%, whereas the most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it is necessary to consider the energy source used and its efficiency to generate the electricity to provide a more well-rounded analysis named: well to wheel. In this perspective EVs' efficiency can drop to similar or lower levels than those found in ICEVs (Albatayneh et al., 2020).

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

Figure 1

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



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

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

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

The combination of the existing literature establishes that the operation of motors in overload leads motors to saturation, providing higher electrical power input, which increases disproportionally 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 building upon the literature. This paper is organized as it follows: in first place, section 2 expands the theoretical background with more context of how magnetic saturation affects the properties of electric motors 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 magnetic flux density, average torque, mechanical output, copper losses, and overall efficiency; section 5 discusses the significance of the results, limitations, and how it compares to the literature reviewed; and finally, section 6 concludes the paper with some suggestions on future research.

2. Context

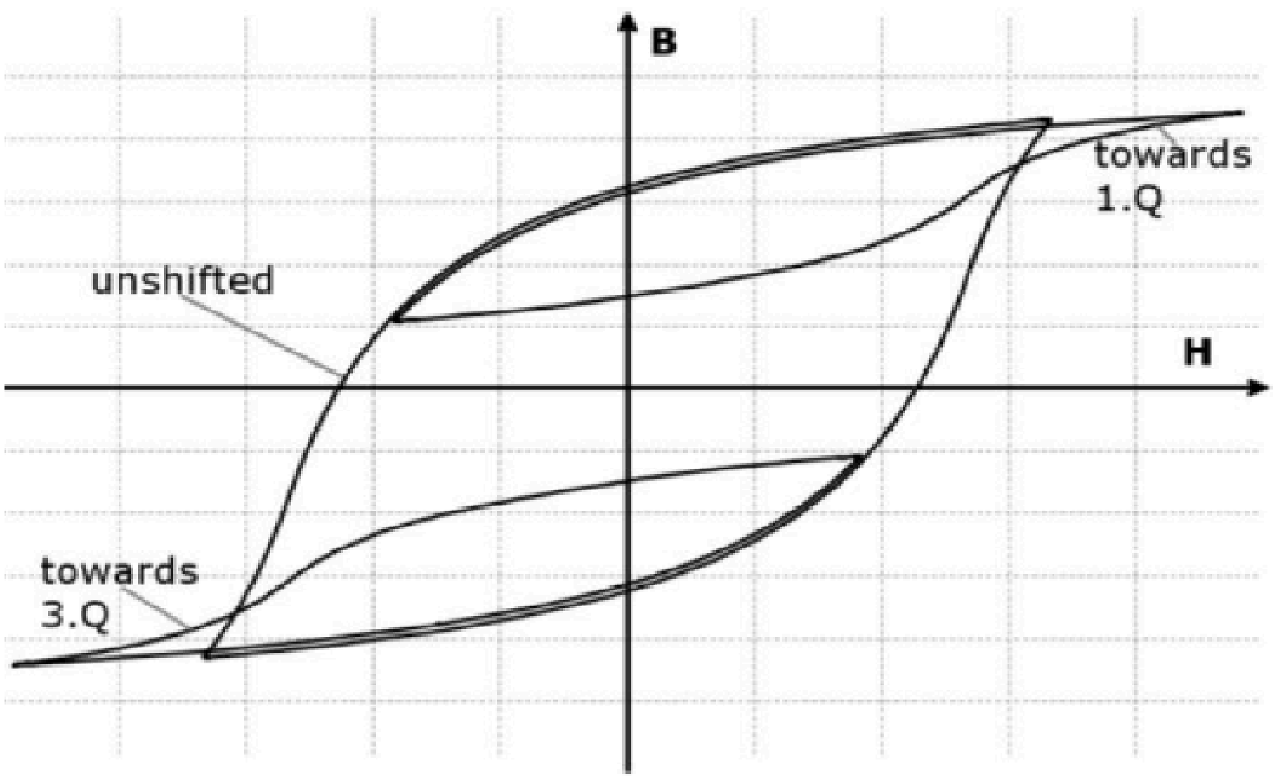
In this section, supplementary context is provided to understand more deeply the relationship between magnetic flux density, electromagnetic torque, mechanical power output, copper losses, and overall efficiency, and what these equations show based on the hypothesis. Additionally, it is presented what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

Figure 2

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



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

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

Where $\mu_0 = 4\pi\, 10^{-7}\, [T\, m\, A^{-1}]$ 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.

The direct relationship between torque and magnetic flux density explains the reason because 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)

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

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:

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

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 angular speed constant, as a result decreasing angular speed.

2.2 Overall efficiency

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

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

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

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

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

2.3 Permanent Magnet Synchronous Motor (PMSM)

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

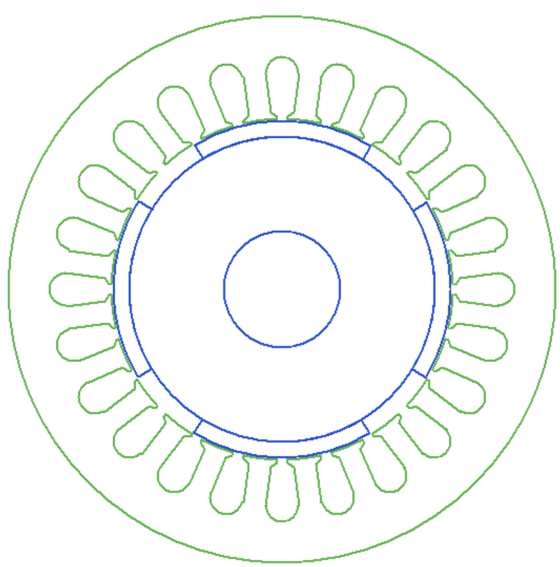
Table 3

Permanent magnet's specifications

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

Figure 3

RMxprt modified model



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

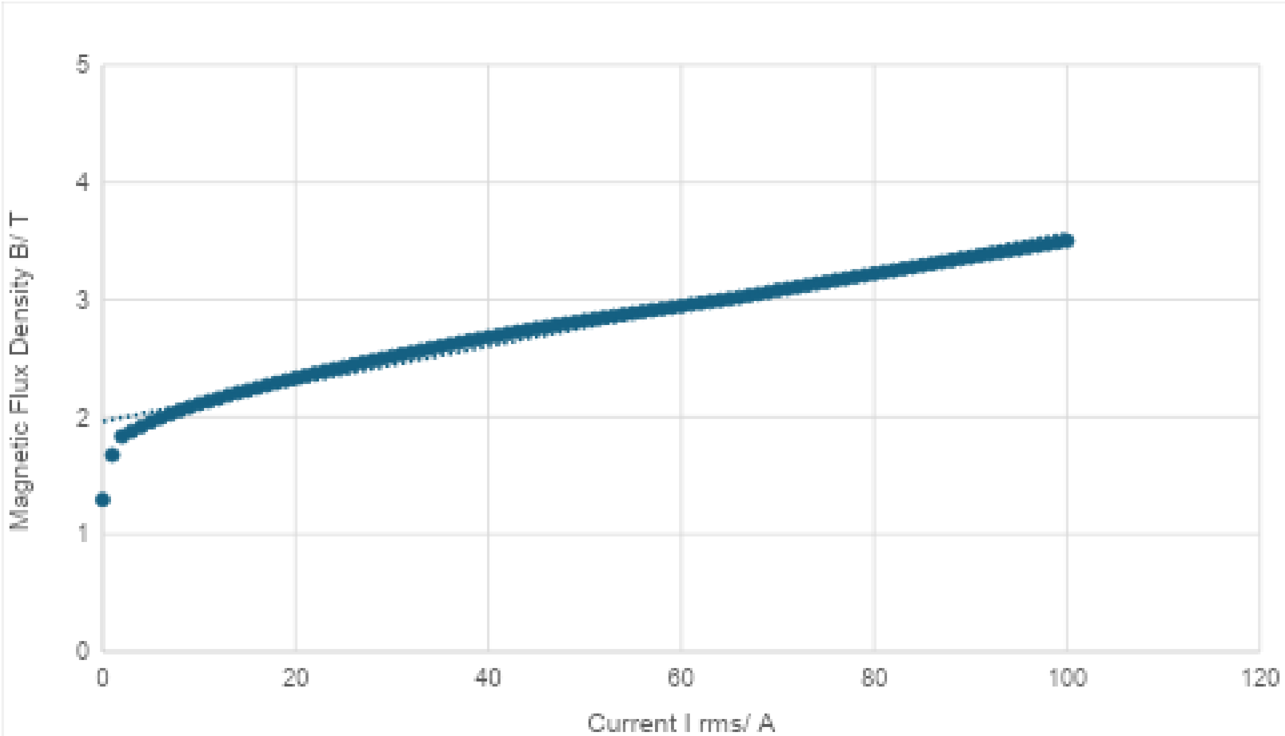
3.2 Numerical model

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

4. Results

Figure 4

Magnetic flux density vs. I RMS graph



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

Figure 5

Average torque vs. RMS current graph

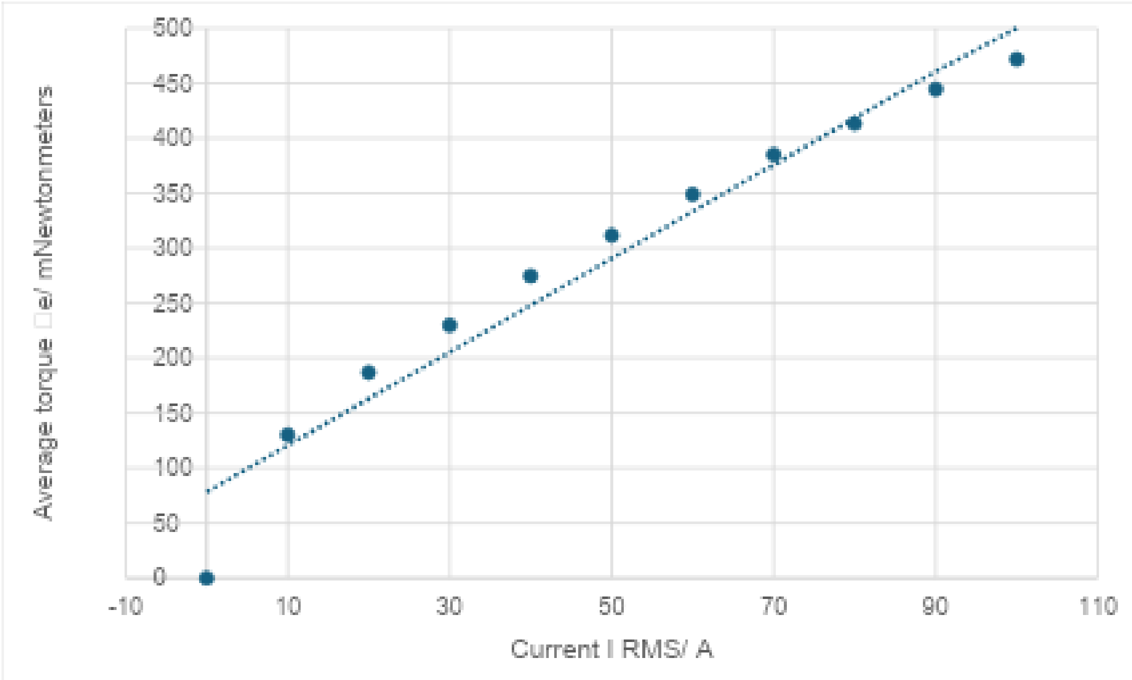


Figure 5 shows how average torque changes as a result of increases in current, the values of average torque shown are apart by 10 A of current input. The trend followed by the average torque is nonlinear, almost logarithmical. It showcases signs that average torque started to stabilize after a sequence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

Figure 6

Copper losses vs. I RMS graph

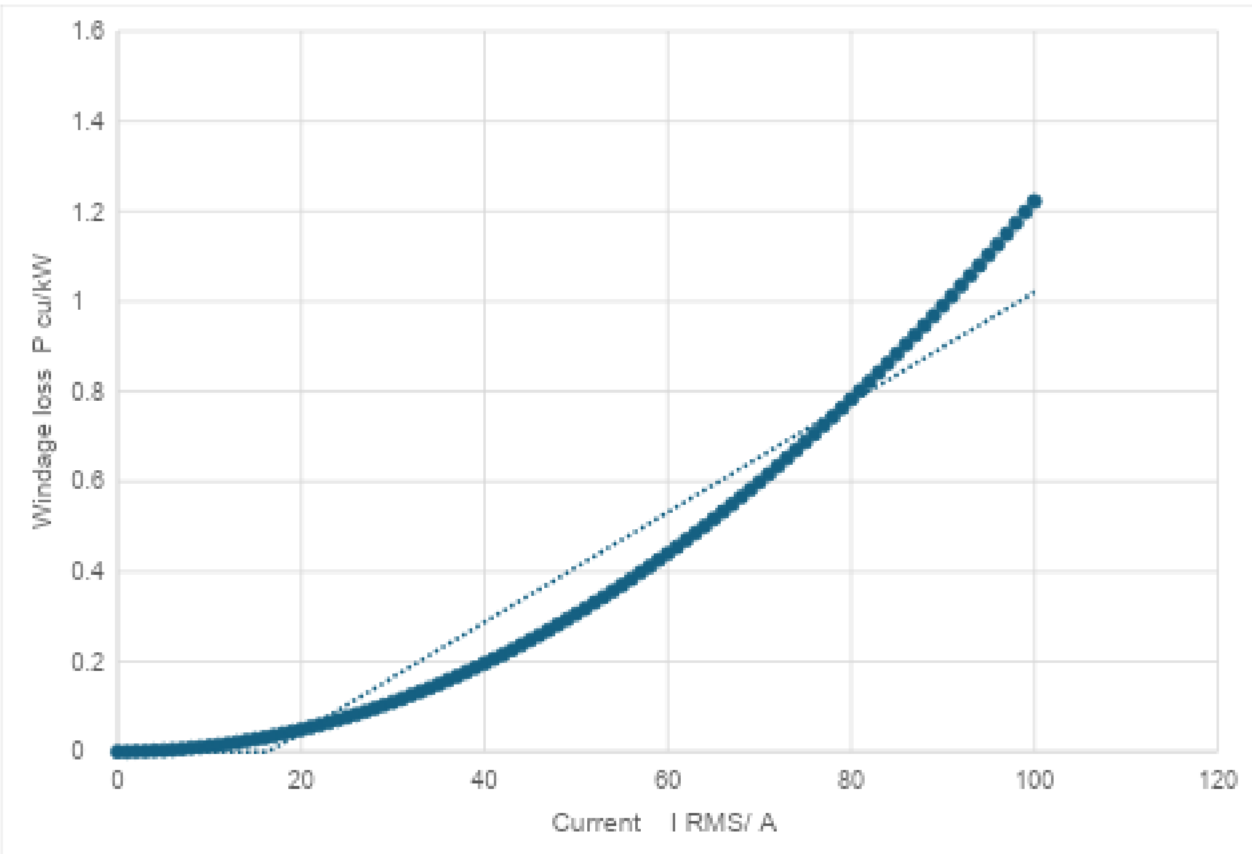
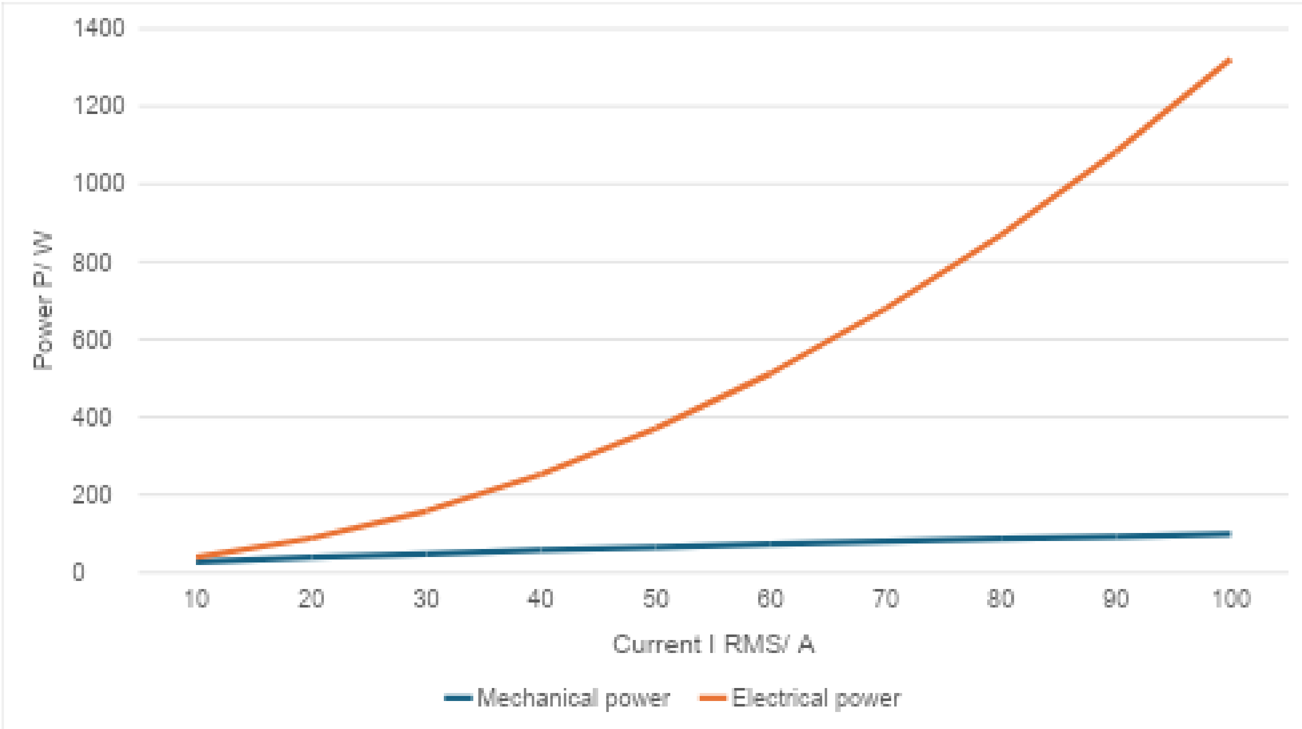


Fig. 6: Copper losses vs. I RMS graph

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

Electrical and mechanical output vs. RMS current graph

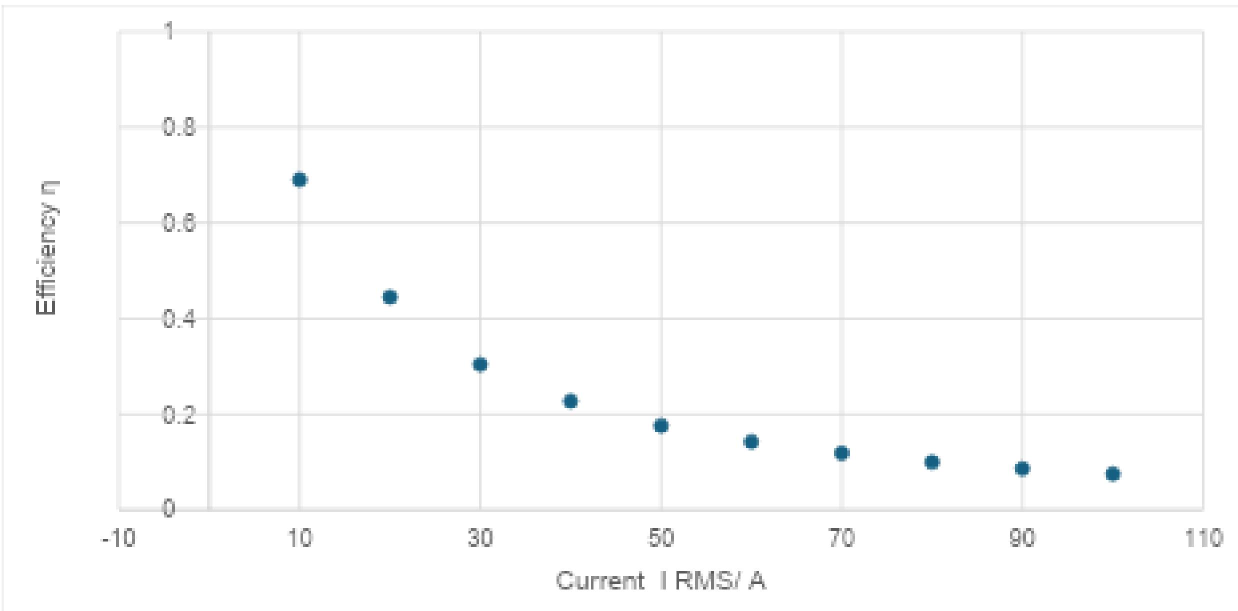


Electrical input was calculated by summing windage losses with mechanical power output. Despite that it underestimates electrical input, since iron core and eddy current losses were not taken into consideration due to copper losses being a variable type of loss that takes up to 60% of all the losses 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 converting into rad/s, is approximately 209. Nonetheless, because it is a magnetostatic analysis angular speed needed to be fixed.

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

Figure 8

Efficiency vs. RMS current graph



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

5. Discussion

As stated in the hypothesis, it was expected that when load conditions are increased, the saturated PMSM would draw additional current into the system. 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 (Moghimi Dehkordi 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 due to the dramatic increase in copper losses this disproportion results in a sharp decline of overall efficiency.

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

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

7. Acknowledgements

This paper was mentored by [mentor and program name redacted]. [Mentor name redacted] advised on how to build an academic paper and provided feedback during the production of the paper.

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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 respectively 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".

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

Abstract

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

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

1. Introduction

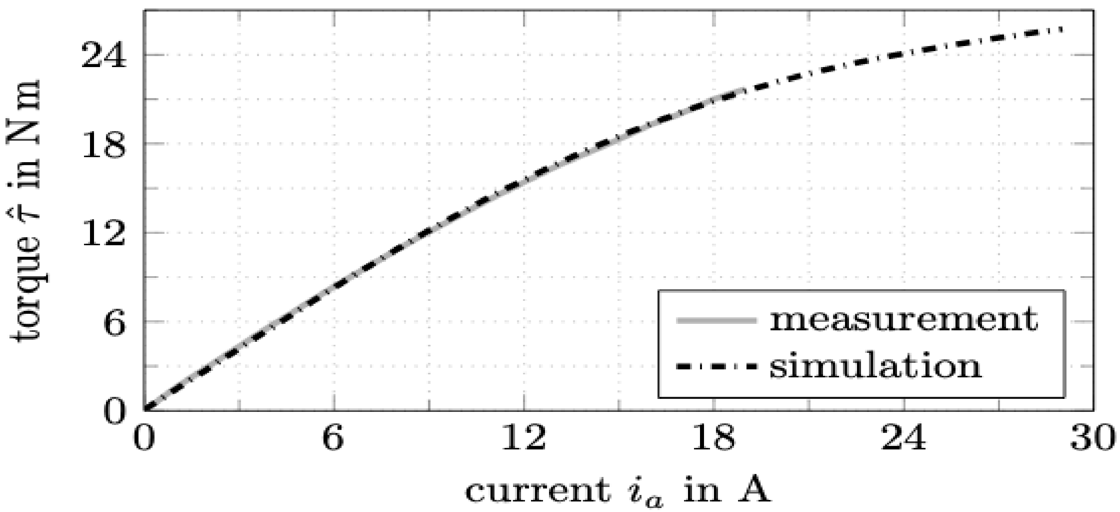
In the modern day, electric motors are used in a variety of utilities that range from basic household appliances to heavy industrial machinery (Saidur, 2010). In fact, they are one of the fundamental pillars in the context of global decarbonization, since electric motors generate lower greenhouse gas (GHG) emissions in comparison to internal combustion engines (ICEs) during their use phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among countries due to the difference between the energy source used for power generation. Moreover, a comparative analysis on the overall efficiency between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded that the efficiency from battery to wheels ranges from 50% to 80%, whereas the most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it is necessary to consider the energy source used and its efficiency to generate the electricity to provide a more well-rounded analysis, namely: well to wheel. In this perspective EVs' efficiency can drop to similar or lower levels than those found in ICEVs (Albatayneh et al., 2020).

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

Figure 1

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

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



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

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

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

The combination of the existing literature establishes that the operation of motors in overload leads motors to saturation, providing higher electrical power input, which increases disproportionally 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. 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 follows: 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.

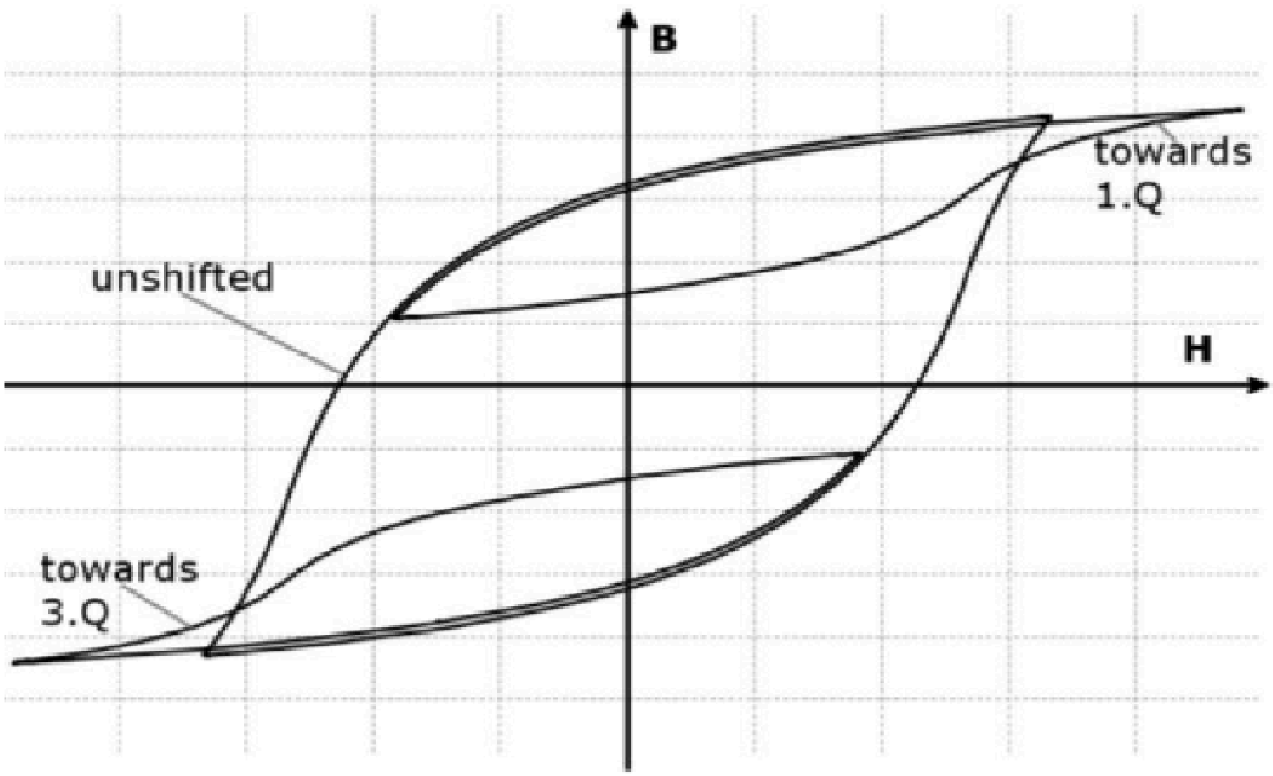
2.1 Mechanical output in saturation

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.

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.



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

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

Where $\mu_0 = 4\pi\ 10^{-7}\ [T\ m\ A^{-1}]$ 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.

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:

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

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

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

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

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

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

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

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

2.3 Permanent Magnet Synchronous Motor (PMSM)

A PMSM is a type of AC electric motor that consists of two main parts: the stator and the rotor (see Figure 3). The stator consists of two components: the stator core and the stator windings. The core is composed of laminated silicon sheets to house the stator windings and reduce energy loss; the stator windings are sets of coils wounded inside cages within the stator's core and are fed with electric current to create a rotating magnetic field. Similarly, the rotor has two components: the rotor core and permanent magnets. The rotor core serves almost the same 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 RMxprt'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

Table 3

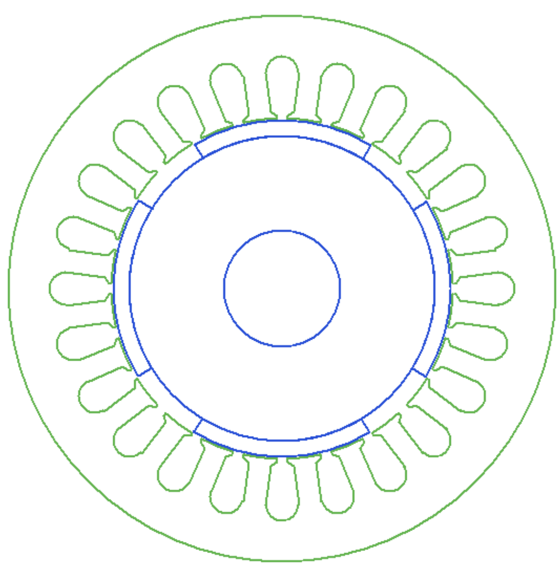
Permanent magnet's specifications

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

Figure 3

RMxprt modified model

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



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

3.2 Numerical model

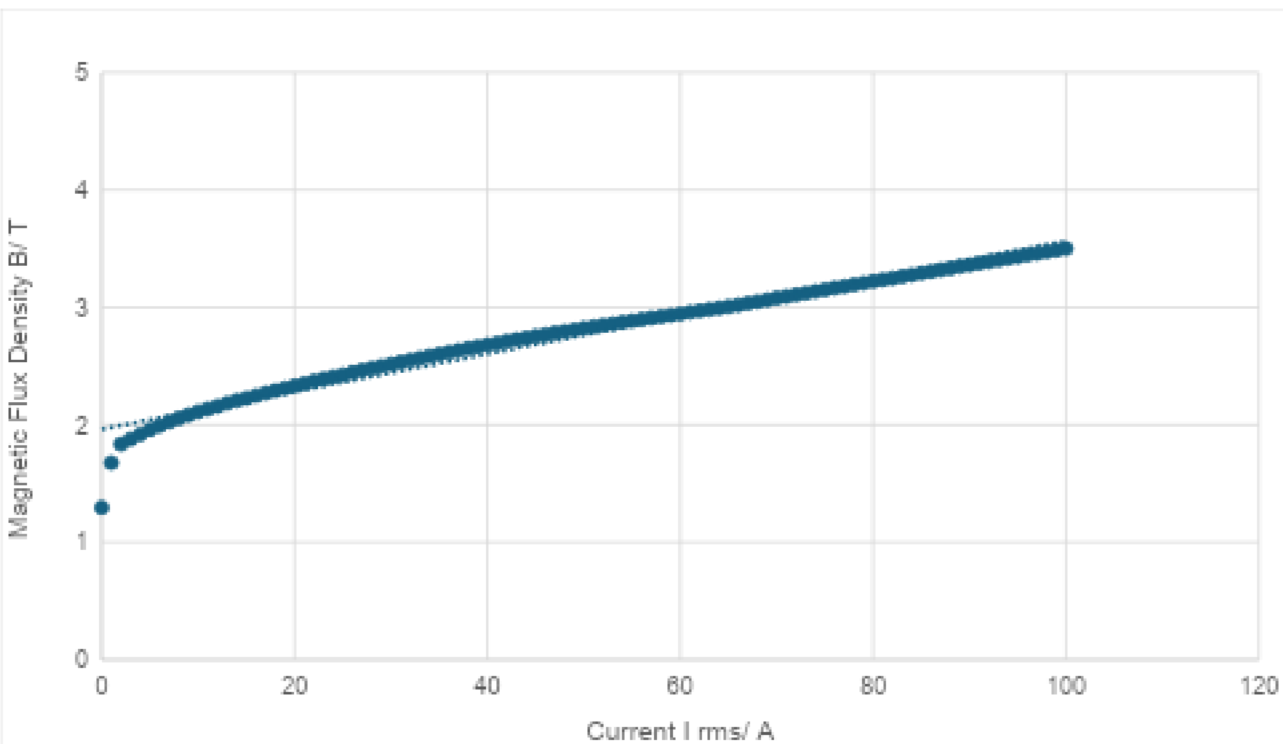
The solution type used for the simulation was magnetostatic. Moreover, the constant variables were angular speed fixed at 2000 rpm to represent steady state, and resistance was fixed at a temperature of 75°C. There were two different parametric sweeps: root mean square (RMS) current and mechanical angle.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

4. Results

Figure 4

Magnetic flux density vs. I RMS graph

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



Although magnetic flux density continues to increase, it follows a nonlinear path that reduces the pace at which B increases as current becomes greater. For instance, to increase one T in flux density, initially, it takes about a 15 A increase, but the next increase of one T demands 63 more A than the last increase. That means that the magnetic flux density produced by the current starts to stabilize, since it takes more than four times the current to increase it by the same amount.

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

Figure 5

Average torque vs. RMS current graph

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

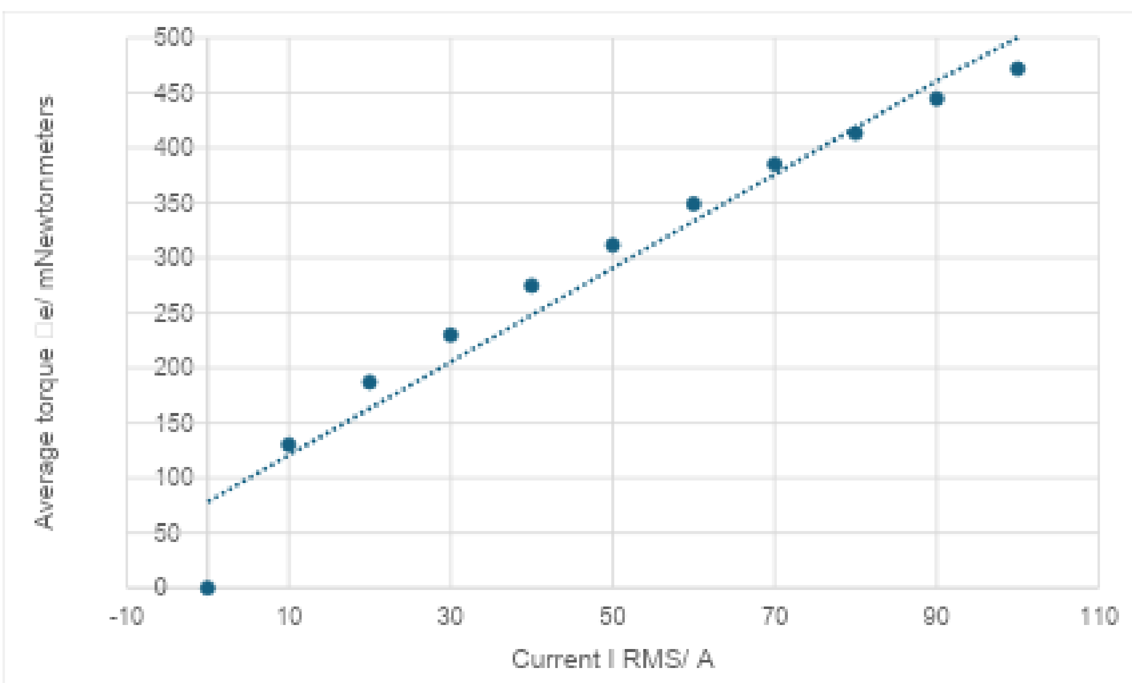
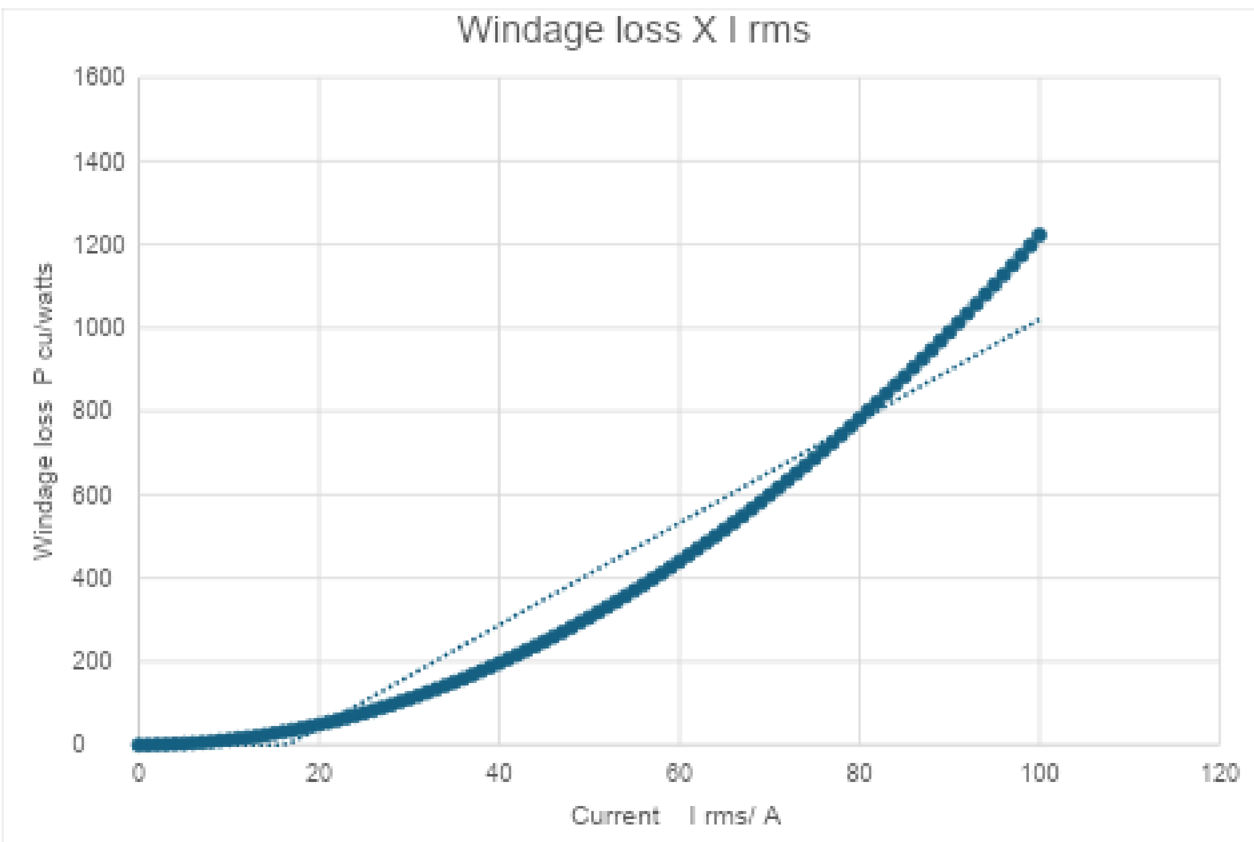


Figure 5 showcases signs that average torque started to stabilize after a sequence of increases in current, reducing the rate of gains in torque. For example, the increase produced by the first 10 A is 130 mNewtonmeters, whereas the increase of 10 A from 90 A to 100 A is 27 mNewtonmeters, showing a reduction of 79.3% on the ratio of increments in average torque, aligning with the disproportionality showed previously on magnetic flux density, since it caps torque production. Since torque is one of the components of mechanical power, its stabilization stalls mechanical power values.

Figure 6

Copper losses vs. I RMS graph

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

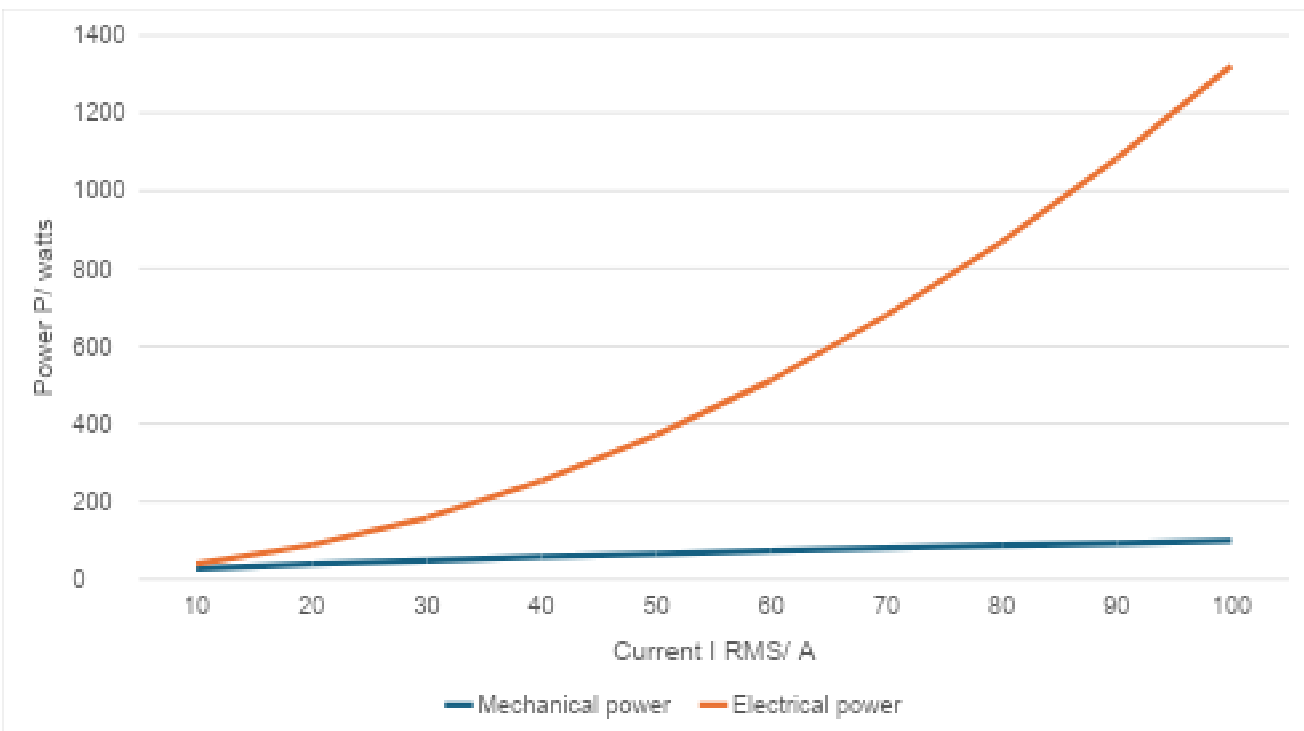


The behavior illustrated in this figure is close to exponential growth, since the rate copper losses increase grows steeply at every step exemplified in the final values as the separation among the points becomes more prominent. Up to 40 A copper losses comprise approximately 200 watts, but as current 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.

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.



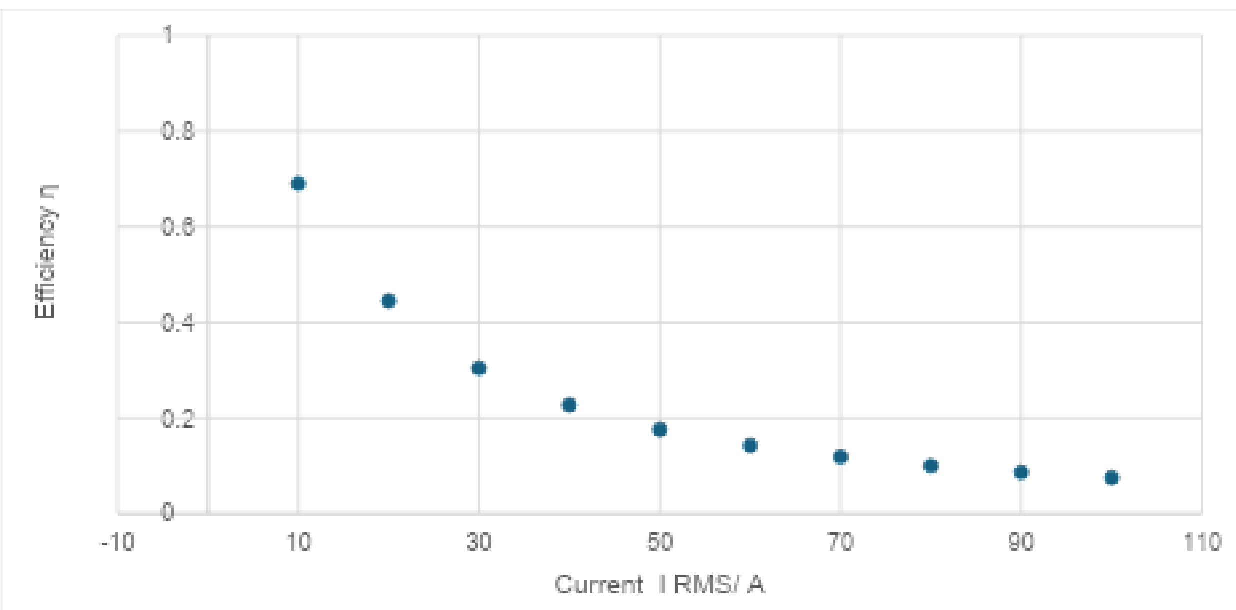
Electrical input was calculated by adding windage losses with mechanical power output. Despite that, electrical input is underestimated, since iron core and eddy current losses were not taken into consideration (Saidur, 2010). Furthermore, the mechanical output due to software's limitations and angular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

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

Figure 8

Efficiency vs. RMS current graph

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



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

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

5. Discussion

As stated in the hypothesis, it was expected that when load conditions are increased, the saturated PMSM would draw additional current into the system. 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 the rate of gains in magnetic flux density was held back around 10-20 A, average torque follows the same path. 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 the 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 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 neglected.

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, 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 (Moghimi Dehkordi 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 due to the dramatic increase in copper losses causes a sharp decline in overall efficiency.

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

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

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

Abstract

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

1. Introduction

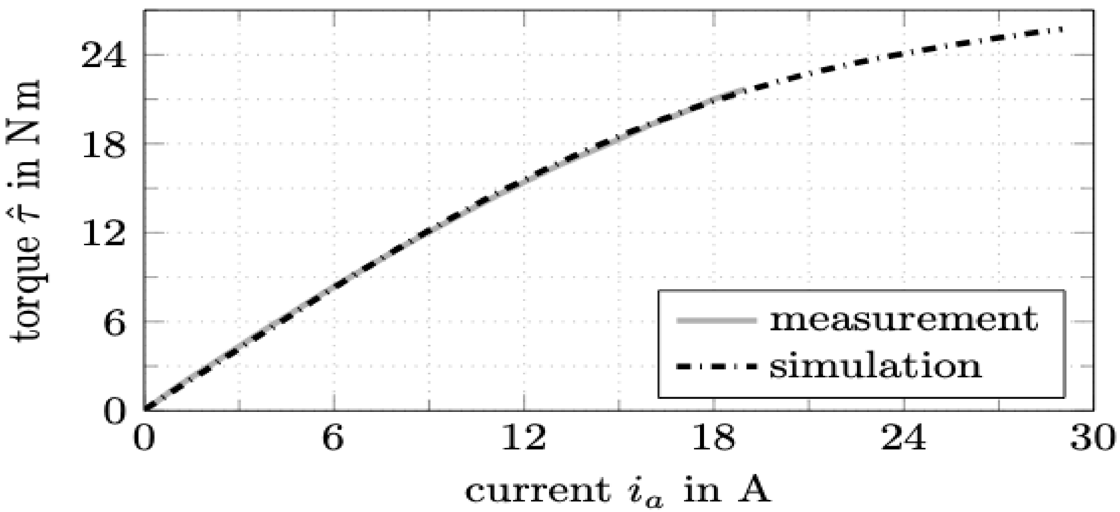
In the modern day, electric motors are used in a variety of utilities that range from basic household appliances to heavy industrial machinery (Saidur, 2010). In fact, they are one of the fundamental pillars in the context of global decarbonization, since electric motors generate lower greenhouse gas (GHG) emissions in comparison to internal combustion engines (ICEs) during their use phase (Tagliaferri et al., 2016). However, this is subject to fluctuations among countries due to the difference between the energy source used for power generation. Moreover, a comparative analysis on the overall efficiency between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) concluded that the efficiency from battery to wheels ranges from 50% to 80%, whereas the most efficient ICEVs reach efficiencies of 42% from tank to wheels. Nonetheless, it is necessary to consider the energy source used and its efficiency to generate the electricity to provide a more well-rounded analysis, namely: well to wheel. In this perspective EVs' efficiency can drop to similar or lower levels than those found in ICEVs (Albatayneh et al., 2020).

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

Figure 1

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

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



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

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

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

The combination of the existing literature establishes that the operation of motors in overload leads motors to saturation, providing higher electrical power input, which increases disproportionally 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.

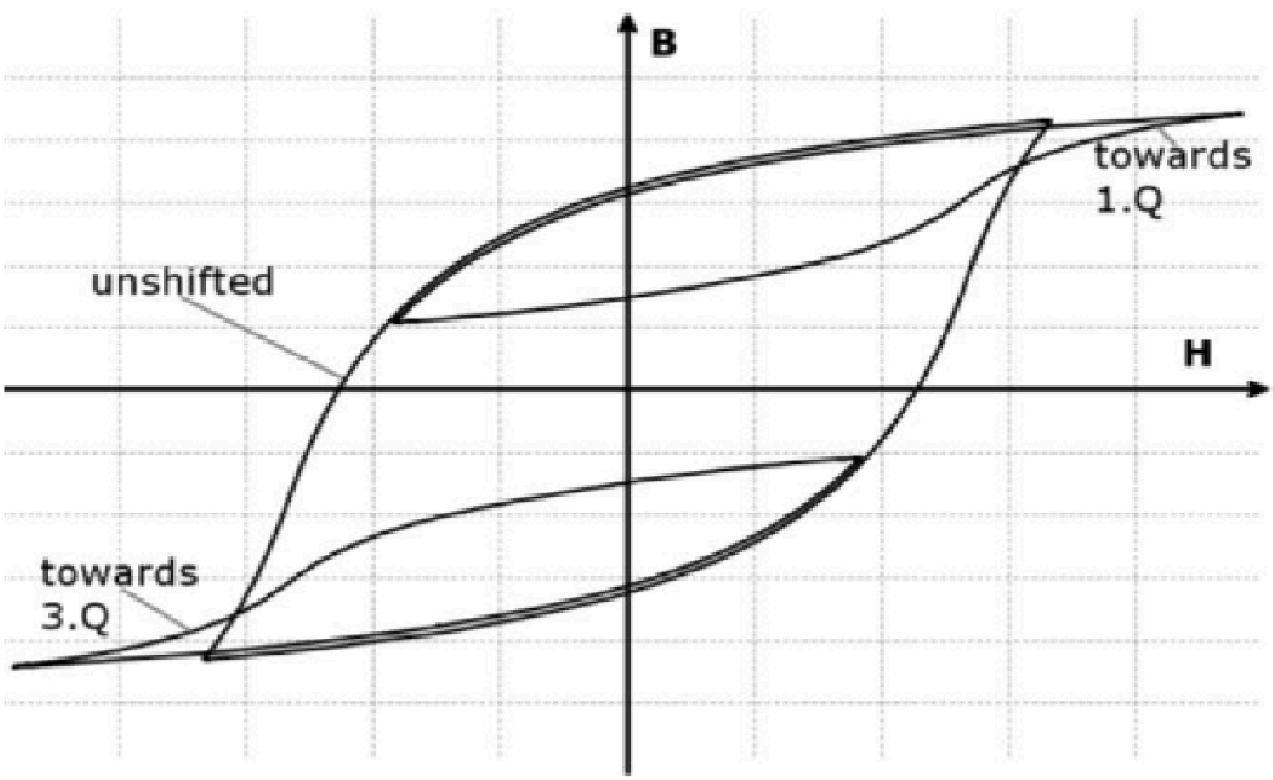
2.1 Mechanical output in saturation

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:~~

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.



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

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

Where $\mu_0 = 4\pi\ 10^{-7}\ [T\ m\ A^{-1}]$ 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:

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

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

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

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

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

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

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

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

2.3 Permanent Magnet Synchronous Motor (PMSM)

A PMSM is a type of AC electric motor that consists of two main parts: the stator and the rotor (see Figure 3). The stator consists of two components: the stator core and the stator windings. The core is composed of laminated silicon sheets to house the stator windings and reduce energy loss; the stator windings are sets of coils wounded inside cages within the stator's core and are fed with electric current to create a rotating magnetic field. Similarly, the rotor has two components: the rotor core and permanent magnets. The rotor core serves almost the same 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 RMxprt'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

Table 3

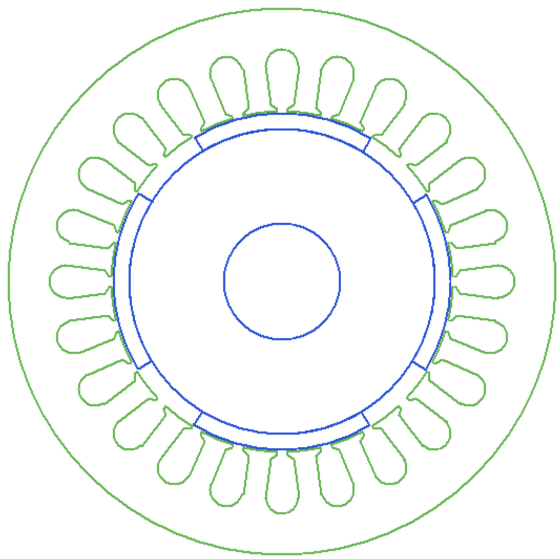
Permanent magnet's specifications

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

Figure 3

RMxprt modified model

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



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

3.2 Numerical model

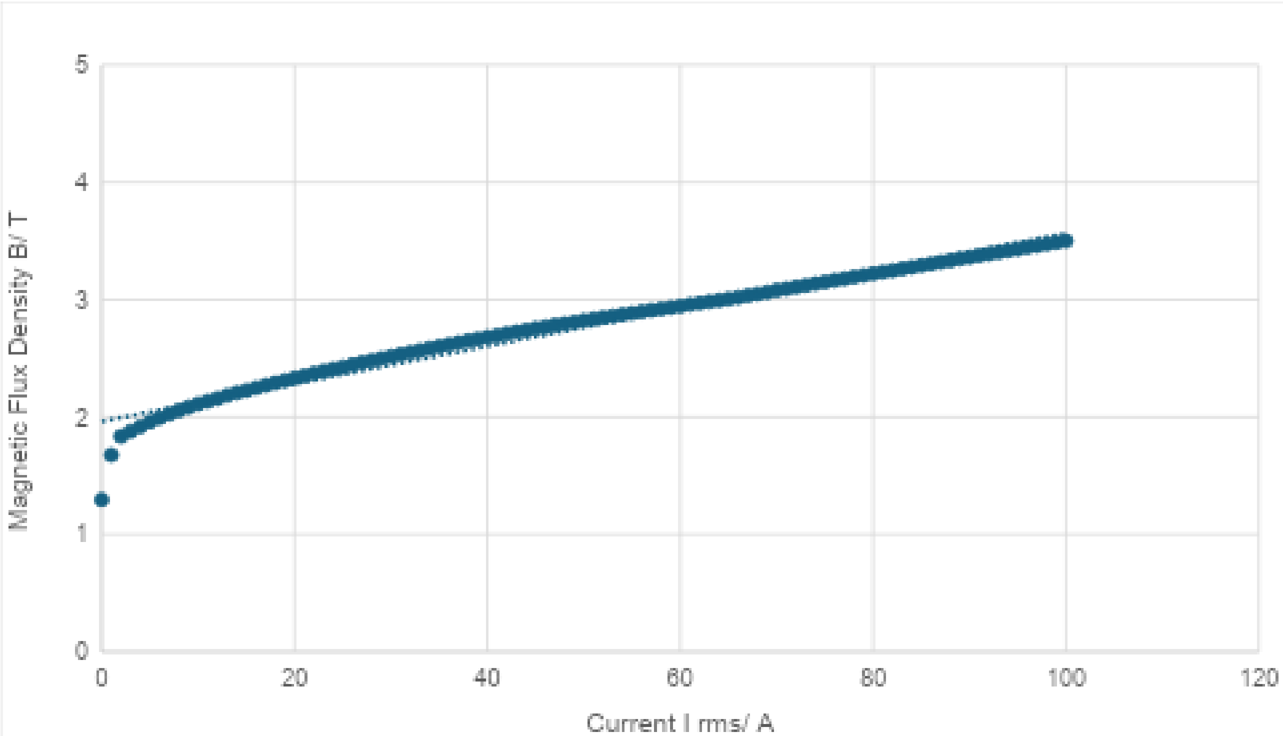
The solution type used for the simulation was magnetostatic. Moreover, the constant variables were angular speed fixed at 2000 rpm to represent steady state, and resistance was fixed at a temperature of 75°C. There were two different parametric sweeps: root mean square (RMS) current and mechanical angle.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

4. Results

Figure 4

Magnetic flux density vs. I RMS graph

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



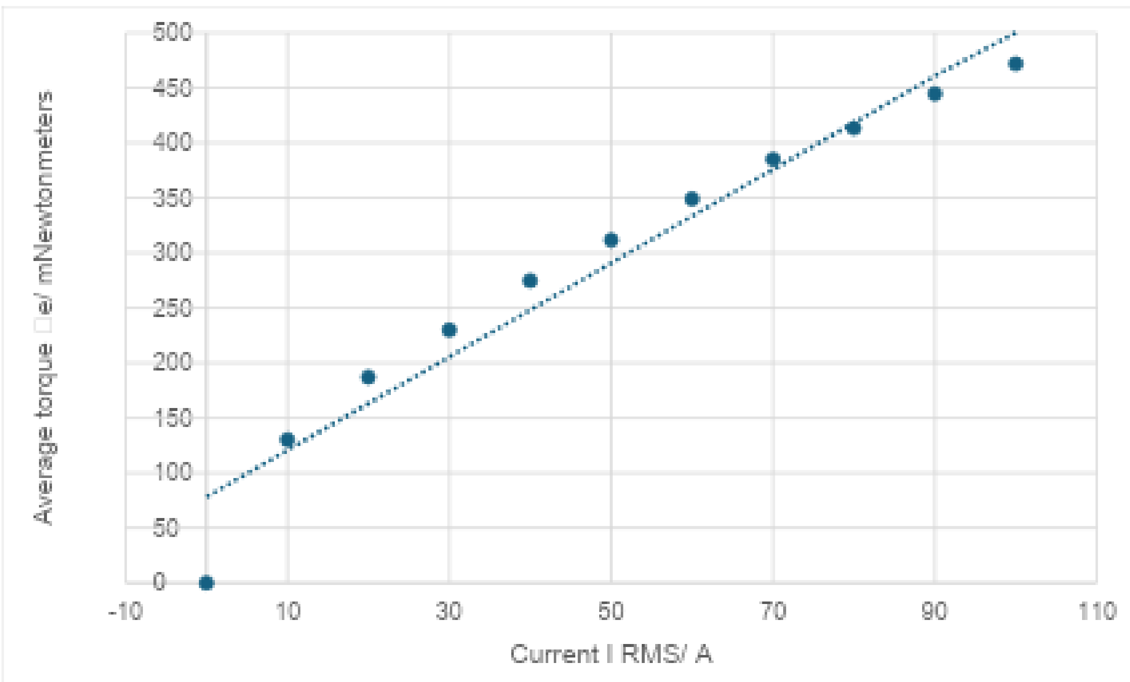
~~In Figure 4, a graph is shown between RMS current and the maximum magnetic flux density identified within the stator, each point is the correspondent value of magnetic flux density to current, from zero to 100 ampere.~~ Although magnetic flux density continues to increase, it follows a nonlinear path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

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

Figure 5

Average torque vs. RMS current graph

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

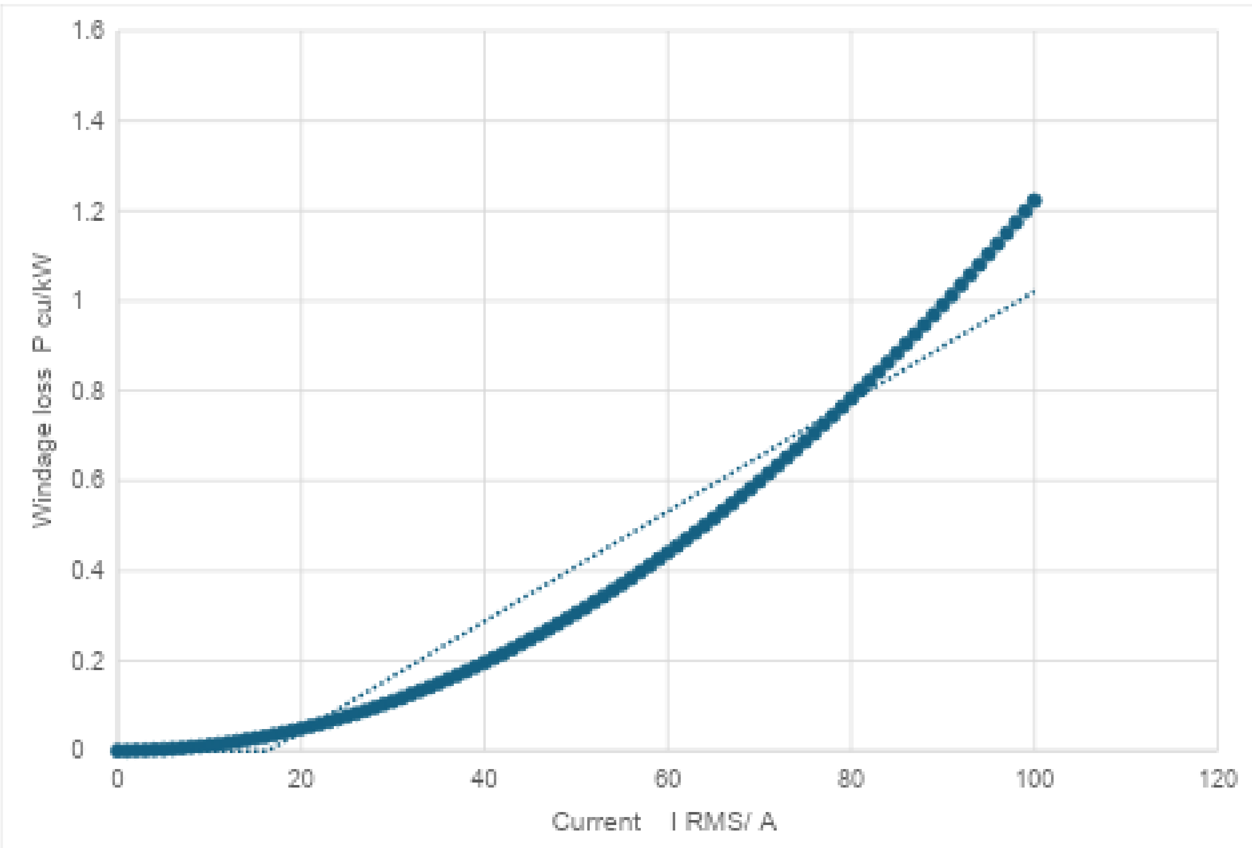


~~Figure 5 shows how average torque changes as a result of increases in current, the values of average torque shown are apart by 10 A of current input. The trend followed by the average torque is nonlinear, almost logarithmical.~~ Figure 5 showcases signs that average torque started to stabilize after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

Figure 6

Copper losses vs. I RMS graph

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

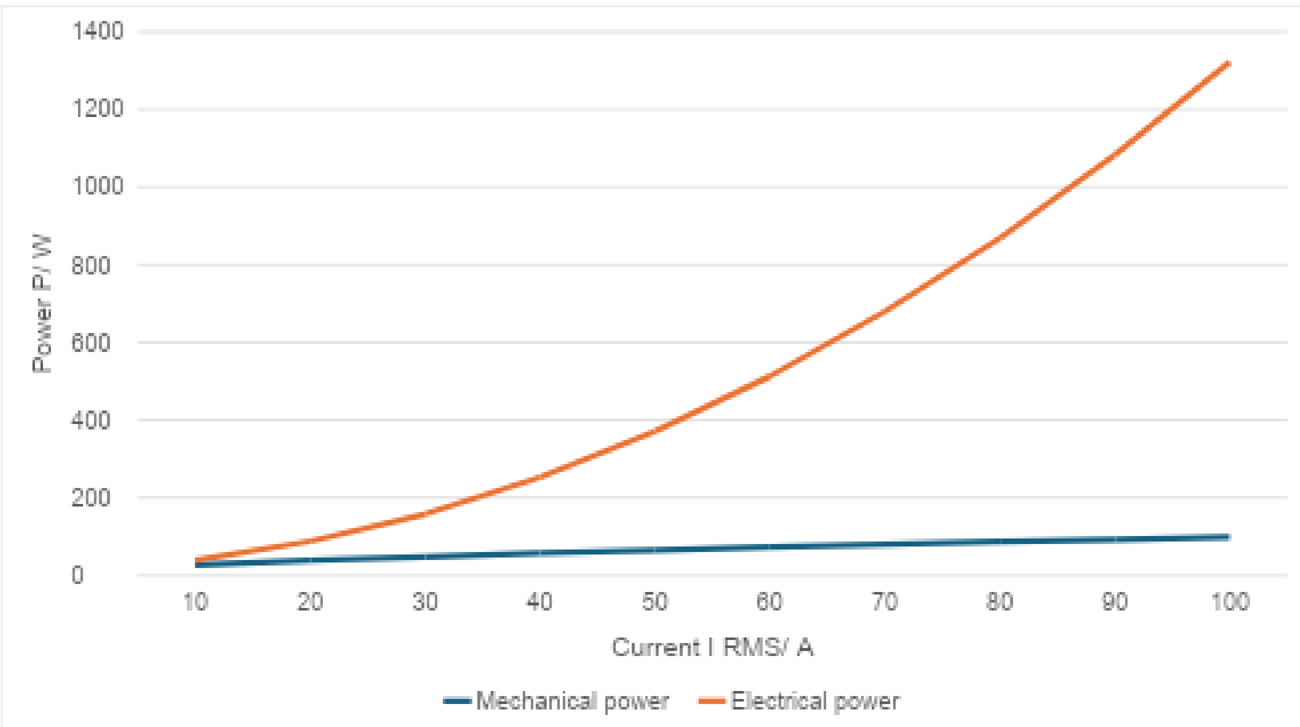


~~The graph shown in Figure 6 illustrates the relationship between copper losses and RMS current, each value of power lost due to heat is spaced by 1 A from 0 to 100 A.~~ The behavior illustrated in this figure is close to exponential growth, since the rate copper losses increase grows steeply at every step exemplified in the final 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 ~~lost to heating~~. ~~This behavior is assigned 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.



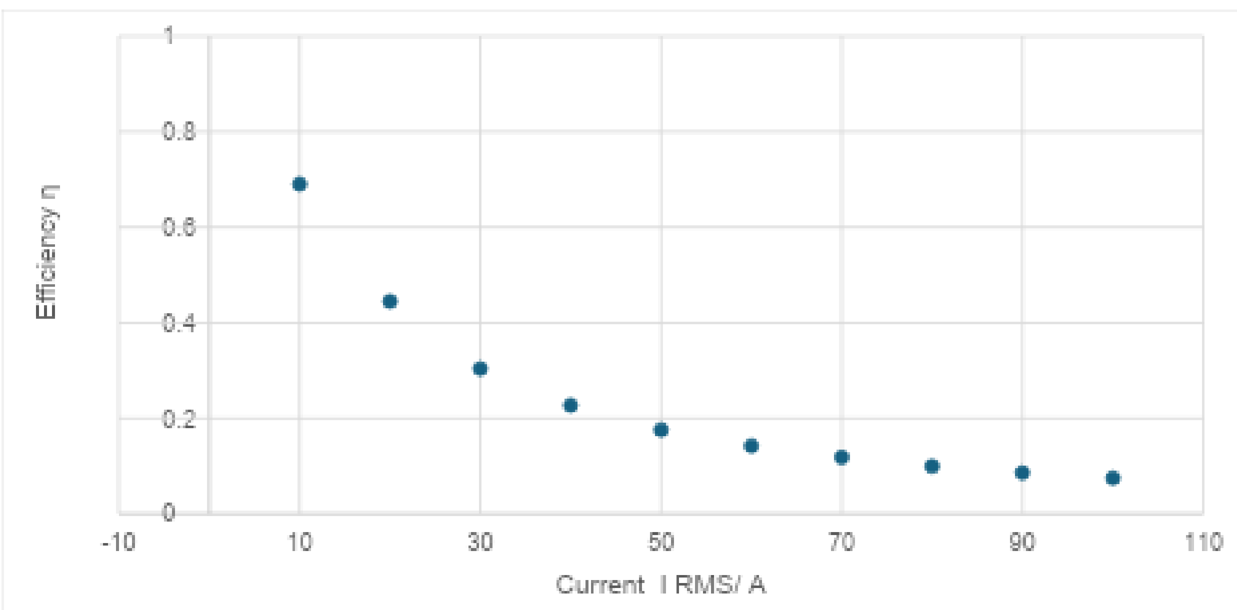
Electrical input was calculated by adding windage losses with mechanical power output. Despite that, electrical input is underestimated, since iron core and eddy current losses were not taken into consideration due to copper losses being a variable type of loss ~~that takes up to 60% of all the losses 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.

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

Figure 8

Efficiency vs. RMS current graph

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



~~Lastly, Figure 8, a scatterplot of the RMS current and the overall efficiency calculated is shown.~~ This scatterplot exposes how efficiency plummets as more current runs into the system, and it starts to converge towards 0, despite it not being possible unless the motor is stopped. At 10 A, efficiency is decently high with approximately 70%, but after surpassing 20 A, the efficiency is below 50 %, which continues to decline at a fast pace, only at 7.47% efficiency when the current reaches 100 A. ~~Due to magnetic saturation, mechanical power output stalls, whereas the electrical power input continues to increase rapidly.~~

5. Discussion

As stated in the hypothesis, it was expected that when load conditions are increased, the saturated PMSM would draw additional current into the system. 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 the rate of gains in magnetic flux density was held back around 10-20 A, average torque follows the same path. 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 the 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 neglected.

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 than beneficial to the environment as those damages demand the extraction of more minerals, which is a highly polluting industry (Moghimi Dehkordi 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 due to the dramatic increase in copper losses causes a sharp decline in overall efficiency.

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

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

7. Acknowledgements

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

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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 neglection 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 respectively 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”