A COMPARISON BETWEEN PMSM ROTOR DESIGNS SUITABLE FOR USING FERRITE MAGNETS

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ABSTRACT

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Increasing concerns over costs and supply of rare earth magnets have introduced more attention to Permanent Magnet Synchronous Machine (PMSM) designs that can work with ferrite magnets. Ferrite magnets have a major disadvantage in that they don’t produce as much flux density as rare earth magnets do, which leads to lower torque density and thus less power in PMSMs. Several approaches have been taken in design of PMSMs in order to tackle this problem. Two of these designs are presented and compared in this work. The first design is the spoke-type (or Flux squeeze) PMSM which places the magnets radially in the rotor to increase the magnetic flux density in the airgap. The second design is the Permanent Magnet Assisted Synchronous Reluctance Machine (PMASynRM) which produces the majority of its torque from saliency and uses permanent magnets to produce an additional magnet torque component.

The main metrics used to evaluate the performance of each design are: maximum torque, operating range, torque ripple, magnet material required, and efficiency. Finite Element Analysis (FEA) is used to simulate and analyze both designs. Experimental characterization results are shown for the spoke-type PMSM and are compared to the same results obtained with FEA in order to have a guideline as to how accurate the FEA results are. A prototype of the PMASynRM design was constructed in the laboratory and some experimental results are presented.
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I. INTRODUCTION

Much work and attention has been dedicated to the selection of magnet material to be used in Permanent Magnet Synchronous Machines (PMSMs). Rare earth permanent magnets (PMs) have been traditionally used because of their high magnetic flux producing capabilities, but due to rising costs and limited availability, the possibility of continuing to rely on them has recently been put into question. In terms of cost and availability, ferrite PMs are currently the only feasible alternative for the more expensive and less accessible rare earth PMs [2]. However, ferrite magnets cannot be used as a direct solution, because they produce less magnetic flux density than rare earth PMs. This in turn leads to less output power when used in PMSMs. In order to overcome the challenges of using ferrite PMs over rare earth PMs, different approaches have been taken regarding the placements of the PMs on the rotor of the machine. Thus, several designs have been presented in the literature that can make up for the low magnetic flux density of ferrite magnets and increase the power density of PMSMs. Two of those approaches are examined in this work and compared to determine which one offers the best performance results.

The two designs compared are the spoke-type PMSM and the Permanent Magnet Synchronous Reluctance (PMASynRM) design. The main variable of this comparison will be the configuration of the magnets in the rotor. The spoke-type PMSM heavily relies on the PMs for torque production, having the magnets positioned so that the flux they produce is reinforced and increased. The PMASynRM is an extension of the classical Synchronous Reluctance machine (SynRM), where PMs are inserted into the flux barriers placed on the rotor in order to increase its torque production and efficiency.

This thesis covers work done on control, characterization, modeling and design of Permanent Magnet Synchronous Machines (PMSMs) with the goal of obtaining the necessary
tools for comparing the two PMSM designs selected. A theoretical background covering the basics of PMSMs is included in Section 2. This includes general construction and operation principles, control of PMSMs using the direct/quadrature \((d-q)\) frame of reference, the conventional equations used to model the behavior of PMSMs and torque production in PMSMs. A characterization procedure used to obtain the aforementioned PMSM model is presented. The theory behind the two designs compared in this work is presented, including the techniques that make them strong contenders to work with ferrite PMs. The spoke-type PMSM design is taken from an existing prototype, whereas the PMASynRM was designed from the beginning. The comparison between designs is done using a combination of experimental work and simulation, where the latter encompasses both simulation of the machine’s performance and simulation using Finite Element Analysis (FEA) to aid in the design of the PMASynRM. The tools used for both experiments and simulation are presented. Apart from FEA, a real time platform using an FPGA was used for experimental control of the PMSM designs, and MATLAB was used to implement the machine’s model.

The work performed is presented in Section 3, beginning with a description of the tools used for both the experimental work and for the design and simulation of machines. Experimental characterization of the existing PMSM prototypes with different magnet material is presented. This is followed by a comparison between experimental and FEA results for the spoke-type PMSM with ferrite magnets. The design process of the PMASynRM is then provided in detail. Some of the best practices found in the literature for design of PMASynRMs that improve the machine's performance were used and are presented here. The winding design is shown in detail. In addition to modifications that improve the machine’s performance, the PMASynRM design was further modified in order to simplify and quicken the manufacturing of
a prototype. The main concern for the comparison is the maximum torque produced by each
design. Other key results, such as torque ripple, operating range, Back EMF waveforms and
magnet material used are also presented for each design. Section 5 gives the final conclusions of
this research and ways that the work presented here can be expanded.
II. BACKGROUND

This section presents the fundamental theory that governs the modeling and control, as well as the design, of PMSMs. The basic characteristics of operation, advantages and challenges of using PMSMs are presented. The $d$-$q$ frame of reference is presented, parting from a short review of Space Vector theory. The classical voltage and torque equations used to model PMSM behavior in the $d$-$q$ frame of reference are also shown. These equations can be used to construct an analytical PMSM model, in order to conveniently estimate the machine's performance. Efficient modes of operation within the operating region are also discussed. The characterization procedure performed in order to obtain the parameters needed to construct the model is presented.

The two PMSM designs compared in this work are presented. First, some background is provided regarding the selection of the two designs chosen for the comparison. Then, each design is presented separately. The specific theory included in this section includes a description of the typical rotor geometry employed in each design and the approach that is followed to overcome the challenges of ferrite magnets and which makes each a suitable contender for this comparison. In addition, location of the $d$ and $q$ axes and saliency, and their effects on torque production are also discussed.
2.1 Permanent Magnet Synchronous Machines

2.1.1. General characteristics of PMSMs

Permanent Magnet Synchronous Machines (PMSMs), also known as Permanent Magnet AC machines (PMAC), are known for their high power density, wide operating range and efficiency when compared to other machines, such as induction machines. They achieve these characteristics by means of permanent magnets (PMs) located in the rotor. This makes them the preferred choice for Electric and Hybrid Electric Vehicle (HEV) applications [1]. One of the special considerations (which can be considered a drawback of PMSMs) that arise from having magnets in the rotor of a PMSM is that with its rotation, the flux from the magnets induces a voltage on the stator windings. This voltage is known as the Back Electromotive Force, or Back EMF, and its peak is proportional to the speed of the machine. Because of this, a voltage needs to be applied to the machine that exceeds this Back EMF in order to guarantee that current flows from the supply side to the machine side. Because Back EMF magnitude increases with speed, this becomes an issue because it conflicts with the sizing of the power converter used to supply the machine.

The basic operation of a PMSM consists of applying voltages at the machine’s windings that produce a rotating flux in the airgap of the machine which then interacts with the flux coming from the magnets in the rotor in order to produce torque [12]. The magnets in the rotor of a PMSM can have various configurations. The most common ones are Interior PM (IPM) and Surface PM (SPM) machines. Figure 1 shows the basic difference between the rotor geometries of an IPM and a SPM.
2.1.2. Space Vector and the $d$-$q$ frame of reference

In analysis and control of 3 phase electric machines, the use of space vectors plays a key role in simplification of the control methodology. One of the most attractive features of this technique is that the number of quantities to be analyzed is reduced from 3 to 2. By using space vectors, instead of analyzing and controlling three different signals (e.g. three phase sinusoidal currents in a motor), a single, time dependent, constant amplitude vector that represents the combined effect of all 3 signals is used. This vector can be decomposed into two orthogonal components in a two axis complex coordinate system [11]. Figure 2 shows an example of three phase quantities and their corresponding space vector, along with its real and complex components. For any given three phase quantities $X_a$, $X_b$, and $X_c$, which are given by:

$$X_a = X_m \cdot \sin(\omega t)$$

(1)

$$X_b = X_m \cdot \sin(\omega t - \frac{2\pi}{3})$$

(2)
The corresponding space vector, $X_{SV}$, is given by:

$$X_{SV} = \frac{2}{3} [X_a(t) + a X_b(t) + a^2 X_c(t)]$$  \hspace{1cm} (4)$$

where

$$a = e^{j\frac{2\pi}{3}}$$  \hspace{1cm} (5)$$

This concept has been incorporated into control of three phase Pulse Width Modulation (PWM) inverters, in what is known as Space Vector PWM (SVPWM). Here, the desired three
phase voltages are converted to two phase voltages which are offset by 90 degrees, and represent the magnitudes of the real and complex components of the rotating space vector. This is achieved through what is called Clarke’s transformation, and the resulting vector rotates in what is known as the alpha-beta frame of reference. The equation for converting three phase quantities into the corresponding alpha and beta components is given by:

\[
X_{\alpha\beta} = P \cdot X_{abc}
\]

where:

\[
X_{abc} = \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}
\]

\[
X_{\alpha\beta} = \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix}
\]

\[
P = \frac{2}{3} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}
\]

In electrical drive applications, this is particularly useful because the application of 3 phase voltages to the machine results in a rotating flux in the airgap of the machine which can also be expressed as a single rotating vector [12].

In synchronous machines, as is the case of PMSMs, the rotor rotates at synchronous speed, meaning that this speed is synchronized with the frequency of the stator currents and thus with the frequency the flux that it creates (assuming a sinusoidal distribution of the flux in the airgap of the machine [8]). The frequency of the currents in the stator windings and the speed of the rotor are related by:
Here, \( f_e \) denotes the frequency of the stator currents, \( f_r \) is the mechanical frequency at which the rotor spins and \( p \) is the number of pole pairs of the machine. Having the rotor position synchronized with the stator currents is advantageous because the frame of reference for controlling the flux can be set to lie directly in phase with the rotor position. Using a rotating frame of reference further simplifies the problem, because the quantities that rotate at the fundamental frequency are now constant [8]. A conversion between frames of references can be employed by knowing the angle between the stator frame (stationary frame of reference) and the rotor flux (rotating frame of reference), which for PMSMs is the rotor position because of its synchronous nature. With this conversion between frames of reference, the quantities in the rotating frame of reference can be directly linked to quantities in the stator frame of reference (i.e. stator voltage space vector).
Figure 3 shows the stator and rotor frames of reference along with the stator current space vector and its components. The usefulness of applying the space vector concept to control the rotor flux is that the components of said vector have specific effects on the machine. The horizontal component is referred to as the direct component because it lies in the same axis as the peak of the flux coming from the magnets. Generating a flux component in this direction will therefore add up to the flux from the magnets. Because of this, it is also known as the flux producing component. The vertical component is denoted as the quadrature component, and increasing it, will increase the torque produced by the machine. This component is also known as the torque producing component. The stator currents can then be applied in a way that the direct and quadrature components of the flux coming from the stator are independently increased or decreased to generate more (or less) torque or flux. This new, rotating frame of reference is called the $d$-$q$ frame of reference. In order to achieve a conversion between the stationary frame
of reference (three phase) and the rotating (d-q) frame of reference, a generalized form of
equations (6)-(9) is used:

\[ X_{dq} = P(\theta_e) \cdot X_{abc} \]  \hspace{1cm} (11)

where:

\[ X_{abc} = \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \]  \hspace{1cm} (12)

\[ X_{dq} = \begin{bmatrix} X_d \\ X_q \end{bmatrix} \]  \hspace{1cm} (13)

The matrix, \( P \), is dependent on the electrical rotor position, \( \theta_e \), and is given by:

\[ P = \frac{2}{3} \begin{bmatrix} \cos(\theta_e) & \cos(\theta_e + \frac{2\pi}{3}) & \cos(\theta_e - \frac{2\pi}{3}) \\ \sin(\theta_e) & \sin(\theta_e + \frac{2\pi}{3}) & \sin(\theta_e - \frac{2\pi}{3}) \end{bmatrix} \]  \hspace{1cm} (14)

\( \theta_e \) follows the same concept shown in equation (10), and is given by:

\[ \theta_e = p \cdot \theta_r \]  \hspace{1cm} (15)

where \( \theta_r \) is the mechanical rotor position that can be directly measured from the machine using a
position measuring device, such as an incremental rotary encoder.

Figure 4 shows the convention of the d-q axes used in this work along with the key
parameters taken into consideration. Because of the relationship between voltage and flux in a
machine, the peak of the machine’s Back EMF is displaced by 90 degrees from that of the flux
from the magnets and is said to align with the q-axis. \( \lambda_{pm} \) denotes the magnitude of the flux from
the permanent magnets and aligns with the d-axis.

![Diagram of d-q axis convention](image)

**Figure 4: d-q axis convention used for control and characterization of PMSMs**

2.1.3. d-q Model of PMSMs

Having an accurate model that describes the behavior of a machine is critical if high performance control is to be achieved. Based on the Space Vector and d-q frame theory, the equations that describe the behavior of a PMSM in the synchronous rotating d-q frame of reference are given by:

\[
V_d = R_s I_d + \frac{d}{dt} \lambda_d - \omega e \lambda_q
\]  
\[ (16) \]

\[
V_q = R_s I_q + \frac{d}{dt} \lambda_q + \omega e \lambda_d
\]  
\[ (17) \]

\( V_d \) and \( V_q \) are the d and q axis voltages, respectively, while \( \lambda_d \) and \( \lambda_q \) are the flux linkages associated with the d and q axes (respectively). Figure 5 shows the d-q axis equations in
circuit form. The flux linkages are themselves a function of \( I_d \) and \( I_q \) and, in their simplest form, are given by:

\[
\lambda_d = \lambda_{pm} + L_d I_d \tag{18}
\]

\[
\lambda_q = L_q I_q \tag{19}
\]

\( L_d \) and \( L_q \) are the \( d \) and \( q \) axis inductances of the machine. It should be noted that \( \lambda_d \) contains two components: the magnet flux and the flux generated by the \( d \)-axis current [13]. These equations do not take into account more realistic effects such as saturation and cross saturation, and thus serve mainly to give a general guideline of how the machine operates. A significant simplification occurs when the machine operates at steady state, since the derivative terms become zero due to the fact that this model is taken to be in the rotor frame of reference, where values of current, voltage and flux are constants. The simplified machine equations in steady state come out to be:

\[
V_d = R_s I_d - \omega_e \lambda_q \tag{16}
\]

\[
V_q = R_s I_q + \omega_e \lambda_d \tag{17}
\]
Another important equation is the magnitude of the Back EMF of the machine. This parameter is a function of both the machine speed and the magnitude of the flux coming from the magnets. The relationship between these three parameters is given by [13]:

\[ V_{Bemf} = \lambda_{pm} \cdot \omega_e \]  \hspace{1cm} (18)

where \( \omega_e \) is the speed in rad/s.

Because the voltages and currents can be measured in three phase form and converted to \( d-q \) form, the flux linkages are the remaining parameters to obtain in this machine model. By knowing what the flux linkages are, the steady state behavior of the machine can be closely approximated with equations (16)-(17) and a controller can be designed. In addition to the equations that model the relationship between the voltages, currents and flux linkages, another important equation is the one used to describe the production of torque in PMSMs. This equation is given by:

\[ T = \frac{3}{2} p(\lambda_d I_q - \lambda_q I_d) \]  \hspace{1cm} (19)
This equation can also be written as

\[ T = \frac{3}{2} p ((L_d - L_q) I_d I_q + \lambda_{pm} I_q) \]  \hspace{1cm} (20)

The second variation of the torque equation is useful when determining how much of the total torque makeup comes as a product of the magnets in the rotor and how much corresponds to the saliency of the rotor [18]. The saliency of the rotor corresponds to the difference between \( L_d \) and \( L_q \). A highly salient motor is able to produce what is known as reluctance torque, whereas a motor with little or no saliency depends greatly on the effect of the magnets. The term most commonly used for describing a machine’s saliency is the saliency ratio, given by

\[ \xi = \frac{L_d}{L_q} \]  

One thing that is important to note that convention for positioning of the \( d \) and \( q \) axes varies in the literature. For example, [18] has the axes inverted with respect to the convention that is shown here. For the purposes of the convention used here, the \( d \)-axis lies aligned with the peak of the flux coming from the magnets. The reluctance and magnet torque components can be seen more clearly in equations (21)-(23). This equation contains a term that takes the difference between the inductances, which corresponds to the reluctance torque. The second term contains the magnitude of the flux from the magnets, and represents the component of the torque that comes from the magnets. Therefore, equation (20) is equal to

\[ T_{total} = T_{rel} + T_{mag} \]  \hspace{1cm} (21)

where \( T_{rel} \) is the reluctance component and \( T_{mag} \) is the magnet component, given by:

\[ T_{rel} = \frac{3}{2} p ((L_d - L_q) I_d I_q) \]  \hspace{1cm} (22)
In this work, a characterization procedure is adopted in which the machine flux linkages are calculated for a specific region within the \(d-q\) axes [4]. In order to understand this characterization procedure for PMSMs and how it contributes to safe and efficient operation, it is vital to first take a look at the reasoning and motivation behind the specific region for which the flux linkages are calculated. As was mentioned previously, one of the problems is that Back EMF in PMSMs increases with speed. In most applications, a 3 phase inverter is typically used to drive the stator currents and voltages to the machine, and this in turn has a limited DC link. In addition to this, it is desired that a PMSM be operated as efficiently as possible over a wide speed range. For high speeds, the machine must still be continued to operate in the most efficient way possible without the problem having the Back EMF exceed the maximum possible voltage output from the inverter. Finally, there are also constraints on the currents that are applied to the machine, given by the PMSM’s maximum rated current value.

There are two main modes of operation for PMSMs over their speed range based on the previous considerations [20]. These modes look to operate the machine with minimum losses and maximum performance, but at the same time maintaining the voltage and current under their respective limits. The term corner, or base, speed is used to denote the value of speed at which the machine’s Back EMF causes the inverter to reach its maximum output voltage. The two main modes correspond to the regions of speed that lie below this corner speed and above it. The first mode is called Maximum Torque per Ampere (MTPA) and is applied in the range of speeds that are below the corner speed. In the MTPA region, the only constraint present is the current limit,
and so the focus is to obtain the maximum possible torque with the minimum amount of current possible. The second one is called the Field Weakening (FW) mode and is applied when the speed of the machine exceeds the corner speed. As its name suggests, the objective of the FW mode is to weaken the flux coming out of the magnets, which is the proportional constant between speed and the peak of the Back EMF, as seen in equation (18). Thus, because the flux from the magnets lies on the positive side of the d-axis as seen in Figure 4, applying positive d-axis current will only reinforce the flux from the magnets. Because of this, field weakening is achieved by applying negative $I_d$ and the operating region of the machine is restricted to the quadrant that has negative $I_d$ and positive $I_q$. Because there is a limit on the current magnitude that can be applied to the machine, the larger $I_d$ is, the smaller $I_q$ will be. Because $I_q$ is the component of the current that produces torque, reducing it will also reduce the torque output. Thus, as the speed of the machine increases, the maximum torque that it can produce will typically be constant during the MTPA region (as there are no voltage limits) and then decrease in the Field Weakening region. This is evident when evaluating a machine’s Torque-speed relationship. When looking at the machine’s power versus speed, however, it is seen that the power increases in the MTPA region and typically stays constant during the FW region. The constant power region results from the fact that the current and the voltage have both hit their limits, as opposed to the MTPA region, where the voltage is still under the inverter limit and only the current limit comes into play.
2.1.5. Characterization of PMSMs

In this work, the characterization procedure found in [4] and [13] was employed. Knowing the region within the $d$-$q$ axes in which the machine will be operated, the objective of this characterization procedure is to determine the flux linkages for that region. For this procedure, the machine is coupled to a dynamometer and run at a constant speed. The machine is then operated at different points within the operating quadrant. The current magnitude is varied from zero to maximum rated, and the control angle $\delta$ from 90 to 180 degrees in order to cover the operating quadrant. This is the equivalent of saying that the $d$- and $q$-axis currents input into the machine are varied to go from $(I_q=I_{\text{max}_\text{rated}}, I_d=0)$ to $(I_d=I_{\text{max}_\text{rated}}, I_q=0)$. The dynamometer serves to counter any torque that is produced by the machine being characterized and thus maintain the speed constant. Figure 6 shows the general setup used for characterization of PMSMs.

![Diagram showing the experimental setup used for control and characterization of PMSM designs](image)

Figure 6: Diagram showing the experimental setup used for control and characterization of PMSM designs

For each point at which the machine is operated, it is necessary to record three waveforms at steady state: the rotor position, the phase voltage and the phase current. Other parameters required are the phase resistance, which can directly be measured from the machine terminals,
the rotation speed, and the magnet flux. The magnet flux is obtained by running the test machine at a constant speed and recording the Back EMF waveform. The magnet flux is then obtained using equation (18).

The data recorded for multiple points within the operating quadrant is then post-processed in order to obtain the $d$- and $q$-axis flux linkages, each as a function of both $I_d$ and $I_q$. This is done by using the steady state PMSM model equations (16)-(17) and solving each one for the value of flux linkage, which leads to:

$$\lambda_d (I_d, I_q) = \frac{V_q - R_s I_q}{\omega_e}$$  \hspace{1cm} (24)

$$\lambda_q (I_d, I_q) = \frac{R_s I_d - V_d}{\omega_e}$$  \hspace{1cm} (25)

For each point recorded, the values of $V_d$, $V_q$, $I_d$ and $I_q$ can be obtained from the logged waveforms of position, voltage and current, as is shown in Figure 7. The rotor position is converted to electrical position in order to have all quantities running at the electrical frequency. It is important to note that although the normal convention followed for PMSM operation dictates that the $d$-axis component is placed at 0 degrees and the $q$-axis component is placed at 90 degrees, Figure 7 shows the opposite. While Figure 7 may appear to contradict Figure 4, this is done in order to achieve a proper alignment, as explained in [13]. It is also possible to compute $d$ and $q$ axis inductances, by:

$$L_d = \frac{\lambda_d - \lambda_{pm}}{I_d}$$  \hspace{1cm} (26)
$$L_q = \frac{\hat{\lambda}_q}{I_q} \quad (27)$$

Figure 7: Voltage, current and rotor position (electrical) waveforms and extraction of d and q components for use in the analytical model. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

2.2 PMSM designs that work with ferrite magnets

2.2.1. Selection of designs for comparison

To put things in perspective, this work is a continuation of the work found in [20], where several designs containing ferrite magnets are explored. Here, the author starts by taking a PMSM designed for use with NdFeB magnets, replaces the magnets by ferrite magnets, and compares their torque outputs. The results show that the version with ferrite magnets achieves a maximum torque output that is 37% of the same design but with NdFeB magnets. The author
then studies and compares 3 other designs which are variations of the spoke-type PMSM, and which contain ferrite magnets, with the objective of increasing the torque output. Finally, the author constructed three machines with different magnet material (SmCo, NdFeB and ferrite). The work presented in this thesis parts from this point. Experimental characterization results are obtained for the SmCo and ferrite machines, and the exact same ferrite machine design is then used for the comparison part of this work. The second design in this comparison is a Permanent Magnet Assisted Synchronous Reluctance Machine (PMASynRM). The PMASynRM offers a different approach from the spoke-type PMSM to increase the torque output and it has been examined and presented in the literature as a viable option for using ferrite magnets. Figure 8 shows one pole of each design, and shows the direction of the magnet flux as well as the location of the $d$-$q$ axes on the geometry.

![Diagram of PMSM designs with ferrite magnets compared in this thesis. Spoke-type (Left) and PMASynRM (Right).](image)

**Figure 8: PMSM designs with ferrite magnets compared in this thesis. Spoke-type (Left) and PMASynRM (Right).**

2.2.2. Spoke-type PMSM

The Spoke-type PMSM, also known as Flux Squeeze PMSM, is characterized by having the magnets placed radially in the rotor and magnetized tangentially. By doing this, the magnet faces are large and able to push great levels of flux density towards the machine’s airgap [16].
This concentration of the flux allows the machine to achieve an airgap flux density that is as high as that of a rare earth magnet motor [6], which helps it to achieve a higher torque density [17]. Thus, these machines are suited for both rare earth magnets, such as NdFeB, and also for ferrite magnets. As a matter of fact, it has been shown that for this design, rare earth magnets do not improve the performance greatly, showing a 10% increase in power density. This machine design is used by Honda in Electric Vehicle applications [16]. Some drawbacks found in this type of machine design include a restricted Field Weakening operation at high speeds, risk of irreversible demagnetization of the permanent magnets [6] and distortion of the Back EMF waveform [17].

Figure 8 shows the location of the $d$ and $q$ axes in a spoke-type PMSM. The $d$ axis lies completely in the iron wedge that lies between adjacent magnets, whereas the $q$ axis lies along the magnet length. Because of this, the spoke-type PMSM has a greater $d$-axis inductance than it does $q$-axis inductance $L_d > L_q$, which according to [16], gives a saliency ratio greater than one. Figure 11 shows plots of the $d$ and $q$ inductances as functions of their respective axis currents ($L_d(I_d)$ $L_q(I_q)$) for both machine designs. This data was obtained by use of Finite Element Analysis software, where for each machine design; steps of current were applied while aligned with the $d$ and $q$ axes. In this plot, it can be seen that the $d$ and $q$ inductances are very similar for the spoke-type PMSM, but they vary significantly for the PMASynRM. Because of this, it can be assumed that a spoke-type PMSM will provide no reluctance torque component, as is stated in [2]. Figure 9 shows the direction of the magnetic flux lines in a spoke-type PMSM design.
2.2.3. PMASynRM

The Permanent Magnet Assisted Synchronous Reluctance Machine, or PMASynRM, follows a different approach from the spoke-type PMSM. This machine design is based on the classical Synchronous Reluctance Machine (SynRM), which works by achieving a high saliency, which allows them to achieve a wide field weakening region and high power factor operation [5]. The objective for this type of machines is to have a large difference between the $d$ and $q$ axis inductances. This is achieved by placing flux barriers, which limit the flux in the $d$ axis direction, and having regions of iron between them that serve as flux guides for the $q$ axis flux [18]-[19]. This type of machines is largely dependent on reluctance torque, which is generated by the difference in $d$ and $q$ inductances. SynRMs have disadvantages, such as low torque density, power factor and efficiency when compared to machines that make use of permanent magnets [1]. Based on this, permanent magnets can be added to SynRMs inside the flux barriers [19] to increase the torque density, efficiency and power factor [3]. Permanent magnets help by assisting in the production of torque in the machine by adding a magnet torque component, hence the name of PMASynRM. Figure 10 shows the direction of the magnetic flux lines in a PMASynRM design. In Figure 11, it can be seen how the $d$ and $q$ axis inductances show a larger
difference between them, which allows the machine to develop this reluctance torque component, as compared to the spoke-type PMSM.

*Figure 10: Magnetic flux lines in a PMASynRM design*

*Figure 11: Examples of d and q inductances as functions of their respective axis currents (i.e. Ld(id), Lq(iq)) for a spoke and a PMASynRM design.*
III. WORK PERFORMED

In this section, the details of the work that was performed for this thesis are provided. First, the tools used for control, simulation and design of PMSMs are presented. These tools include a Real Time LabView (RTLV) platform, as well as Finite Element Analysis (FEA), which is a crucial tool in the process of design of PMSMs. RTLV is used for the control of PMSM designs, allowing the user to build a controller, monitor important variables and store data. FEA is used for simulating the performance of electrical machines under different scenarios. Some of the key capabilities of each one are discussed, as well as advantages over other similar tools. The process for experimental characterization is discussed, with a focus on the experimental setup and the controller used. As mentioned before, experimental characterization was performed on two PMSM prototypes containing different magnet material, one with SmCo and the ferrite design compared in this part of the work. Said experimental results are presented, followed by FEA results for the ferrite machine and a comparison between the FEA and experimental results.

The comparison between FEA and experimental characterization results for a specific PMSM design serves as a guideline for designing new PMSM designs because it gives an idea of how close the simulated performance will be to the actual experimental performance. Once a comparison between FEA and experiment has been obtained for the ferrite spoke-type PMSM design, a PMASynRM is designed and simulated using FEA. The parameters on which the comparison will be based are discussed. The main goal of this part of the work was to determine which rotor configuration has a better performance. Because it is known that ferrite magnets lead to a decreased power output when compared to designs with rare earth magnets, it was desired to determine which rotor geometry was more efficient in achieving a higher torque output.
The process for design of a PMASynRM with ferrite magnets is presented. A literature review of designs that use ferrite magnets is included. Also included in this literature review are various PMASynRM designs on which the design presented here is based. After preliminary results are obtained for the initial design, additional refinements from the literature are done to it in order to improve its performance. The process for design of the windings on the PMASynRM is discussed and a diagram is presented, along with the windings of the spoke-type PMSM. In addition to these techniques, further modification of the rotor geometry is done in order to facilitate the construction of a prototype for experimental work, as it was desired to have an ease of implementation and construction as well as a quick turnaround of parts. The design used for a prototype is shown here.

Finally, the process for evaluating the performance of each design is presented. A program was developed to generate torque speed curves for the designs using flux linkage data obtained from characterization. The details of incorporation of Maximum Torque per Amp and Field Weakening, such as the voltage limit on the inverter, are also given. This lays the groundwork needed for better understanding the procedure of obtaining the important results, which are then presented in section IV.

3.1 Tools used

3.1.1. Real time programming platform

Figure 12 shows the setup used for experimental characterization and testing of PMSMs. Control of PMSM prototypes is done by means of a Real Time LabView (RTLV) programming platform from National Instruments (NI). In this platform, two computers are set up, one of them serving as a host computer and the other one serving as a target computer. The main idea behind this configuration is to have a separate computer whose main priority is to run the controller that
will be applied to the drive of the test machine. These computers are connected by Ethernet which allows them to send information back and forth to each other.

![Diagram of experimental setup for characterization of PMSMs](image1)

*Figure 12: Diagram of experimental setup for characterization of PMSMs*

![Components of the real time programming platform and their interactions](image2)

*Figure 13: Components of the real time programming platform and their interactions*

Figure 13 shows the interaction between the host and target computers in more detail. Initially, the controller is created in the host computer and then deployed to the target computer, which contains an FPGA card to run it. In addition to running the controller, the target computer is used to store files containing experiment data from any point within the controller. During an experiment, the target computer interfaces with both the host and with an external connector block. The interface with the host computer allows the user (at the host computer) to interact...
with the controller by means of monitoring variables and changing controller parameters (e.g. P.I. controller gains) and commands in real time. This interface also serves for retrieving stored data from the target computer, and post processing it with a program like MATLAB or Excel. On the other side, the interface with the connector block is used to read and write both analog and digital signals. The connector block is used to read voltage, current and position sensor outputs, as well as output the PWM signals that go into the inverter switches.

The main advantages of this platform over other methods (e.g. DSPs) stem from the fact that a separate computer is used for running the controller and read/write variables. The processing power of the target computer is used mainly for running the controller, rather than having the controller as an additional task on the host computer. In addition, and unlike a DSP, the target computer contains enough memory space so that a large amount of variables can easily be logged by the target computer, which allows the user to store a great deal of information to be post processed and analyzed later. With this, the user is able to inspect variables from virtually any point within the controller which can help with troubleshooting. The creation of the controller was done using a toolkit by NI called the Simulation Interface Toolkit (SIT) that interfaces MATLAB and LabView, so that the basic program can be created in block diagram form using Simulink and then converted to LabView useful code.
3.1.2. Finite Element Analysis

Finite Element Analysis (FEA) is a powerful tool when it comes to design of electrical machines. With FEA, approximate solutions to boundary-value problems of mathematical physics are obtained [10]. The method used in FEA consists of four principal steps [9]:

- Splitting up the solution region into a finite number of subregions
- Deriving the equations that govern the element under analysis
- Assembling the elements in the region
- Solving these equations obtained for all the subregions

Programs have been created to automate this procedure, where the user can create the geometry of an electrical machine and have the program solve it iteratively. The simulation capabilities of such programs extend to the point where the magnetic flux lines, as well as the magnitude can be displayed for the machine design. One of the strong points of these programs that makes them suitable for analysis and design of electrical machines is that, by dividing the region into multiple subregions, they are able to incorporate the magnetic saturation present in the steel used in the stator and rotor of an electrical machine. Thus, a realistic result that gives an idea of what to expect with a real machine prototype is obtained. In addition, the program incorporates periodicity, allowing the user to only simulate one pole of a machine design. Finally, FEA programs allow machine designs to be simulated under different conditions, allowing the user to define the rotation speed of the machine and the currents that are injected into the stator windings. A scenario can be created where the machine design is solved for different magnitudes of current and with different control angles. This makes the program useful for replicating the characterization procedure that was done experimentally where the machine is rotated at a constant speed and has sinusoidal currents injected into the windings with different magnitudes.
and control angles. After the simulation is complete, a wide array of parameters and variables are given by the program, such as torque and iron losses.

One of the challenges of FEA is that computation time is often long. Even when FEA allows the user to simulate a region of the machine (e.g. one pole), which reduces the computation time significantly, computation time can still be expected to be long. This is especially the case when running a complex scenario that involves solving the region for several values of current magnitude and control angle. For example, if the machine is to be subjected to current magnitudes ranging from 2A to 10A in steps of 2A (5 magnitudes), and control angles from 90 to 180 degrees in steps of 10 degrees (10 control angles), then the machine region must be solved repeatedly a total of 50 times. This is one of the reasons why it is desired to obtain and work with a machine model containing the characterization data. This will allow the performance of the machine to be evaluated quicker than if it was analyzed with FEA.

3.2 Experimental characterization of PMSM designs and comparison with FEA

Characterization of PMSM designs was done using the setup found in Figure 12 and following the procedure described in section 2.1.E, in order to obtain the flux linkages for the machine’s operating region on the $d$-$q$ axis for a specific speed. A basic diagram of the controller used can be seen in Figure 14. This controller is a basic current controller, where the desired current is commanded in the $d$-$q$ frame of reference by providing the magnitude $|I|$ and the control angle $\delta$, to then be converted to the corresponding $d$ and $q$ components. These commands are then compared with the actual phase currents, which are converted from the stator frame of reference to the $d$-$q$ frame of reference. Proportional-Integral (PI) controllers are used to regulate the commanded currents, giving a voltage command which should be applied in order to obtain
the desired currents. These voltages are then converted from the $d$-$q$ frame of reference to the stator frame and Space Vector PWM (SVPWM) is used to determine the duty cycles ($D_a, D_b, D_c$) required by the switches of the inverter used in order to generate the desired voltages.

**Figure 14: Basic diagram of controller used in characterization of PMSMs**

For these experiments, 300RPM was chosen as the dynamometer speed. RTLV was used to control the inverter connected to the test machine, and also to save data for the phase voltage, phase current, and rotor position for the points within the operating region. A Matlab program was developed to compute the flux linkages from the logged data, based on solving equations (24)-(25) as was described in 2.1.E. Because rotor position has been aligned with the machine’s $d$ and $q$ axes, the necessary variables to compute the flux linkages are obtained from the phase voltage and phase current along with the position as shown in Figure 7.

Figure 16 shows the $d$ and $q$ flux linkages over the entire operating range for two PMSM designs with different magnet material, whereas Figure 15 shows the rotor geometries of each design. Table 1 shows the important parameters for the two PMSM designs, such as maximum current, voltage, etc. Design A is a PMSM with Samarium-Cobalt (SmCo) PMs, whereas design B is a spoke-type PMSM design containing ferrite magnets. Typical behavior is observed for the
flux linkages influenced by both $d$ and $q$ axis currents. For the $d$ axis, the flux linkage decreases with an increment in both current and angle, because that means more flux is being put in the negative direction of the $d$ axis. The $q$ axis flux linkage will increase with current magnitude, but will decrease with an increment in angle, which corresponds to putting a larger component of the flux on the $d$ axis. The SmCo machine design shows higher values of flux linkages than the spoke design, as well as higher maximum output torque. All this is due to the greater flux producing capabilities of the SmCo Permanent Magnets.

<table>
<thead>
<tr>
<th>Magnet material used</th>
<th>SmCo</th>
<th>Ferrite (Spoke)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Stator slots</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>Maximum rated power</td>
<td>10kW</td>
<td>6.5kW</td>
</tr>
<tr>
<td>Maximum Voltage/Current (rms)</td>
<td>480V, 18A</td>
<td>480V, 15A</td>
</tr>
<tr>
<td>Max Torque</td>
<td>64 N-m</td>
<td>37 N-m</td>
</tr>
<tr>
<td>$\lambda_{pm}$</td>
<td>0.8 V.s</td>
<td>0.259 V.s</td>
</tr>
</tbody>
</table>

Table 1: Parameters for PMSMs with different magnet materials characterized experimentally
Figure 15: Rotor geometries for PMSM designs with different magnet material which were experimentally characterized. Design A, using SmCo (Left) and Design B, with Ferrite (Right).

Figure 16: Experimental flux linkages for designs A (left) and B (right).
The spoke-type PMSM design with ferrites (Design B) was also characterized using FEA and compared with the characterization results obtained experimentally. The results obtained from FEA for this design are shown alongside the experimentally obtained flux linkages in Figure 17. It can be seen that the waveforms for the flux linkages over the operating region follow the same trend. However, FEA gives higher values than the experimental results, and shows smoother looking waveforms.

![Diagram showing FEA and experimental results for flux linkages](image)

*Figure 17: Comparison of experimentally obtained flux linkages with those obtained from FEA for spoke-type PMSM containing ferrite magnets (Design B).*
At the time of submission of this document, the properties of the materials used in FEA are being examined in order to find the source of this discrepancy between experimental and FEA values.

3.3 Comparison of PMSM designs with ferrite magnets

3.3.1. Objective & goals

Having obtained a comparison between FEA and experimental results for the spoke-type PMSM with ferrite magnets, the next step of this work is to investigate if the spoke-type PMSM offers the best performance when used with ferrite magnets. For this, a second PMSM with different rotor geometry is designed with the goal of having its performance compared to the spoke-type PMSM. Because the spoke-type PMSM comes from an already fabricated prototype for which experimental data is available, that design is left as is. The second design is selected from a literature review of PMSM designs that can work with ferrite magnets. Said literature review and the PMSM design selection are discussed briefly in section 3.3.2. The physical dimensions of the machine are to be kept the same between both designs, and can be seen in table 2. In addition to the overall dimensions, the stator used (seen in figure 15), along with the magnet type and properties, are also kept constant. The magnet used is Ferrite Y34, with a remanent flux density of $B_r=0.4T$. 
Table 2: Parameters and dimensions for the spoke-type PMSM which are used in the second PMSM design

With this in mind, the main objective of the design of this second PMSM is to keep as many parameters as possible constant between both designs and keep the difference in magnet configuration in the rotor as the main difference between the designs. This way, the study focuses on which rotor geometry offers the best performance. The items for which the designs are compared include:

- Maximum torque
- Torque ripple
- Operating range
- Magnitude of Back-EMF
- Amount of magnet material required
- Efficiency

Out of these, the most important items in the design of PMSMs are the maximum torque and the operating range. It is normally desired to have a PMSM design that can give a high torque output and sustain it over a wide operating range. In fact, it is said that one of the drawbacks of the spoke-type PMSM is that they cannot achieve as wide an operating range as other designs [17]. As a starting point, the spoke-type PMSM can output a maximum torque of around 37N·m when equipped with ferrite magnets, and it achieves a corner speed of around
1850RPM. These two parameters serve as guidelines to measure how well the second design succeeds in attaining better performance.

3.3.2. Literature review for selection of second design

A literature review was done to determine which design to select for the comparison with the spoke-type PMSM. Because this second design was to be designed all the way up to implementation in the form of a prototype, the main requirement for the designs researched (apart from the mandatory requirement of being able to use ferrite magnets) was simplicity of manufacturing and assembly. [22] shows a surface PM machine that incorporates both NdFeB magnets along with ferrite magnets. The NdFeB magnets are magnetized radially, whereas the ferrite magnets are magnetized circumferentially. The authors indicate that the NdFeB magnets serve to achieve the high airgap flux needed for high power density, and the ferrite magnets are used for smoothing the Back EMF waveform produced. Because it was desired to have a design which can only use ferrite magnets, this design was discarded. [23] presents an axial gap machine with ferrite magnets, which was discarded for this application because of it being a complex model to manufacture. The same obstacle was found for [24], where the use of a line-start PMSM is proposed. This design would require the inclusion of metal bars in the rotor and was also discarded in favor of another design which would be simpler to manufacture.

Apart from this, it was found that a large amount of papers make use of the Permanent Magnet Assisted Synchronous Reluctance Machine (PMASynRM), whose theory and operating principle were presented in section 2.2.3. This design is considered an Interior PM machine, and only requires the insertion of magnets in the rotor, which makes it suitable for simpler manufacturing and assembly. Although several different variations of PMASynRM designs were found in the literature, the design used here is based mainly on the designs presented in [1] and
[3]. In addition, other design variations were also studied in order to collect techniques which improved the performance (e.g. reduce torque ripple, increase maximum torque, etc.) of PMASynRMs and incorporate them into the design presented here. Some of these techniques were incorporated into the initial design, whereas others were incorporated later, in order to refine the design. The following section deals with the techniques applied to the initial PMASynRM used.

![Figure 18: One pole of the initial rotor geometry used for the PMASynRM design](image)

3.3.3. Design procedure for PMASynRM

3.3.3.1 Initial PMASynRM rotor design

Figure 18 shows the initial PMASynRM design considered. One of the most important parameters to consider in the design of the PMASynRM is the number of poles of the machine. [3] showed that out of designs with 4, 6 and 8 poles, the highest output torque in the constant torque region was obtained when using 4 or 6 poles. Although the main difference between the designs was set to be the magnet configuration in the rotor, the number of poles was selected so that the machine would have a higher output torque, as is detailed in [3]. Based on this, the
PMASynRM was designed to have 6 poles, and the windings were redesigned accordingly, as will be shown in the next section. Another basic consideration addressed initially was the number of flux barriers included in the rotor. In [18], it is mentioned that including too many flux barriers is detrimental to the machine’s performance mechanically because the steel that makes up the flux guides in between the flux barriers becomes narrower, and thus the laminations become indesigned in the literature was followed and three layers were chosen. Also, the ends of the flux layers were tapered, following the study found in [1], showing that this technique helps reduce the effect of irreversible demagnetization on the magnets.

Regarding barrier thickness, [5] shows the influence of the thicknesses of both the flux barriers as well as the flux guides (the regions that lie between the flux barriers) on the machine’s torque production capability. A ratio between these quantities is defined as:

\[
W_{tot} = \frac{W_{ins}}{W_{ins} + W_{iron}}
\]

(28)

\(W_{ins}\) is the sum of the thicknesses of the individual flux barriers, and \(W_{iron}\) is the sum of the thicknesses of the flux guides. In this study, it is reported that maximum torque is obtained when this ratio is between 0.5 and 0.6. The barriers were then designed to stay within these limits. Also in [5], it is stated that in order to have mechanical strength, the ends of the flux barriers cannot extend all the way to the circumference of the rotor, and so a tangential rib must be added which could not have a thickness smaller than the thickness of the laminations. In addition, in this and other works, such as [1] a radial (or center) rib is also included in between the flux barriers, also with the purpose of preserving mechanical integrity. The effect of the width of both these ribs on the maximum torque production is examined and presented in [5]. It is seen that increasing these ribs generally leads to a reduction in torque. Initially, taking into account that the thickness of the
lamination to be used was 0.355mm, these ribs were set to be 0.5mm thick.

3.3.3.2. Winding configuration for PMASynRM design

As was mentioned, although the stator size and shape (teeth, slots) were kept the same as in the spoke design, the winding configuration was different due to the change in the number of poles. Figure 20 shows the winding configuration adopted for the PMASynRM design with 6 poles along with the winding design for the spoke-type design. Both machine designs used a double layer winding. The winding configuration for the Spoke-type PMSM was fixed by the design, and the winding configuration of the PMASynRM was designed using [15]. Both designs have two separate windings (A1 & A2), which could be connected in series or in parallel, depending on the voltage being used. Figure 19 shows a summary of how the windings were designed for the PMASynRM. Q is the number of slots, is the number of pole pairs, and \( \alpha \) corresponds to the angle of each slot. The conventional three phase integral slot distributed winding is used for one layer. By using a diagram of the voltage phasors in each slot for one pole pair [13], the arrangement of the coils in the slots for the first layer was determined. The second layer was done by shifting the first layer by a certain number of slots and examining the Back EMF waveform with FEA. The shift that produced a Back EMF waveform that was closest to sinusoidal was employed. For this case, 30, 60 and 90 electrical degrees were examined, with 60 (two slots) giving the best result for the Back EMF waveform which is shown in the results section. The diagram is done for one pole pair, or the first 12 slots, and the exact same pattern is followed for slots 13-24 and 25-36. The resulting winding configuration for one pole pair of the PMASynRM design (starting with A+ at 0 degrees) can be seen at the bottom of Figure 19. Finally, diamond winding configuration was used to determine the phases in each layer. Layer
one, for example, consists of: A+ C- C+ B+ B+ A- A- C+ C+ B- B- A+ (for one pole pair), whereas layer 2 consists of: C- A+ B+ C- A- C+ A+ B+ C+ A+ B-.

Figure 20 shows that the PMASynRM winding ends up with fewer coils but longer end turns, due to the larger coil span. The spoke-type PMSM had a coil span of 3 slots on one side and 5 slots on the other side. The PMASynRM has a coil span of 5 slots on one side, and 8 slots on the other side.

Figure 19: Process for arranging the windings used in the PMASynRM design.
3.3.3. Estimation of saliency and preliminary results

As was discussed in the background section, most of the torque produced in PMASynRM designs come from the effect of saliency. The saliency, in turn, is useful for estimating how much reluctance torque the machine will produce. For this, it is necessary to compute the d and q axis inductances of the machine, $L_d$ & $L_q$. This was done using a feature within the FEA program, known as a Magneto Static simulation, which allows the user to solve the machine’s geometry in a single instant of time. This speeds up the computation time, because only one rotor position is considered. Also, because only an instant in time is considered, the currents applied to each phase are now DC. The $d$ and $q$ axis inductances are then computed by performing a Magneto Static simulation for two cases, corresponding to the $d$ and $q$ axes. For each case, each axis was aligned with phase A in the stator and the magnitude of the current is varied from zero to maximum rated. For each current magnitude, the phase A flux linkage (which, depending on the rotor alignment, would correspond to the $d$ or $q$ axis flux linkage) can be extracted. This procedure is similar to the characterization presented in 2.1.5, with the exception that here, the

![Figure 20: Winding configuration for a phase of the Spoke (above) & PMASynRM (below) designs.](image)
inductances are only obtained for two angles (90 and 180), and each inductance is a function of only its respective axis current (i.e. \( L_d(I_d), L_q(I_q) \)).

Figure 21: Block diagram of program used to estimate the machine’s torque components

Figure 21 shows a diagram of a program that was used to compute the machine’s torque, using equations (22)-(23) and (26)-(27). This program incorporates the \( d \) and \( q \) flux linkage data extracted from FEA. Using the Magneto static simulation along with this program is particularly useful because it quickly gives an idea of how changes to the geometry affect the output torque. In addition to maximum torque and its components, the current magnitude and angle for maximum torque can be determined. Using this procedure, it was found that the PMASynRM design used was able to achieve a maximum torque of 34N-m, with 26N-m of reluctance torque. This maximum torque was obtained at a current of 21A (max rated) and an angle of 160 degrees, with \( L_d \) & \( L_q \) around 15mH and 56mH, respectively.
3.3.3.4. PMASynRM design refinement

After initial results were obtained using FEA for the PMASynRM, additional changes were included into the PMASynRM for three main reasons:

- Reduction of torque ripple
- Mechanical integrity
- Simple construction of a prototype

Figure 22 presents the points within the rotor of the PMASynRM design where techniques were applied to further refine the performance of the PMASynRM. A technique presented in [1] was incorporated, where the ends of the middle flux barrier are altered on alternating poles, as is presented in Figure 22. By varying the shape of the ends of these barriers so that they face further inwards, the torque ripple is reduced. The results for this change on the PMASynRM design shown here can be found in section 4.2.

In terms of mechanical integrity, it is stressed in [5] that tangential and radial ribs are needed in the rotor for mechanical strength. It is also shown that the smaller these tangential and radial ribs are, the higher the output torque is. With smaller ribs, the flux density saturates quickly in those areas and thus not a lot of flux leaks through those ribs. Initially, these ribs had been designed to be slightly larger than the lamination thickness, at around 0.5mm (Lamination thickness of the steel used is 0.355mm). However, they were later set to be around 3 times the initial value for preserving mechanical integrity. This expansion in the ribs proved to be detrimental to the machine’s maximum torque, as was expected. The maximum torque of the machine was reduced to around 30 N-m, which is 81% of the maximum torque produced by the spoke PMSM, and 88% of that from the previous results with smaller tangential and radial ribs.
Another issue addressed was the simplicity in manufacturing a prototype. The classical design found in the literature uses a curved shape for the flux barriers and the magnets that are inserted in these barriers. For actual implementation, this becomes a problem because fabrication of custom curved magnets requires a custom mold which increases the lead time for ordering them. Other PMASynRM designs have been introduced that have adjusted the barriers in order to fit squared (or block) magnets, such as [5] and [19]. For the design developed in this work, a similar approach was taken, where the barriers were designed to house block magnets, but they were designed to approximate the barriers from curved design as much as possible. The PMASynRM rotor design that was used for implementation can be seen in Figure 23. At the time of this writing, a PMASynRM design was in the process of being manufactured and tested. Pictures for the rotor and stator can be seen in the Appendix section.
3.3.4. Procedure for evaluation of performance for PMSM designs

As mentioned previously, one of the drawbacks of FEA is that the computation time is long. One of the main points of the performance of a PMSM that is evaluated here is the machine’s operating range. For examining the machine’s operating range, a Torque-Speed curve is obtained. The point \((I_d, I_q)\) where maximum torque occurs changes with speed in order to guarantee maximum torque per ampere at every speed. Because of this, setting up a simulation in FEA that changes the current magnitude and angle for a wide range of speeds to find the maximum torque at each speed takes a large amount of time. To solve this problem, the analytical model is used for each design that uses data from the characterization procedure performed for each design and equations (16)-(17). For a given speed, this model gives an idea of what stator voltage is needed to apply a given current (up to maximum rated) to the machine, and what the generated torque for that current is.
With this in mind, a simulation is setup that can incorporate the PMSM model and take into account maximum voltage and current limits in order to generate a Torque-Speed curve. Figure 24 shows a block diagram of the simulation used. First, current magnitude and angle are input and converted into $d$ and $q$ axis components. As in characterization, the simulation sweeps the current magnitude from 0 to maximum rated, and the control angle from 90 to 180 degrees. By means of lookup tables, the flux linkage data obtained from characterization is incorporated into the program so that for every $(I_d, I_q)$ point entered, $\lambda_d$ and $\lambda_q$ are known. Using equations (16)-(17) & (19)-(23), and knowing the flux from the magnets, the resistance of a stator phase winding, and the speed of the machine, the program calculates $V_d$, $V_q$ and Torque for every $(I_d, I_q)$ combination entered. Equations (22)-(23) are used to calculate the composition of torque. Values of magnet flux are obtained from a no-load simulation of each design in FEA where the Back EMF is recorded and equation 18 is used. The speed is the desired speed for which the maximum torque is to be calculated. The stator phase resistance is measured directly (For the case of the PMASynRM where no prototype was available at this point, the resistance was

Figure 24: Diagram of simulation used to generate the Torque-Speed curve for PMSM designs using the analytical model
assumed to be the same of the spoke-type PMSM). The final step of the program is to determine if the voltage magnitude exceeds the voltage limit given by the inverter and the PWM technique used. The voltage magnitude was calculated as:

$$|V| = \sqrt{V_d^2 + V_q^2}$$

(29)

For both machines, a DC link voltage of 676V was assumed along with a Space Vector Modulation PWM used, in which the maximum possible line to line RMS voltage is given by

$$V_{\text{max}_{-l-l}} = 0.707 \cdot V_{dc}$$

(30)

From this, the peak of the maximum available phase voltage is calculated to be 390V. The program then excluded all the points for which the required voltage magnitude exceeded the limit of 390V and found the point that contained the maximum torque among the remaining points. The torque speed curves for both designs are found in the results section.
IV. RESULTS

4.1. Block Magnets vs Curved Magnets

To determine what would be changed by replacing curved magnets by block magnets, both designs were simulated and compared using FEA. Using the procedure in 3.3.E to create the PMSM model with FEA data, the maximum torque of each design, as well as the necessary current and control angle, were obtained. It is noted that the change from curved magnets to block magnets resulted in a slight increase in the magnet flux and the maximum torque. The design with the curved magnets was able to achieve a magnet flux of around 0.14V.s and a maximum average torque of around 29 N-m, whereas the design using block magnets showed a magnet flux of 0.18V.s and a maximum average torque of 30N-m. In table 3, the results show that the block magnet design has a higher magnet torque component than the design with curved magnets, which leads to the conclusion that the block magnet design achieves this by having a larger magnet volume (Given the lack of anisotropy in the block magnet design).

4.2. Performance results for Spoke-type and PMASynRM designs

Figure 25 presents four torque waveforms which show the torque ripple of multiple designs. The first one corresponds to the spoke-type PMSM, and the others to the PMASynRM design. Out of the waveforms corresponding to PMASynRM, one waveform comes from the design with curved magnets and without incorporating the change on the middle flux barrier (PMASynRM A), while another shows the result of incorporating this change and keeping curved magnets (PMASynRM B). It can be seen that even without this change at the ends of the middle barrier, the PMASynRM design already produces less torque ripple than the spoke-type PMSM. The fourth waveform included corresponds to the PMASynRM design with block
magnets (PMASynRM C). It is therefore concluded that the PMASynRM design provides the opportunity to further reduce the torque ripple by means of changes made to the rotor geometry.

![Graph showing FEA results of torque ripple for spoke-type PMSM and variations of PMASynRM.](image)

**Figure 25:** FEA results of torque ripple for spoke-type PMSM and variations of PMASynRM.
Figure 26: Torque-Speed curves for spoke-type PMSM and PMASynRM using analytical model and FEA data.

Figure 26 shows torque-speed curves which correspond to the spoke-type PMSM and PMASynRM with block magnets, which were generated using the analytical model and flux linkage data from FEA. Table 3 shows a comparison of the performance of both machines as obtained directly from FEA at a speed of 300RPM. As expected, the PMASynRM offers an extended constant torque region, with a corner speed of 2600RPM, in comparison with the spoke-type PMSM, which has a corner speed of around 1600RPM. In agreement with this, the PMASynRM also shows a reduced back EMF magnitude which comes from both the reduced number of poles and the reduced magnet flux. Figure 27 shows the Back EMF waveforms of both designs, the spoke-type PMSM and the PMASynRM with block magnets.

However, having a reduced magnet flux hurt the PMASynRM design in terms of torque
production. The results show that for the constant torque region, the maximum torque produced by the PMASynRM design does not match or exceed the maximum torque obtained with the spoke design. After around 5000 RPM, there is not such a big difference in the curves, as there is in the lower speed region. Additionally, as was shown before, the PMASynRM shows significantly less torque ripple. It should also be noted that in addition to producing higher torque in the constant torque region, the spoke design used half the magnet material required by the PMASynRM design.

At this point, the selection of one design over the other becomes a matter of evaluating trade-offs. The spoke-type PMSM uses low amount of magnet material compared to the PMASynRM and was able to achieve a higher torque. On the other hand, the PMASynRM shows an extended constant torque range, and a reduced torque ripple when compared to the spoke-type PMSM. In addition, it has fewer poles which in general is better in order to have a lower electrical frequency, and thus lower iron losses in the machine.

<table>
<thead>
<tr>
<th>Design</th>
<th>Spoke</th>
<th>PMASynRM curved</th>
<th>PMASynRM block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterization Speed</td>
<td>300 RPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Torque</td>
<td>37N-m</td>
<td>29N-m</td>
<td>30N-m</td>
</tr>
<tr>
<td>Current Magnitude/Angle</td>
<td>21A/120</td>
<td>21A/160</td>
<td>21A/160</td>
</tr>
<tr>
<td>Magnet Flux</td>
<td>0.25 V.s</td>
<td>0.14V.s</td>
<td>0.18V.s</td>
</tr>
<tr>
<td>Reluctance/Magnet Torque (%)</td>
<td>0-100</td>
<td>84-16</td>
<td>80-20</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>~20N-m</td>
<td>~10N-m</td>
<td>~6N-m</td>
</tr>
<tr>
<td>Back EMF peak</td>
<td>47V</td>
<td>14V</td>
<td>16.6V</td>
</tr>
<tr>
<td>Total magnet material required</td>
<td>124cm³</td>
<td>218cm³</td>
<td>256cm³</td>
</tr>
</tbody>
</table>

Table 3: FEA results for spoke-type PMSM and PMASynRM using both curved and block magnets

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Figure 27: BackEMF waveforms for both designs at 300 RPM (From FEA).

In terms of the torque make up, the spoke-type PMSM contains only the magnet component of the torque, as was expected. The PMASynRM design contains both a reluctance torque component and a magnet torque component, with the reluctance torque component being larger than the magnet torque component, confirming that the magnets assist in the production of the torque. It was also expected to have the maximum torque to occur at a control angle of around 90 degrees (No $I_d$ component) for the spoke-type PMSM, and closer to 180 for the PMASynRM design, which is confirmed by the results. At 300 RPM, the spoke-type PMSM had its maximum torque at a control angle of 120, and the PMASynRM at around 150 degrees. This is because the spoke-type PMSM design requires a larger $I_q$ in order to maximize the magnet torque component, whereas the PMASynRM requires more $I_d$ in order to decrease the overall flux in the D-axis and, thus, reduce the inductance in that axis, which effectively increases the saliency.
it is expected that the PMASynRM design will have better efficiency because of its lower electrical frequency given its smaller number of poles. For this efficiency analysis, both iron and copper losses were taken into account. The Bertotti method was used to calculate the iron losses. This method takes into account three types of losses (Hysteresis losses, eddy losses and excess losses), and is modeled using the following equation:

\[
dP_m = k_f \left( k_h B_m f^2 \frac{2}{hysteresis} + \pi \frac{2}{6} \sigma d^2 \frac{e^{\text{eddy}}}{(B_m f)^2} + 8.67 k_e \frac{3}{excess} (B_m f)^2 \right)
\]  

(31)

\(k_f\) is the fill factor of the laminated stator and rotor. (A number between 0 and 1)

\(k_h\) is the coefficient of losses by hysteresis \(\left[ \frac{W \cdot s}{T^2 \cdot m^3} \right]\)

\(k_e\) is the coefficient of losses produced in excess \(\left[ \frac{W \cdot s^{1.5}}{T^{1.5} \cdot m^3} \right]\)

\(\sigma\) is the conductivity of the iron laminations \(\left[ \frac{S}{m} \right]\)

\(d\) is the thickness of each laminations [m]

\(f\) is the frequency of the stator currents [Hz]

\(B_m\) is the magnetic flux density [T]

This equation describes the losses per unit volume. The FEA program used provides the capability of computing this quantity over the whole volume regions of the stator and the rotor,
provided the user inputs the loss coefficients and the conductivity of the iron used \((k_e, k_h, \sigma)\). These quantities were obtained from the supplier of the rotor and stator laminations.

Copper losses were calculated by computing the total length of the winding for one phase, taking into account end windings, and computing its resistance by:

\[
R_{ph} = \frac{l_c}{\sigma A_c}
\]  

(32)

where \(l_c\) is the total length of the conductor of one phase (taking end turn length, number of turns, and number of coils in a phase), \(\sigma\) is the conductivity of the material used (copper), and \(A_c\) is the cross sectional area of the conductor used. The machine resistance in one phase was also measured physically (using a multimeter) once the machine prototype was completed, in order to verify the accuracy of the calculated value. The copper losses were then calculated as:

\[
P_{copper} = 3 \left( I_{max_{rms}}^2 \right) R_{ph}
\]

(33)

It was found that both machines required the same amount of copper in their windings, and thus had the same amount of copper losses. Efficiency was then computed by [20]:

\[
\eta = 100 \times \frac{P_{out}}{P_{in}} = 100 \times \frac{P_{out}}{P_{out} + P_{copper} + P_{iron}}
\]

(34)

where

\[
P_{out} = T \times \omega
\]

(35)

\((\omega)\) is the speed in rad/s)

In addition to this method, the program shown in figure 24 was also used to compute the efficiency of both designs in order to compare with the efficiency values calculated in (34). As
was mentioned, this program contains the $d$-$q$ model of a PMSM and uses the flux linkage data obtained directly from FEA. For a specific speed, the program was used to obtain $V_d$ and $V_q$ for the values of $I_d$ and $I_q$ which would give the maximum torque at that speed. In this second method, the output power was computed the same way, using (35). The input power, however, was calculated as:

$$P_{in} = \Re \{V \times I^*\} = 1.5(V_d I_d + V_q I_q)$$  \hspace{1cm} (36)$$

Figure 28 shows the efficiency as a function of speed for both the spoke-type PMSM and the PMASynRM. Contrary to what was expected, the spoke-type PMSM showed a higher efficiency than the PMASynRM. In order to investigate the reason for this, two speed points were examined in more detail for both designs. Table 4 shows data for a low speed point (300RPM) and a high speed point (3000RPM).
Figure 28: Efficiency vs Speed for both machine designs compared
Table 4: Losses and efficiency data for spoke-type PMSM and PMASynRM designs at 2 speed points.

The efficiency results in table 4 are shown for both methods mentioned in this section for computation of input power. Method #1 refers to equations (31)-(34), where the iron and copper losses were used, whereas method #2 refers to equation (36) which uses the input currents and the voltages obtained from the analytical d-q model that uses the flux linkages from FEA. Both methods used produced very similar results, with percent differences of around 2% between them. At 300RPM, both machine designs are operating below their corner speed which means they operate only under the maximum current limit. Because of this, both are operating at the maximum current magnitude and thus have the same copper losses. In addition, the PMASynRM, as expected, produces iron losses which are almost half of those produced by the spoke-type PMSM. However, these values of iron losses are significantly smaller than their
respective copper loss, which is also expected at low speeds. Because of this, it can be assumed that the overall losses for both machines are the same at this point. Since at 300RPM the spoke-type PMSM produces more torque, it has a higher output power, and thus higher efficiency. At high speed, it is expected that the iron losses will have more of an impact on the total loss, and that its effect will be more pronounced on the spoke-type PMSM. However, it is seen in table 4, that at this point, the spoke-type PMSM requires a lower current magnitude than the PMASynRM. According to equation (31), the iron losses are a function of both the electrical frequency of the stator and the magnitude of the flux density. It is then inferred that a lower current magnitude at 3000RPM leads to a reduced flux density and thus, to lower iron losses. In addition, a lower current magnitude also leads to lower copper losses, as seen in equation (33). It could be concluded then, that because the spoke-type PMSM depends largely on the flux coming from the magnets, it is more efficient at higher speeds because it doesn’t require a large amount of current, as the PMASynRM does. In addition, the PMASynRM is able to produce a larger amount of torque at this point than the spoke PMSM (due to its extended range) and thus requires a larger current.

In addition to comparing both machines’ efficiency over their operating range, the machines were also compared in terms of their efficiency at their respective maximum output power points. Because of its extended constant torque region, the PMASynRM is able to produce more power than the spoke-type PMSM. Table 5 summarizes the efficiency results of both machines at their maximum power points. It is shown here, that the PMASynRM design not only is able to produce more power, but it can do so with a slightly better efficiency.
<table>
<thead>
<tr>
<th>Machine type</th>
<th>Speed</th>
<th>Current magnitude /Angle</th>
<th>Power output</th>
<th>Iron losses</th>
<th>Copper losses</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spoke</td>
<td>1850RPM</td>
<td>21A/143.5deg</td>
<td>7.1kW</td>
<td>96W</td>
<td>1053W</td>
<td>86.19%</td>
</tr>
<tr>
<td>PMASynRM</td>
<td>2600RPM</td>
<td>21A/160deg</td>
<td>8.3kW</td>
<td>93W</td>
<td>1053W</td>
<td>87.87%</td>
</tr>
</tbody>
</table>

*Table 5: Iron and copper losses along with efficiency for spoke and PMASynRM designs at each machine’s maximum power point*
V. CONCLUSIONS AND FUTURE WORK

In this work, control, characterization and design of PMSMs were done with the ultimate goal of accurately determining whether a PMASynRM design can achieve a better performance than a spoke-type PMSM based mainly on the rotor geometries. Experimental characterization of PMSM designs, one with SmCo magnets and the other with ferrite magnets, was performed. The ferrite design, a spoke-type PMSM, was also simulated using FEA and it was shown that results from FEA are close to actual experimental results. A PMASynRM with ferrite magnets was designed keeping the same stator and current density as the spoke-type PMSM. Best practices from the literature were included in the design in order to optimize it as much as possible. These techniques looked to achieve reduction of torque ripple, maximum torque output and sound operation. It was determined that even before incorporating techniques to reduce the torque ripple; the PMASynRM shows a lower ripple than the spoke design. An alternate design of PMASynRM was presented that would simplify the manufacturing and assembly process by making use of block magnets instead of the traditional curved anisotropic magnets. A side by side comparison was done between the PMASynRM and spoke-type PMSM designs, in order to compare their performance. An analytical model for each design was developed using data from FEA and with it, a Torque speed curve was generated using a program that could find the maximum torque for any given speed while maintaining voltage and current limits. From here, the operating range and maximum torque are compared. It was found that a 12 pole spoke-type PMSM produces a larger torque than a 6 pole PMASynRM, but the PMASynRM has an extended constant torque region and shows lower torque ripple. The PMASynRM design, however, takes up twice the magnet material than the spoke-type PMSM does. Both machines were also compared for their efficiency. Contrary to what was expected, it was seen that the
spoke-type PMSM shows better efficiency over its operating range than the PMASynRM. The
PMASynRM, however, can produce more power given its extended speed range, and it shows
better efficiency at its maximum power point than the spoke-type PMSM.

The work presented here can be expanded and built upon. For this work, the PMASynRM
design was kept as close as possible to the basic design presented in [1] and [3]. It was
mentioned that designs found in [5] and [19] made use of modified designs in order to
incorporate block magnets. The design in [5] only includes 2 magnets per pole (located in one
layer only), whereas the design in [19] contains 3 per pole (located at the center of each layer).
The design presented here uses a total of 14 magnets per pole as it attempts to fill the flux
barriers with magnet material in as is done in the original designs. For future work, the
PMASynRM design presented here should be compared with the designs that make use of less
magnet material in the same way that it was compared to the spoke-type PMSM in this work.
This comparison would serve as part of a study to determine the optimal quantity of magnet
material that should be used in a PMASynRM design. A conclusion can be made on what the
minimum amount of magnet is needed, or at what point does adding more magnet material does
not greatly affect the torque production. This would also serve as a guide to determine which
designs are the best for a quick and cost effective manufacturing process.

In terms of performance, the designs can be evaluated under Drive Cycle conditions and
extend the comparison to determine which design works better when analyzed for specific
traction applications.
APPENDIX

Figure 29: Picture of experimental setup used for characterization of PMSMs.

Figure 30: Stator used on PMASynRM and spoke-type PMSM designs.
Figure 31: Rotor of PMASynRM.

Figure 32: PMASynRM rotor with ferrite magnets.
Figure 33: Casing for PMASynRM with the wound stator inside.

Figure 34: Rotor laminations mounted on shaft.
Figure 35: Back EMF for the PMASynRM design obtained experimentally (Left) and from FEA (Right).

Figure 36: Characterization results for the PMASynRM design, obtained from FEA and used in the analytical model.
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