DESIGN OF OUTER ROTOR INDUCTION MOTOR
ALTERNATIVE TO PMSM WITH FIXED STATOR

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ABSTRACT

In the last few decades, the number of electric and hybrid electric vehicles on the road has gone up. Several factors have prompted this resurgence of electric vehicles; chief among them being growing environmental concerns and dwindling supplies of oil. Typically, the motors used in them were permanent magnet motors. With unpredictable variations in the supply and cost of magnets, the search is on for finding suitable alternatives to permanent magnet machines.

With this challenge in mind, this thesis explores the possibility that induction motors can become suitable replacements to permanent magnet counterparts. Indeed expanding on this suggestion, this thesis presents an approach to design an induction motor using the exact same stator as that of a commercially manufactured permanent magnet motor. Important design decisions such as the choice of rotor (squirrel cage or wound rotor), number of rotor bars, choice of material of the rotor bars, air gap length are experimented with and the logic behind the choices made are explained in detail.

The conventional double cage rotor bar shape is further optimized to search for the best possible shape for this application. A novel method to formulate the optimization problem is presented. The final design of the induction motor using the same stator as the permanent magnet motor and showing comparable performance as measured by the torque-speed envelope is presented.
RéSUMÉ

Au cours de ces dernières décennies, le nombre de voitures électriques sur la route a augmenté. Il y a plusieurs facteurs qui ont provoqué la résurgence des voitures électriques, dont les principaux sont des préoccupations environnementales et des difficultés éventuelles de l’approvisionnement en pétrole. Typiquement, les moteurs étaient du genre magnétique permanent. La recherche est lancée pour trouver des alternatives appropriées des machines magnétiques permanentes en raison des variations imprévisibles de l’approvisionnement et du coût des aimants.

Dans cette optique, cette thèse examine la possibilité que les moteurs à induction remplacent son homologue magnétique permanente. Cette thèse présente une approche pour dessiner un moteur à induction en utilisant le même stator que le moteur magnétique permanent qui est fabriqué pour le marché commercial. Des décisions importantes en ce qui concerne la conception, telles que le choix du rotor (un rotor à cage d’écureuil ou un rotor bobiné), le nombre de barres de rotor, le choix de matériel des barres de rotor, et la longueur d’entrefer d’air sont expérimentées et la logique sous-jacente aux choix est expliquée en détail.

La forme de la barre de rotor conventionnelle des rotors à double cage est davantage optimisée afin de chercher la forme la plus appropriée pour cette application. Une nouvelle méthode d’élaborer le problème d’optimisation est présentée. La conception finale du moteur à induction qui utilise le même stator que le moteur magnétique permanent et qui montre une performance comparable, mesurée par l’enveloppe couple-vitesse, est présentée.
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CHAPTER I

INTRODUCTION

1.1 Context and Challenges

Last year, 2014, saw a 23% increase in the sale of electric and hybrid electric vehicles in the United States alone [1] from the previous year (2013). Future projections by Navigant research show that the electric vehicle fleet will reach 6.6 million by 2020. Despite the growing interest, electric vehicles are not a recent invention. They have been around for over a century. But, the last few decades have seen a renewed interest leading to the reinvention of electric car technology, with better success than the early inventors.

To understand the renewal of interest in electric vehicles today, we must begin by understanding the origin of the electric vehicle, its drawback at the time that resulted in the prevalence of gasoline engines, and how several environmental factors such as climate change, air pollution as well as unstable and apparently dwindling oil supplies created the need for building more efficient and less polluting vehicles.

It is hard to pinpoint the exact year of invention of the electric vehicle although the early nineteenth century saw several crude and practical prototypes. This was facilitated mainly by the invention of the electric motor and the battery. Table 1 traces a history of electric vehicles from this time period. The period between the 1840s and 1880s saw the invention of rechargeable batteries, such as the lead acid battery, which were then used in subsequent models of electric cars. These batteries are very bulky and have a very low energy density. The distance travelled before recharging the battery is limited by the energy density of the fuel source. Thus, the first electric vehicles had a small range.
### Table 1 History of the electric vehicle [2]

Recently, other sources of energy to fuel electric vehicles have been invented. One such energy source is the lithium ion batteries that are being used in a number of other applications, notably consumer electronics. Although these batteries have a low energy density, they are quite small and light and if combined in large numbers can provide enough energy to allow for a better range than lead acid batteries. However, there are some concerns with the widespread adoption of lithium ion batteries such as cost, safety and longevity which have ensured that gasoline engine driven vehicles are still more prevalent than electric vehicles. The energy densities of gasoline, lithium ion and lead acid batteries are given in Table 2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Inventor</th>
<th>Description of the vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1828</td>
<td>Ányos Jedlik</td>
<td>Small scale model car powered by a motor designed by Jedlik</td>
</tr>
<tr>
<td>1835</td>
<td>Thomas Davenport</td>
<td>Small scale electric car</td>
</tr>
<tr>
<td>1838</td>
<td>Robert Davidson</td>
<td>Electric locomotive achieved a speed of 6.4 km/h</td>
</tr>
<tr>
<td>1884</td>
<td>Thomas Parker</td>
<td>First electric car to use rechargeable batteries</td>
</tr>
</tbody>
</table>

### Table 2 Energy density of fuel sources

It is worth noting here that battery energy can be measured in different ways. The energy capacity [6] of a battery is the total Watt-hours available when a battery is discharged at a certain discharge current from its full state of charge to empty state. This energy is calculated as the

<table>
<thead>
<tr>
<th>Type of fuel source</th>
<th>Energy Density (Wh/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>8070 [3]</td>
</tr>
<tr>
<td>Lead acid battery</td>
<td>70 [4]</td>
</tr>
<tr>
<td>Lithium ion</td>
<td>400 [5]</td>
</tr>
</tbody>
</table>
product of discharge power and discharge time. The unit used in this thesis (Table 1 and Table 2) is energy density or volumetric energy density measured in Watt-hour/litre. This is dependent on battery chemistry and packaging and helps determine the battery size required to achieve a given electric range.

Now, consider the conversion of energy from the source into useful mechanical work. In the case of a gasoline engine, the chemical energy stored in gasoline is converted to thermal energy in the internal combustion engine which is then converted to mechanical energy by the pistons causing the wheels to turn. The overall efficiency of this process, after accounting for losses (mainly heat), is at best 40% [7]. In the case of a hybrid or electric vehicle, the overall efficiency of converting the chemical energy from batteries to useful mechanical work can be as high as 90%. For instance, the Tesla Roadster has an overall powertrain efficiency of 88% [8]. Thus, it is possible to define an effective energy density, as described in Table 3 that combines the Wh/L energy density of the energy sources along with the efficiency of the technology that enables their conversion into useful mechanical work. In doing so, we find that the difference in effective energy densities between gasoline and other batteries have narrowed significantly. Furthermore, the low efficiency of the gasoline powered engine is harmful for the environment due to the wasted energy usually in the form of heat.

<table>
<thead>
<tr>
<th>Type of fuel source</th>
<th>Technology used for mechanical energy production</th>
<th>Effective energy density (Wh/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>Internal combustion engine</td>
<td>3228</td>
</tr>
<tr>
<td>Lithium ion battery</td>
<td>Electric motor</td>
<td>360</td>
</tr>
</tbody>
</table>

*Table 3 Effective energy density of fuels*
The search for cleaner vehicles has led to inventing energy dense, cost-effective and light batteries to be used in electric vehicles with high overall efficiency. In order to spur innovation in this field, several governments across the world have imposed stringent regulations. These range from imposing fuel efficiency on all vehicles, to providing tax rebates for electric cars. Undoubtedly, such measures have produced some positive results.

1.2 Design of electric vehicles

The electric vehicle design is essentially an integration of automobile engineering and electrical engineering. A number of engineering choices have to be made to design an electric vehicle which in turn determines not only the performance of the vehicle but also the cost. The technical specifications typically involve determining the overall system configuration (for example, battery operated or hybrid), type of energy source, type of electric propulsion drive (motor, converter, transmission, gearbox, internal combustion engine design in the case of a hybrid electric vehicle), requirements of the drive (torque, speed, power, input voltage and frequency), and efficiency of the system at different drive cycles. The following block diagram in Figure 1 describes the composition of the electric vehicle. With such a large number of parameters, the number of ways in which an electric vehicle drive can be designed varies enormously. This project focuses on the design of the motor that drives the electric vehicle.
From the literature [10], [11], a motor used in traction applications is expected to have

- a wide speed range, particularly in the constant power region
- high starting torque and ability to provide constant torque over a range of speeds
- high torque at low speeds and quick torque response to ensure good gradeability
- high power density
- high efficiency over a wide range of operating conditions
- fast and efficient dissipation of heat
- reasonable cost and reliability

Arguably, with such a large number of parameters, it is possible to arrive at several different topologies utilizing different motor types to identify the ‘perfect’ motor. For instance, a good initial acceleration and grade condition can be achieved with a minimum power rating if the powertrain is operated in the constant power region [12]. This will, in turn, lower the cost by keeping the overall power rating low. As in any problem that has a large number of solutions, determining the most appropriate motor can only be done on a case by case basis.
Traditionally, permanent magnet motors have been used in electric vehicle drives. The following are some reasons why such motors are preferred.

- Permanent magnets produce strong magnetic fields that are a source of self-excitation in permanent magnet motors. This means for a given output power, a permanent magnet motor will have the lowest overall weight and volume leading to a higher power density.

- There are no rotor copper losses in permanent magnet motors leading to higher efficiency. (Eddy current losses do occur in the rotor of permanent magnet motors which have other impacts in addition to decrease in efficiency as explained later).

- The major source of heat in a permanent magnet motor is the stator windings and heat can be more easily dissipated here since it is usually the external part of the motor.

Despite the significant advantages, permanent magnet motors are not without limitations. The speed control of a permanent magnet motor can be done by controlling the field. The applied voltage is varied in proportion to the frequency up to the base speed. This ratio of voltage to frequency is a measure of the magnetic flux, and thus this ratio is determined by the torque needed to be produced as well as the saturation of the laminations. In general, at base speed, the field current is chosen by design to be at its rated value. This results in the flux density being at the maximum without causing saturation. Beyond base speed, the applied voltage is kept a constant. Thus, both the voltage and current have hit a roof which limits the maximum speed at which rated torque can be generated. Also, the back emf of the motor increases in proportion to the speed. At higher speeds, the back emf increases so much so that it could exceed the input voltage making the flow of phase current impossible. This situation limits the maximum speed that the motor can reach while generating acceptable torque to give constant power, beyond base speed.
Beyond base speed, with constant applied voltage, the speed of the motor is inversely proportional to the field current. By varying the field current, the rotor speed can be changed. To overcome the drawback of increasing induced emf at high speeds, the air gap flux linkages will have to be weakened. As the permanent magnet field is constant, weakening the air gap flux involves controlling the components (direct and quadrature) of the field current independently to control both flux and torque. Injection of a negative direct component of field current results in a demagnetizing effect weakening the field which allows operating the motor at a higher speed extending the speed range. This approach requires the use of a special controller to allow operation at a higher speed but is limited by the maximum field current that can be passed through the windings.

At very high speeds and temperature, the motor efficiency drops with a risk of demagnetization and possible occurrence of faults. For instance, if the motor is operated at a temperature range nearing or above the Curie point, it affects the magnetic properties. Other faults in permanent magnet motors include mechanical faults in the bearings and electrical faults in the stator winding or the drive.

Eddy currents that occur in permanent magnets are undesirable. In addition to causing a decrease in efficiency, the eddy current losses increase with an increase in the frequency. At very high frequencies, the phase angle of these eddy currents shift such that they form a flux screen that prevents the original exciting B field from penetrating into the conducting material.

The fluctuations in the price of rare earth magnetic materials [13] have caused car manufacturers and researchers to investigate other types of motors such as induction motors and
switched reluctance motors. Commercially available vehicles such as the Tesla electric sedan and Toyota RAV4 have demonstrated the use of induction motors for traction applications.

Induction motors do not use permanent magnets making them a less expensive choice. Since the rotor magnetic field is produced by induction and hence is dependent on the stator excitation, a simpler control strategy will suffice to produce the necessary torque at high speeds, limited only by the available line voltage. They are rugged, reliable and robust. They do have a lower efficiency due to the rotor ohmic loss and this is affected by voltage levels (which in turn affect the flux), slip (variation between synchronous and actual frequency/speed) and operating temperature. By effectively varying these parameters, a method of flux control can be designed such that the motor can be operated more efficiently.

An evaluation of different types of electric motors based on a 5 point rating system (with 5 being the maximum possible score) is shown in Figure 2. It shows that permanent magnet and induction motor drives are close contenders.

<table>
<thead>
<tr>
<th></th>
<th>DC motor</th>
<th>Induction motor</th>
<th>PM brushless motor</th>
<th>SR motor</th>
<th>PM hybrid motor</th>
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<tbody>
<tr>
<td>Power density</td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>Controllability</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Reliability</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Maturity</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td>26</td>
<td>25</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

*Figure 2 Evaluation of different electric motors [14]*

1.3 Problem Statement and Objectives

The objective of this project is as follows:
To design an induction motor for traction applications with a performance similar to that of a commercially manufactured permanent magnet motor while using the exact same stator as that of the permanent magnet motor

For the reasons stated in 1.1 Context and Challenges, motors used in traction applications need to exhibit certain characteristics. The torque-speed characteristic becomes the primary determining factor in this study. Another key goal was to obtain good efficiency and power factor. Such a performance is expected at a nominal current density in both the stator and the rotor to avoid excessive heating. Thus, the current density is also monitored. A liquid cooling system is assumed. The torque generated is constantly verified to match that of the commercially manufactured permanent magnet motor. An efficiency of 80% or above and current densities of 30 A/mm², assuming a liquid cooling system, are the other constraints that the designed motor has to meet. A comparison with the permanent magnet motor is also done.

The two machines being compared are:

- 10 pole, 3 phase, permanent magnet synchronous machine
- 10 pole, 3 phase, 79 rotor bar induction motor

The design process followed is shown in Figure 3. The first step of this project is to determine the specifications of the input. Once that is determined, an initial design is generated. This initial design is further refined to generate starting and peak torque (at base speed) in close proximity to that of the permanent magnet motor. Finally, optimization of the rotor is carried out to arrive at the best possible design showing high efficiency while satisfying torque requirements. A side-by-side comparison of performance characteristics and cost analysis is then carried out.
1.4 Previous work

In 1973, LaFrance and Schult [15] wrote one of the first reports documenting the different types of electrical systems that can be used in a hybrid electric vehicle. The ‘electrical system’, according to their definition consisted of the electric traction motor, a generator, control system and batteries. Five different types of motors were considered and it was concluded that induction motors would become a major contender for traction applications in the future. This was based on
an earlier study by Salihi [16] in 1969 that reported a block diagram approach to simulating an induction motor at variable frequency and controlled slip. Following this, in 1996, Rahman and Ehsani [17] compared permanent magnet, induction and switched reluctance motors and concluded that induction motors are highly suitable for use in hybrid electric vehicle drives.

In 2007, Huijan [18] et al. reported a study where an inverter-fed induction motor was designed and simulated with the aim of being used in traction applications. The geometrical parameters of the motor were determined first, followed by the electromagnetic parameters. A 4 pole, 3 phase, 40 kW machine was the motor model experimented with. An efficiency of 94% at rated speed was set as the target. A visual basic program was used to predict the dynamic performance of the machine in the operating region. The control strategy employed was a closed loop vector control. The importance of the torque-speed envelope in predicting the usability of a motor for a particular application was highlighted. The study concluded that the induction motor is an attractive solution for use in hybrid electric vehicles.

In 2010, Dorrell [19] et al., reported a study comparing an internal permanent magnet motor used in the Toyota Prius hybrid electric vehicle with a copper cage induction machine and a switched reluctance machine. The permanent magnet motor used in the Prius hybrid and whose performance the two other motors have to match was an 8 pole machine. The induction motor and the switched reluctance motors had 8 and 18 stator poles respectively. All three machines being studied used a similar, external stator layout. The induction motor had a standard cage rotor with copper bars. Both a static and a time stepped finite element analysis was carried out. The comparison between the different motor models was done by using the torque generated from 1500 rpm to 6000 rpm, the efficiency during operation, current densities at various operating points and losses produced at those points. Through this comparison, this study establishes that both the
induction motor and the switched reluctance motor exhibit a performance close to that of the permanent magnet motor. An approximate analysis based on the material costs of the motors was also done. Using these two motor models, this paper demonstrated that the permanent magnet motor drive is not the only solution for use in a hybrid electric vehicle.

1.5 Scope of this thesis

As described in 1.3 Problem Statement and Objectives, the torque-speed envelope is the key performance indicator. All the analyses described in this thesis involve 2D models using commercially produced electromagnetic simulation and optimization software packages. 3D modeling is expensive both computationally and in terms of time. Future simulations can be carried out to examine the correspondence of the 2D model results with the results from 3D analyses.

While great attention is paid to meticulously modeling every design aspect of the motor, the control strategy implemented is determined initially based on needs and not varied very much through the course of the project. This is in line with the goal of the project which is to design an induction motor for an electric vehicle drive.

The initial design is then optimized. A few trial runs are done to understand the effect of the increase or decrease of a particular geometrical parameter on the overall torque generated. The goal of optimization is to come up with the best possible rotor bar shape for the starting as well as the peak torque condition. Two separate optimization problems to tackle each of these objectives are set up and simulated. The resulting two different bar shapes are then combined into one using the knowledge from the initial trial runs. The resulting bar shape was tested for performance (torque, current density and efficiency). There is room for optimizing the entire topology of the rotor or even the motor as a whole. However, such experiments are beyond the scope of this project.
This study clearly elucidates the rationale behind each design choice. For example, why is the air gap of this length and not smaller (or larger), why is aluminum used in the rotor bars and not copper, why are a certain number of rotor bars used, why is the input excitation \((V, f)\) of this specific value, are questions explored and answered at length.

1.6 Summary of the thesis

The thesis is organized as follows: Chapter I sets the context for the project, describes the problem statement, specific objectives, previous literature, scope and contributions. Chapter II explains the fundamentals of designing an induction motor, its principle of operation and its control. Chapter III explains the design of the external rotor induction motor, the choice of parameters, the different design decisions made and the reasons for them. Chapter IV explains the need for optimization, the simulations and results from the optimization experiments. Chapter V provides a comparative evaluation of the two motors, summarizes the findings of this project and describes future work.
CHAPTER II

FUNDAMENTALS OF INDUCTION MOTOR DESIGN AND OPERATION

The induction motor was invented by Nikola Tesla in 1887. Since then, it has become one of the most widely used rotating machines in the industry. A key physical phenomenon that helps explain the operation of the induction motor is detailed below followed by the construction and operation of the motor.

2.1 Principle of operation

Michael Faraday discovered electromagnetic induction in 1831. For his experiments, he wrapped two sets of windings around a torus, one of which was connected to a battery and the other to a galvanometer. He observed that when current flowed through one of the windings connected to the battery, the galvanometer recorded a flow of transient current. A similar transient current was observed when the battery was disconnected. Faraday thus established that a change in magnetic flux (when the battery is connected and disconnected) in one of the windings caused a voltage to be induced in the other which in turn caused the flow of current provided the path was closed. The magnitude of the induced voltage was found to be proportional to the rate of change of magnetic flux. Furthermore, the direction of this induced current was such that it opposed the change in magnetic flux that caused the flow of such currents.
According to Faraday’s law of electromagnetic induction, the induced voltage is given by,

\[ \varepsilon = -\frac{d\Phi}{dt} \]  

Equation 1

where \( \varepsilon \) is the induced voltage, \( \Phi \) is the magnetic flux, and the negative sign indicates that the induced emf opposes the change in magnetic flux [20].

### 2.2 Construction and operation of the induction motor

The induction motor is composed of two electrically active components: the stator and the rotor which are separated by a small air gap. The stator has balanced three phase windings, which are connected in either delta or wye, and placed in a number of stator slots that are physically spaced 120° apart. They are excited by a three phase ac supply causing currents of equal amplitude but differing in time-phase to flow. The current in each phase winding sets up a magnetic flux wave in the air gap which varies sinusoidally with time. This flux producing current is called the magnetizing current whose magnitude determines the magnitude of the flux wave. The three flux waves produced by the magnetizing current in each phase winding have a time-phase difference of 120° thus creating a travelling air gap magnetic flux wave. The speed of rotation of this stator magnetic flux wave is given by

\[ N_s = \frac{120f}{p} \text{ rpm} \]  

Equation 2

where \( N_s \) is the synchronous speed in revolutions per minute, \( f \) is the frequency in Hertz and \( p \) is the number of stator poles which is fixed for a machine and is determined by the connection of the stator windings. It is this flux wave that is key to the operation of the induction motor. A good design of an induction motor involves paying particular attention to ensure the maximum flux is produced by the stator and crosses the air gap radially to link with the rotor.
In simple terms, when an alternating voltage, $V$, is applied to a stator winding of an induction motor, an induced emf, $E$, that opposes $V$ is induced. The per phase equivalent circuit with the rotor currents ignored is shown in Figure 4.

![Per phase equivalent circuit with rotor currents ignored](image.png)

*Figure 4 Per phase equivalent circuit with rotor currents ignored [21]*

Using Kirchhoff’s voltage law yields Equation 3,

$$ V = I_m R + E $$

Equation 3

where $R$ is the winding resistance. Since the drop due to the winding resistance is very much less than the induced emf, $E$, it is ignored. That gives, $V \approx E$. The magnitude of the flux wave which is proportional to the winding mmf is given by $B_m$. Now, the induced emf, $E$ is proportional to $B_m$ and frequency, $f$. Thus, we get

$$ E \propto B_m f $$

Equation 4

By combining Equation 3 and Equation 4, we get Equation 5,

$$ B_m = k \frac{V}{f} $$

Equation 5

Equation 5 gives a convenient way to understand how to control the motor: to maintain a constant flux in the motor, the ratio of voltage to frequency will have to be constant.
There are two types of rotors used in induction motors: wound and squirrel cage. In the case of a wound rotor induction motor, the rotor consists of a set of windings similar to the stator placed in rotor slots but with a different number of turns. The squirrel cage induction motor uses a number of bars in slots as its rotor which are short circuited by end rings. A squirrel cage rotor is rugged, cheap and robust.

The travelling air gap magnetic flux wave cuts both the rotor and the stator at the same speed. According to Faraday’s law, emf is induced in the stator at the same frequency as the supply. The stator is stationary and the frequency of the current in the stator windings is the same as the supply. A voltage is induced in the rotor which is made of conductors that have now been exposed to a varying magnetic field. This induced voltage has an associated frequency. If we consider the rotor to be stationary, the stator rotating magnetic field will cut the rotor conductors at a very high speed and hence the induced voltage will be high. However, if we consider the rotor to be running at the synchronous speed, then no voltage will be induced since the relative velocity between the rotor and the field is zero. Thus, the relative velocity between the rotor and the rotating magnetic field plays an important role in determining the magnitude and frequency of the induced voltage. This relative velocity is defined by a quantity known as slip, which is given by

\[ s = \frac{N_s - N}{N_s} \]  

Equation 6

where \( N_s \) is the synchronous speed and \( N \) is the speed of rotation of the rotor. The rate at which the rotor conductors are cut by the field and thus their induced voltage depends on the slip. The induced voltage in each rotor bar will have the same magnitude and frequency but not the same phase. Thus, the induced voltage takes the form of a wave that is a replica of the stator flux wave. This voltage wave is rotating at slip speed, relative to the rotor [22]. Since the rotor bars are short
circuited, this allows the flow of a rotor current. Thus, the axial currents interact with the radial
flux to produce torque in the motor. The magnitude of the torque depends on the magnitude of the
rotor current while its direction can be determined by Fleming’s left hand rule for motors which
states that when a current carrying conductor is placed in a varying magnetic field, it experiences
a force that is perpendicular to both the field and the direction of the current flow.

2.3 Equivalent circuit model of an induction motor

Following the above discussion about the operation of the induction motor, the equivalent
circuit of the induction motor is now discussed which is largely the work of Steinmetz [23]. This
helps to understand and predict the performance of the induction motor under sinusoidal steady
state operating conditions. The equivalent circuit of the induction motor is very similar to that of
the transformer. Accounting for the variation of rotor resistance with slip in the transformer
equivalent circuit gives the induction motor equivalent circuit.

For the equivalent circuit analysis that follows, the stator is considered to be Y connected.
This means that the voltages are all line to neutral while the currents are line currents. $V_1$ is the
voltage applied to the stator windings. This causes a current $I_1$ to flow through the stator windings.
A voltage drop occurs due to the stator resistance $R_1$ and its leakage reactance $X_1$. The remaining
voltage $E_2$ is balanced by the back emf produced by the air gap flux. The stator current $I_1$ can be
resolved into two components: a load component $I_2$ and an exciting component $I_0$. The exciting
component can be resolved further into a core loss component $I_c$ and a magnetizing component
$I_m$. In the equivalent circuit, the exciting current is represented by a shunt branch with a core loss
conductance $G_c$ and a magnetizing susceptance $B'_m$. (This should not be confused with the flux
density, $B_m$).
At standstill, the rotor current is equal to the voltage $E_2$ divided by the impedance at supply frequency.

$$I_2 = \frac{E_2}{R_2 + jX_2}$$

Equation 7

As the rotor speeds up, both the induced voltage and frequency decrease along with the slip, $s$. Thus, the current becomes

$$I_2 = \frac{sE_2}{R_2 + jsX_2}$$

Equation 8

Thus,

$$I_2 = \frac{E_2}{\frac{R_2}{s} + jX_2}$$

Equation 9

where $\frac{R_2}{s}$ is the apparent rotor resistance. This can be thought of as the sum of the rotor resistance and the load resistance $\frac{R_2 (1-s)}{s}$. Thus, the steady state equivalent circuit is shown in Figure 5.

Figure 5 Equivalent circuit of induction motor
The electrical power calculated before the rotor inductance $X_2$ in the Figure 5 is the input power minus the stator ohmic loss and stator iron loss. This is the power that is transferred across the air gap from the stator to the rotor.

$$P_g = \frac{3I_2^2R_2}{s}$$  \hspace{1cm} \text{Equation 10}

The rotor loss subtracted from the air gap power gives the mechanical power output. The mechanical power is given by

$$P_m = P_g - 3I_2^2R_2$$  \hspace{1cm} \text{Equation 11}

$$P_m = (1 - s)P_g$$  \hspace{1cm} \text{Equation 12}

and

$$P_m = (1 - s)\omega_s T$$  \hspace{1cm} \text{Equation 13}

where $T$ is the output torque. Thus,

$$T = \frac{3I_2^2(R_2/s)}{\omega_s}$$  \hspace{1cm} \text{Equation 14}

Thus, the equivalent circuit model of the induction motor has been developed. The analytical approach is useful in gaining a clear understanding of the operation of the induction motor and the effect of changing a parameter on the output.

**2.4 Induction motor control**

There are several methods of controlling the induction motor including variable frequency, variable voltage, constant voltage by frequency, pole changing, vector, and slip recovery. For applications such as electric vehicles, the motor being used has to operate at a wide speed range
while providing the necessary torque requirement. Among the various methods of control, constant $V/f$ control has found widespread use in a variety of applications and is suited for electric vehicles as well. It provides a good range of speed with a wider stable operating region, good running and is easy to implement. Both voltage and frequency reach the rated value at base speed. Some ideal characteristic torque-speed curves using constant $V/f$ control are shown in Figure 6.

![Figure 6 Ideal torque-speed envelope of an induction motor using V/f control [24]](image)

From the equation for synchronous frequency, we understand that changing the stator supply frequency would also change the speed. Thus an adjustable frequency would provide for an adjustable speed drive. If frequency is reduced keeping the voltage constant, to keep the same induced voltage (and hence output torque), the flux has to increase. This is not desirable because the machine is likely to saturate. To avoid this, the flux has to be maintained at some optimal level for the machine such that the maximum torque is obtained at a high efficiency.
In order to understand how to maintain a constant flux, we recall Equation 3 below,

\[ B_m \propto \frac{V}{f} \]

The flux can be maintained constant by maintaining a constant voltage/frequency ratio. While employing this method of control, the voltage is increased until the base speed and kept constant afterwards. The curves shown in Figure 6 are ideal. Typically, a lower starting torque than expected is achieved at low frequencies due to the stator winding drop which reduces the effective volts available to set up the magnetizing current and hence the working magnetic flux. The starting torque at lower frequencies can be improved by employing techniques such as voltage boosting which compensate for the drop across the stator winding resistance.

2.5 Conclusions

The torque generated by the induction motor varies directly as the induced voltage and inversely as the synchronous speed. It is possible to operate the induction motor at varying speeds by varying the voltage by frequency ratio which maintains the flux in the machine at a constant value avoiding saturation.
CHAPTER III

DESIGN OF THE OUTER ROTOR INDUCTION MOTOR

The design problem, at hand, is one of designing an outer rotor induction motor with a performance comparable to that of its permanent magnet counterpart. Furthermore, utilizing the same stator as that of the reference motor is imposed as an additional design constraint. In theory, it is possible to produce a similar performance using the same stator for both kinds of machines – permanent magnet and induction. Ensuring these performance constraints are met imposes geometrical boundaries helping reduce the search space. The final design should ensure that all of the objectives are met.

3.1 Machine sizing and dimensions

An open-ended design problem, such as meeting the performance objectives alone would involve searching a large design space. With the help of the output equation, this large space can be narrowed to a solution space from which the ideal design evolves. The issue, however, is one of practicality. There is no guarantee that the design so produced will be manufacturable or that the costs of manufacturing are reasonable.

Retaining the same stator as that of the permanent magnet motor means that only the rotor needs to be newly manufactured thus keeping manufacturing costs low. Furthermore, to effectively compare two types of motors that differed only in their rotors, staying within roughly the same geometrical dimensions and/or volume so the motors would occupy similar amount of space and weigh within comparable limits is important. Thus, the axial length of the induction motor is kept the same as that of the permanent magnet motor. Since this is an outer rotor induction motor, the inner of the rotor is determined by the length of the air gap. The rotor width i.e., the length of the
back iron and the slot depth is selected in a way that allows for sufficient flux density without saturating the core while producing the necessary output torque while also staying within a size comparable to the permanent magnet motor. Two different values for the air gap, 0.75 mm and 1.5 mm, were tried. The resulting manufacturable design was checked for adequate torque production at the determined speed. The design dimensions, so arrived at, are summarized in the Table 4. A starting point for the key geometrical parameters has thus been established.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Induction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial length (mm)</td>
<td>135</td>
</tr>
<tr>
<td>Air gap (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Outer rotor diameter (mm)</td>
<td>184</td>
</tr>
<tr>
<td>Inner rotor diameter (mm)</td>
<td>153</td>
</tr>
</tbody>
</table>

*Table 4 Geometrical parameters of the induction motor*

The performance objectives that the design has to meet are summarized in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>At startup</th>
<th>At peak torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (rpm)</td>
<td>--</td>
<td>~3800</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>157.5</td>
<td>157.5</td>
</tr>
</tbody>
</table>

*Table 5 Performance characteristics of the permanent magnet motor*

Next, the shape and the number of the rotor bars and the material to be used in them will have to be determined. To perform a detailed analysis within a reasonable timeframe, finite element analysis (FEA) is used. Commercially manufactured electromagnetic simulation software, MagNet [25], is used to design and predict the performance of the induction motor. As the 3D modeling process is time consuming and complex, 2D models are built and analyzed in this design.
process. These results are valid because the simulations are carried out on a model with axial length same as the permanent magnet motor and long enough that the end effects can be ignored.

3.2 Typical torque-speed profile

Motors used for traction applications need to supply a constant torque over a wide speed range (from start-up to base speed, which is hence called the constant torque region) and continue to provide a reasonable torque in the extended speed range as well (constant power operation). Thus, the starting torque of the induction motor to be designed has to be as high as the torque produced at base speed.

The reference machine has the torque-speed profile [26] as shown in Figure 7. The objective is to design an induction motor that can follow a similar torque-speed envelope, which is taken as the key performance indicator. Efficiency and current density are two other factors that are monitored.

![Figure 7 Torque-speed envelope of the permanent magnet motor](image-url)
3.3 Preliminary design

The reference motor under consideration uses an external rotor topology [27] which is lighter [28] and hence used as hub motors in in-wheel drives. Given that the goal of this project is to produce an induction motor equivalent to the permanent magnet motor, an external rotor design is discussed.

Preliminary work [29] explored the possibility of using an external rotor with 60 rotor bars. The number of rotor bars was chosen based on consultation with senior designers as a starting point of the design development. The choice of six rotor bars per pole was made to have as many rotor bars per pole as possible to allow for more induced current which in turn would produce more torque. However, this would mean a tradeoff between the spacing of the bars and the number of slots. More rotor bars would mean more induced current but also greater flux density in the iron between the bars leading to a risk of saturation. So, with expert advice six induction bars per pole were chosen.

The next design choice was the shape of the rotor bars. Three different shapes – oval, round and double squirrel cage – were tested. The initial analyses resulted in a double squirrel cage rotor, as seen in Figure 8, which showed promise offering the highest starting torque with better correspondence to the torque-speed characteristic of the permanent magnet motor. With this design as a starting point, modifications were made.
3.4 Design decisions

Given the initial design process resulted in a conventional design that showed potential, further experiments were conducted to refine the number and shape of the rotor slots, and to determine the supply voltage and frequency, air gap length and material of the rotor bars to produce a torque-speed envelope similar to that of the reference motor. A design process is iterative in nature which was the case in this project as well. Different parameters were varied in each iteration while others were kept constant until an agreeable design was found. However, the discussion here follows a linear trajectory.

3.4.1 Shape and material of the rotor bars

The preliminary design described above used a double squirrel cage rotor. The double squirrel cage rotor possesses several advantages such as higher efficiency and higher power factor.
than a slip ring induction motor [30]. They are also more robust, reliable and easier to manufacture.

With a double squirrel cage rotor bar, it is possible to produce the effect of variable impedance. When current flows through the lower end of the bar that is closer to the stator, the current is tightly coupled to the stator making the leakage inductance smaller. The upper end of the bar being further away from the stator has a larger leakage inductance. At starting condition, the rotor is stationary and the slip is high. As the induced emf in the rotor is directly proportional to the slip, the induced emf is high at the start. Also, at high slip, the reactance of the bars are larger compared to the resistances. Thus, the induced current is forced to flow in the low reactance part of the bar closer to the stator, as noted earlier. As the effective cross section decreases, the rotor resistance is high producing a high starting torque. However, because of the considerable reactance as compared to the resistance at high slip condition, the induced current lags behind the induced emf. Hence, the resultant torque,

\[
T = B I_r l_r r \cos \Phi
\]

Equation 15

where \( B \) is the magnitude of the magnetic flux wave, \( I_r \) is the induced rotor current, \( l_r \) is the length of the rotor, \( r \) is the radius of the rotor and \( \Phi \) is the lag angle. Thus the torque produced is reduced by a factor of \( \cos \Phi \). As the slip decreases, the reactance of the bars also decreases which increases \( \cos \Phi \). So, at some value of slip closer to 0, maximum torque is produced.

When \( V/f \) control is employed, the starting voltage is quite low when compared to the rated voltage. A part of this starting voltage appears as a stator resistance drop, which in turn causes a reduction in starting torque as compared to the peak torque.
For the reasons stated above, the starting torque of the double squirrel cage induction motor can never be as high as the peak torque. However, the demanding starting torque requirement can be met through the employment of additional measures while starting. These measures include but are not limited to changes in the material used in the rotor bars, increasing the rotor resistance while avoiding overheating due to increase in starting current, improving the air gap flux by voltage boosting at starting frequencies. A few of these techniques are explored later.

<table>
<thead>
<tr>
<th></th>
<th>Voltage (V)</th>
<th>Frequency (Hz)</th>
<th>Current (A)</th>
<th>Speed (rpm)</th>
<th>Power factor</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start-up</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>16.79</td>
<td>25</td>
<td>237.8</td>
<td>0</td>
<td>0.76</td>
<td>146</td>
</tr>
<tr>
<td>Cu</td>
<td>16.79</td>
<td>25</td>
<td>276.4</td>
<td>0</td>
<td>0.74</td>
<td>128</td>
</tr>
<tr>
<td><strong>Base speed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>176.77</td>
<td>300</td>
<td>264.4</td>
<td>3312</td>
<td>0.57</td>
<td>182</td>
</tr>
<tr>
<td>Cu</td>
<td>176.77</td>
<td>300</td>
<td>318.7</td>
<td>3312</td>
<td>0.49</td>
<td>177</td>
</tr>
<tr>
<td><strong>Top Speed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>318.19</td>
<td>1020</td>
<td>127.5</td>
<td>11995</td>
<td>0.55</td>
<td>47</td>
</tr>
<tr>
<td>Cu</td>
<td>318.19</td>
<td>1020</td>
<td>154.7</td>
<td>11995</td>
<td>0.48</td>
<td>47</td>
</tr>
</tbody>
</table>

*Table 6 Comparison of aluminum and copper rotor bars along the torque-speed curve*

For the purpose of this design, aluminum was used in the rotor bars while traditionally, copper has been the favorite material preferred by the industry. A comparison between copper and aluminum bars at three different points along the torque-speed envelope is shown in Table 6.
During the initial design of the induction motor, aluminum was experimented with and as the results were satisfactory it was retained.

There are some trade-offs involved in choosing one material over the other. Copper has a higher conductivity than aluminum and hence can produce higher torque. But, the results from the simulations show the motor with aluminum bars as producing higher torque which can be explained in the following way: aluminum has a mass density that is almost four times lesser than copper which makes the motor with aluminum bars that much lighter than copper. As the electromagnetic torque, $T_e$ and the load torque, $T_L$ are given by

$$T_L = T_e - J \frac{d\omega}{dt}$$

Equation 16

where $J$ which is the moment of inertia is dependent on mass. The factor $\frac{d\omega}{dt}$ is positive when the motor is accelerating, 0 at base speed and negative as the motor decelerates. Thus, the factor $J \frac{d\omega}{dt}$ explains why when the motor starts up from rest, the load torque produced in the rotor with aluminum bars is 18% more than that of copper and this difference reduces to 2% at base speed and 0% at maximum speed. At this stage, the model could have been redesigned for copper bars. But, given that aluminum is cheaper and lighter, it was retained for further analyses.

### 3.4.2 Number of rotor bars

The initial design has 60 double cage rotor bars as seen in 3.3 Preliminary design. The number of rotor bars in combination with the number of stator slots has a significant impact on the electromagnetic noise, vibration and torque anomalies arising from their interaction. The rotor slot harmonics produce detrimental effects on the operation of the motor. They have a tendency to induce voltages in the stator coils which then appears in the stator current spectrum. The rotor slotting also causes the production of space harmonics which can result in locking and magnetic
noise among other effects [31]. From theory and experience, a set of empirical rules were formulated to determine the optimal combination of rotor and stator slots. A survey of literature shows that one of the earliest recordings of these rules was by Kron [32] in 1931. Through experimental verification, he listed a set of ten rules showing the rotor and stator slot relationships that would cause noise, vibration or other irregularities in the torque-speed envelope. In 1989, Timar produced a more extensive set of rules in his book [33] utilizing a larger amount of experimental data available.

A survey of these rules and consultation with experts showed that avoiding, as much as possible, any relationship between the number of stator and rotor slots would be ideal. The choice of a number, 79, co-prime to the number of stator slots is hence chosen as the number of rotor slots. Additional design refinements to the shape and number of the slots were made and will be discussed in Chapter IV.

### 3.4.3 Supply voltage and Frequency

The synchronous speed \( N_s \) is given by

\[
N_s = \frac{120f}{p}
\]

Equation 17

where \( f \) is the supply frequency and \( p \) is the pole number. The base speed, \( N \) of the reference motor is \( \sim 3800 \) rpm. The rotor speed of the induction motor never reaches the synchronous speed, \( N_s \).

The relative speed between the rotor and the field is called the slip, \( s \). Defining synchronous speed using slip results in

\[
N_s = \frac{N}{1-s}
\]

Equation 18. Assuming that the maximum torque required at base speed occurs at a low slip (0.08), the synchronous speed can now be found.
\[ N_s = \frac{N}{1-s} \]  

Equation 18

Once the synchronous speed is determined, the frequency can also be determined as the number of poles is known. The frequency thus obtained was 333.68 Hz.

The supply voltage \( (V) \) is determined by two factors: the maximum torque output required to be produced at the base speed and the maximum available battery voltage. As noted earlier, the torque produced is proportional to the magnitude of the magnetic flux wave which in turn is determined by the excitation supplied to the stator.

The stator of the motor is delta connected and thus line and phase voltages are the same. Given the torque requirement needed, and the frequency that was previously determined, the supply voltage is found to be 317 V.

![Figure 9 Torque-speed envelope of the induction motor](image)

Before proceeding further with the discussion of the design of the induction motor, a brief note on the methodology used in producing the torque-speed envelope is discussed.
A time harmonic (TH) analysis of the developed model was performed. As MagNet’s TH solver solves the field equations of the model, we get a clear picture of the steady state operation of the machine. One of the desirable characteristics of a motor used for automotive applications is the ability of the motor to provide a constant torque over an extended speed range. To realize this with the induction motor, a constant voltage/frequency control mechanism is employed.

At first, a single torque-speed curve was generated. Next, both voltage and frequency were changed appropriately to keep the $V/f$ ratio a constant. This ratio was chosen because for a voltage of 317 V and a base frequency of 333.68 Hz (~4000 rpm), the torque developed was 190 Nm. The reference motor generated a torque of 157.5 Nm up to the base speed.

Below the base frequency, the $V/f$ ratio was maintained constant while above the base frequency, the voltage was kept constant to generate the torque-speed envelope. The slip values at which maximum torque was reached were noted. The current at which maximum torque was generated was also noted. From this, the current densities were calculated and checked to be within the values set at the beginning of the design process. The variation of excitation voltage with speed for generating a torque-speed envelope is shown in Figure 10.
3.4.4 Voltage boosting

In an ideal scenario, one expects the starting torque developed will be as high as the torque seen at base speed. However, a practical induction motor does not behave in this fashion. The stator reactance voltage drop at low frequencies is high. Thus, the magnetizing flux at low frequencies is quite low and thus the starting torque also tends to be low [34]. In order to provide a higher flux at lower frequencies, the voltage of operation can be increased. The following figure shows the torque-speed characteristics of the motor with voltage boosting.

For frequencies of 20 Hz, 25 Hz and 30 Hz an incremental boost voltage of 5 V is applied. The effects in starting torque observed can be seen in the figure below. The decision to implement voltage boosting depends on the cost of additional circuitry involved and the practical limits involved in boosting the voltage. In this case, the maximum voltage doesn’t exceed the peak voltage even after boosting. Increasing the voltage will increase the current density and potentially lead to overheating. So, the current density will have to be monitored closely to ensure the cooling system is capable of dissipating the heat produced.
3.4.5 Air gap length

The magnetic circuit of a motor is a closed loop consisting of a low reluctance material, such as iron, and air. The presence of air in the path of flux lines linking the stator and the rotor is necessary although the total reluctance of the path is now much higher due to the high reluctance of the air gap. The question of how long this air gap should be is an interesting one. Intuitively, we are bound to come to the conclusion that a smaller air gap is better since the total reluctance, and effects of fringing and thus leakage are minimized.

The initial design began with an air gap length of 0.75 mm. The starting torque and current were quite satisfactory. In a spirit of experimentation, the air gap length was doubled to 1.5 mm. As expected, the starting current rose, as did the starting torque. Another factor that contributed to the rise in starting torque was the effect of saturation that was more prominent at a smaller air gap than the larger air gap. The rotor iron closer to the air gap was found to be more saturated in the case of the smaller air gap thus making the total reluctance of the magnetic path higher than when the air gap was doubled.
Further increments are made to the air gap length and the corresponding starting torque values are recorded. Figure 12 shows this variation. It can be seen that increasing the air gap length yields an increase in starting torque only up to a certain value beyond which the starting torque decreases, as expected.

![Graph showing variation of starting torque for varying air gap lengths](image)

*Figure 12 Variation of starting torque for varying air gap lengths*

From the manufacturing point of view, a larger air gap is easier to build while maintaining the alignment with respect to the centre and keeping the air gap clean. Figure 13 shows the comparison in the torque-speed envelope between the two air gaps.
3.4.6 First pass design

In summary, the first pass design of the induction motor resulted in the envelope shown in Figure 9. Thus, this version of design of the induction motor model developed in MagNet consists of a 3 phase, delta connected stator with 10 poles and 30 stator slots. The number of rotor bars was chosen to be a co-prime of the stator teeth to avoid cogging, locking, crawling, harmonics and any other irregular effects observed in the torque-speed envelope of the rotor. The squirrel cage rotor was modified to have 79 rotor bars. A cross section of this model is shown in Figure 14. (Another way to avoid cogging is to skew the rotor but the effect of skewing the rotor is not part of this study).
Figure 14 Induction Motor MagNet Model

The performance characteristics seen are as follows:

<table>
<thead>
<tr>
<th></th>
<th>At startup</th>
<th>At peak torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (rpm)</td>
<td>--</td>
<td>~4000</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>105</td>
<td>190</td>
</tr>
<tr>
<td>Torque with voltage boosting at start-up (Nm)</td>
<td>140</td>
<td>190</td>
</tr>
</tbody>
</table>

Table 7 Performance characteristics of the induction motor

While the peak torque is beyond the required value, the starting torque even with voltage boosting still falls short. Any design problem requires exploration and probing. Thus, the next step in this
process of finding a magnet free alternative is further refining the first pass design. This is done through optimization as explained in the next chapter.
CHAPTER IV

OPTIMIZATION

Following the initial design phase, the first pass design of the induction motor is further refined through optimization. As seen in Chapter III, the stator and the axial length of the motor are kept the same as the permanent magnet motor. The outer and inner diameter of the rotor; number, shape and material of the rotor bars and the air gap length, are experimentally determined. The shape of the rotor from the initial analyses is a standard double squirrel cage bar which is further investigated and the experiments and results of that line of inquiry are presented in this chapter.

4.1 Need for Optimization

A squirrel cage rotor bar possesses several desirable characteristics such as production of high starting and peak torque which takes advantage of the double bar construction, higher efficiency and higher power factor compared to a wound rotor induction motor. However, the question of whether this is the best possible rotor bar shape for this application remains to be seen.

Optimizing the rotor bar is a way of arriving at a bar shape that is specifically tailored to produce the necessary performance, matching that of the permanent magnet motor. The process of device optimization requires the satisfaction of a set of specifications or constraints and the minimization of a goal or objective.

A conventional design procedure involves a trial-and-error approach where the design is iteratively analyzed. Through the use of experimental reference data from available motors, and skill and experience of the designer, requirements are satisfied and the goal is met. However, with
improvements in the mathematical formulation of optimization problems and programming
techniques, several formal optimization methods have been devised. These have often resulted in
unusual improvements in performance which are otherwise not possible by an individual designer.
This approach is more elegant and focuses time and effort on arriving at the best possible design
solution to a given problem.

4.2 Review of optimization methods in literature

In 1959, Godwin [35] described a computer program to optimize a squirrel cage induction
motor. Optimized design, according to this program, was the lowest cost design, arrived at by
varying design parameters within permissible limits, which met all of the design criteria. The
optimization of the parts of the motor is divided into two problems: the standard parts that are the
same for a class of motors and the unique parts that change depending on the application
requirements. The program is designed to select the standard parts that meet the output
requirements and optimizing the unique parts for minimum cost. In a sense, this approach uses a
‘knowledge’ library to select a design that is best in terms of output performance and then refines
the design for minimum cost.

In 1987, Appelbaum, Khan and White [36] investigated the possibility of improving
efficiency of motors after giving special attention to the increase into cost of electric energy. Their
claim is that improving motor efficiency by optimization may result in a higher efficiency motor
but will likely lead to higher production costs. The optimization problem as formulated by them
includes the effect of production cost, the properties of electrical steel and the power factor. Using
motor characteristics such as power factor, locked rotor current, starting torque, breakdown torque,
rated slip, and temperature rise as inequality constraints and geometrical parameters and current
density of stator and rotor as design variables, their study used efficiency to define the objective
function and production costs to define the cost function. Some interesting results from this study concluded that higher motor efficiencies are associated with lower motor power factors and that a relatively large increase in production costs is needed to improve the efficiency by a relatively small amount.

In 1994, Poloujadoff, Christaki, and Bergmann used a synthesis approach [37] to determine the starting ‘feasible’ machine resulting in a reliable choice of variables leading to an unconstrained optimization problem. More emphasis is laid on the synthesis part of the problem than ‘optimization proper’. The authors conclude that this results in a better appreciation of the choice of independent parameters avoiding the need for complex transformations seen in several other optimization procedures.

Williamson and McClay [38] present the results of a design optimization study where the goal is to discover the best possible rotor bar shape for a double cage induction motor to be used in specific applications. The best shape as defined by them is one that meets the performance specifications while having the highest efficiency. A generic rotor bar shape is chosen. The dimensions (depth and width) of the end of the bar with the starting cage is fixed while the other end had 14 depths and 2 widths giving a total of 16 design variables which is deemed a satisfactory compromise between finer modelling with more design variables and coarser modelling. The cost function defined is a measure of the margin by which a particular design fails to meet performance specifications. Seven performance indices are chosen. The minimum acceptable values for locked-rotor torque, pull-up torque, breakdown torque, and power factor and maximum acceptable values of breakdown torque and locked-rotor current are set. A target value for efficiency is also set and raised in subsequent optimization runs. Each performance index is measured by an error function which are then summed up to get the cost function. The range of feasible geometries are imposed
as constraints. In addition to geometrical constraints, further constraints (such as acceptable values of aspect ratios of bar sections, nominal values of tooth width to ensure reliability of laminations) are introduced as penalty functions. The process of optimization of this problem then followed a two-step approach (using 12 variables each) as opposed to 16-variable optimization where the time taken to converge would have been excessive. In the first step, the entire rotor bar is optimized to provide good estimates for the design variables. A more detailed optimization of the top region is then performed as starting torque is an important component of performance specification. The second step is used for fine-tuning the design from the first. A 37 kW, 4 pole motor is optimized using this approach for three particular applications (general purpose, fan drive and oil rig). Each of these applications have their special requirements which are considered. Additionally, a 150 kW, 2 pole general purpose motor is also optimized using this approach. The authors claim that their approach is capable of producing revolutionary rather than evolutionary changes to rotor bar shapes.

In general, most approaches to optimization of induction motors used several variables, objectives and constraints. Besides being computationally expensive, if conflicts arose, they also required a way to establish priorities and assign penalties.

4.3 Optimization problem setup

The optimization process for this project began with parameterizing the double squirrel cage bar. Vertices on the bar were chosen such that the width of the bar can be modified by varying the co-ordinates of these points. Figure 15 shows the double cage bar with the green lines showing the possible variations in shape of the rotor bar. Each point was varied within a range that was determined to ensure no conflicts (for instance, overlap between components) arose. The first objective was to improve the starting torque of the induction motor. As mentioned in CHAPTER
I, Section 1.3 Problem Statement and Objectives, current density values were noted to ensure they did not exceed 30 A/mm$^2$. In this project, an optimal model was defined as one with a torque-speed envelope matching that of the permanent magnet motor and having an efficiency of 80% with current density not exceeding 30 A/mm$^2$.

![Parameterized double squirrel cage bar](image)

Figure 15 Parameterized double squirrel cage bar

4.4 Optimization software - OptiNet

OptiNet [39], a commercially manufactured software package based on an evolutionary strategy, was used to optimize the rotor bar. It uses a set of specifications which sets bounds on the parameters and helps define the solution space. A point in this space is chosen to be the starting point. The cost function which is to be minimized is calculated at this point. When no further minimization of the cost function is possible, the optimal solution is reached.
OptiNet offers a robust, global search-oriented, derivative free and fast means of arriving at an optimal solution. A parameterized MagNet model is helpful to analyze what-if scenarios. That model can now be used by OptiNet to systematically search for an optimal solution.

4.5 Optimization strategy

The optimization approach used in this thesis followed a slightly different method of formulating the problem by breaking down the multi-objective optimization problem into separate single objective, micro-optimization problems. The multi-objective approach would have involved maximizing the output torque at every single point of operation along the torque-speed envelope to match the torque values of the permanent magnet motor at the corresponding points of operation. When the motor optimization is formulated as multiple micro-optimization problems, each problem can be solved separately with the goal of finding the best possible design for a single objective. Thus, the latter approach avoided the use of penalty functions and took advantage of the operation of the induction motor. The two micro-optimization problems are described below.

The challenging requirement during the induction motor design process was improving the starting torque to match that of the peak torque. Thus, the first step of the optimization process began with the objective of finding a bar shape that had a high output torque at start-up only, starting with the initial double cage design (Model 1). The optimization results from this step suggested moving towards a single cage bar configuration.

Using this model, in the next step, the optimization problem was broken down into two ‘micro-optimization’ problems each with the objective of improving the torque at starting and base speed conditions respectively. At starting condition, the rotor frequency is the same as the supply frequency resulting in a low value of skin depth which limits the induced current to the front
portion of the bar. The starting torque is determined mainly by the rotor resistance and the induced current. The optimization simulations on Model 1 showed that Model 2 has higher induced flux linkage and current and hence, higher starting torque.

### 4.6 Experimental observations and comparison

Using Model 2, the first micro-optimization problem was set up for an input supply of 23.75 V and 25 Hz. The second micro-optimization problem is set up with the objective of improving the torque operating at an input voltage of 250 V at 300 Hz (Model 3). Using the results from these two models, the final bar shape of Model 4 is obtained. The complete evolution of the bar shape from double cage to the final shape is shown in Figure 16.

The initial configuration was a double cage bar and the input for starting condition (23.75 V, 25 Hz) is the same throughout for all the models. The torque at base speed in the constant torque region for the double cage model required an input voltage of 317 V at 333 Hz. For the optimized model, an input voltage of 250 V at a frequency of 300 Hz was used. The optimized rotor also provided the necessary output power at high speeds (up to 12,000 rpm). For instance, at 12,000 rpm, an output power of 59.5 kW was generated.
Figure 16 Flux distribution of the different rotor bar shapes

Table 8 presents a comparison of the starting and base speed torque achieved for the various configurations shown in Figure 16. Model 4 generates the maximum starting torque and base speed torque comparable to the permanent magnet motor. This model is the final outcome of the optimization process. At each point, the loss and the current density have been noted. The power factor and the efficiency have been computed. Comparisons of the power and torque-speed characteristics of the optimized induction motor design are shown in Figure 17 and Figure 18, respectively.
Table 8 Comparison of torque at starting and base-speed

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Start-up Torque (Nm)</th>
<th>Base Speed Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105</td>
<td>190</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>190</td>
</tr>
<tr>
<td>3</td>
<td>146</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>148</td>
<td>182</td>
</tr>
</tbody>
</table>

Figure 17 Comparison of torque-speed envelope between PM and IM
Figure 18 Comparison of power between PM and IM

Several points on the torque speed envelope were selected to validate the performance of the machine. The results of this performance analysis have been shown in Table 9.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Start-up</th>
<th>Base speed</th>
<th>Constant power region</th>
<th>Maximum speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (Vrms)</td>
<td>16.8</td>
<td>177</td>
<td>233</td>
<td>318</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>25</td>
<td>300</td>
<td>525</td>
<td>1020</td>
</tr>
<tr>
<td>Slip (%)</td>
<td>100</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Stator current (Arms)</td>
<td>238</td>
<td>264</td>
<td>185</td>
<td>153</td>
</tr>
<tr>
<td>Stator current density (A/mm²)</td>
<td>8</td>
<td>8.8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Average rotor current density (A/mm²)</td>
<td>27</td>
<td>30</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.76</td>
<td>0.57</td>
<td>0.57</td>
<td>0.48</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>148</td>
<td>182</td>
<td>99.8</td>
<td>48</td>
</tr>
<tr>
<td>Output power (W)</td>
<td>0</td>
<td>63111</td>
<td>63196</td>
<td>59543</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>--</td>
<td>79</td>
<td>85.4</td>
<td>83.2</td>
</tr>
<tr>
<td>Eddy current loss (W)</td>
<td>0.704</td>
<td>129</td>
<td>197</td>
<td>285</td>
</tr>
<tr>
<td>Hysteresis loss (W)</td>
<td>11</td>
<td>268</td>
<td>293</td>
<td>254</td>
</tr>
</tbody>
</table>

Table 9 Operating characteristics of the optimized motor
At each of these operating points, the current density in each of the 79 rotor bars was verified to be below 30 A/mm². The electrical and geometrical parameters of the rotor of the final optimised design are shown in Table 10.

<table>
<thead>
<tr>
<th>Rotor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap length (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of rotor bars</td>
<td>79</td>
</tr>
<tr>
<td>Shape of rotor bars</td>
<td>Closed slot single cage</td>
</tr>
<tr>
<td>Material of rotor bars</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Material of rotor core</td>
<td>M 19 G 29 steel</td>
</tr>
<tr>
<td>Outer rotor diameter (mm)</td>
<td>184</td>
</tr>
<tr>
<td>Inner diameter of the rotor (mm)</td>
<td>153</td>
</tr>
</tbody>
</table>

*Table 10 Optimized rotor specs*

4.7 Conclusion

The optimization process used here was formulated to consider the most challenging objective namely torque requirements at various speeds (mainly start-up and base speed). This resulted in a rotor bar shape that is quite different from the conventional bar shapes seen today. It is important to note here that while this shape of the rotor bar may produce the highest starting torque for this application, its power factor performance declines at higher speeds ultimately impacting efficiency. With increased consumption of apparent power, the size of the electronics increases creating the need for using suitable power factor correction devices.
CHAPTER V
CONCLUSION

The goal of this project was to design an induction motor with a performance equivalent to an industrially manufactured permanent magnet motor. Equivalence in performance is established primarily by comparing the torque-speed envelope within limits of current density and efficiency. Chapter III laid the foundation for the design methodology followed in creating the permanent magnet motor equivalent. Various design decisions such as length of the air gap, number, shape and material of the rotor bars as well choice of electrical parameters such as excitation voltage and frequency were explained.

Chapter IV explored the rotor bar shape further through a unique formulation of the optimization problem. What would have been a traditional multi-objective optimization problem was broken down into two single objective micro-optimization problems at two different operating points: starting and base speed. In this final chapter, an approximate material cost analysis is presented. A comment on the green-ness of electric cars is made and plans for future work are laid out.

5.1 Material cost analysis

An important motivation to search for an alternative to the permanent magnet motor was the prohibitive cost of magnets that continues to fluctuate [40]. Table 11 shows an approximate comparison of material costs between the permanent magnet and induction motor. These costs, however, do not take into account the machining and production costs.
<table>
<thead>
<tr>
<th>Component</th>
<th>PM</th>
<th>Induction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor iron</td>
<td>Weight</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>Cost\textsuperscript{a}</td>
<td>1.17</td>
</tr>
<tr>
<td>Magnet (NdFeB)</td>
<td>Weight</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>Cost\textsuperscript{c}</td>
<td>98\textsuperscript{c}</td>
</tr>
<tr>
<td>Rotor bars (Aluminum)</td>
<td>Weight</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>0.408</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Cost is in USD/kg, \textsuperscript{b} London Metal Exchange, \textsuperscript{c} HEFA Rare Earths, Inner Mongolia

Table 11 Approximate material cost comparison of the permanent magnet and induction motor

From the above table, we can see that induction motor material costs are significantly lower than the permanent magnet motor material costs. However, it remains to be seen if the savings in cost from the materials is lost during the machining, production or other processes involved in manufacturing the motor.

5.2 Green-ness of electric cars

Electric cars are by no means a new technology. Pressing environmental concerns have led to their rebirth. Advancements in motor technology, batteries, control systems, charging infrastructure and widespread consumer acceptance have made electric cars more mainstream. While they have earned an image of being clean and green in the eyes of the end consumer, the measure of their green-ness remains to be seen. The debate over how clean they are can be traced back to an article in the IEEE Spectrum in June, 2013 titled Unclean at any Speed\textsuperscript{[41]}. The author suggests that using an electric car while the power grid is still fueled by dirty sources of energy such as coal would be just as environmentally taxing as a conventional car. This scenario is rapidly changing. In 2014, the Union of Concerned Scientists\textsuperscript{[42]} published data showing that a combination of improvements and upgrades in electric vehicles and more recent power electricity
emissions data for the United States has resulted in lower overall emissions while driving an electric vehicle. Overhauling the power infrastructure is not a fast, easy or cheap process but the trend seems to be going in the right direction.

Even if the power stations produced greener power, the carbon dioxide emissions would still exist given that manufacturing of cars in itself involves energy intensive processes. A possible solution to this problem would be a life cycle analysis of an electric vehicle that takes into account a holistic approach and looks at materials, manufacturing processes, power sources along with tail pipe emissions. This is popularly known as the well-to-wheel analysis [43]. Using such tools, it is possible to continuously validate and improve the emissions prediction of electric vehicles.

5.3 Future work

There is potential for future work in improving the current design of the induction motor. A 3D analyses will provide further confidence in the behavior of the motor. Thermal analyses would also provide us with further knowledge of the heating of the motor at various operating points. Furthermore, the motor model can be analyzed along with the drive so as to ensure that the predicted behavior of the motor is as close to real life as possible. Finally, structural analyses can help predict noise and vibration of the motor.
REFERENCES


