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Brushless Doubly-Fed Machines have potential benefits in variable speed generation and adjustable speed drive applications by combining a robust machine structure with a reduced power converter rating. While recent work has demonstrated feasibility, steady-state performance has not been optimized. The nature of doubly-fed operation causes rotor currents of varying, relatively high frequency. Moreover, the rotor structure deviates from conventional squirrel cages. Consequently, induction machine rotor bar geometries need to be carefully examined and refined for applicability in the doubly-fed system.

The present thesis uses finite element analysis to investigate alternative rotor bar design. Two-dimensional finite element analysis is used to investigate basic rotor bar characteristics. Interface with a detailed simulation program enables investigation of assembled rotors, otherwise a three-dimensional analysis problem.

Rotor bar geometries for a high speed alternator are investigated. Bar shapes are
kept simple to allow manufacturing of the rotor in the absence of die-casting equipment. Rotor prototypes are constructed using custom, laser-cut laminations and experimental results for the alternator verify improved line-to-shaft efficiencies over conventional rotor geometries as well as off-the-shelf alternators.
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for the Brushless Doubly-Fed Machine

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1.1 Background

With the advent of solid state power electronics, the cascaded machine, first developed in 1907 by Hunt [1], is gaining popularity as a potential adjustable speed drive (ASD) and variable speed generator (VSG). The development of the self-cascaded or brushless doubly-fed machine (BDFM) at Oregon State University is documented in references [2-5].

Theoretical analyses, as well as evaluation of BDFM prototypes, indicate high rotor losses [6]. The high rotor losses are attributed to skin effect due to the high frequency rotor currents during steady state operation and also to core loss. Unlike a conventional induction machine, the BDFM exhibits relatively high frequency rotor currents at all steady state operating points. This effect has to be considered in the design of BDFM rotor bars in order to reduce the rotor losses.

It is the objective of this thesis to optimize the rotor electrical performance through finite element based design improvements.

1.2 Literature Review

Ever since Winslow first applied finite element analysis (FEA) to electrical engineering problems [7], its application has grown rapidly. A decade ago FEA was
executable only on mainframes or minicomputers [8]. Today there are a few software packages on the market for PCs that can evaluate both linear and non-linear magnetic circuits. Some of the quantities that can be extracted from a finite element solution include: flux distribution, flux density, eddy currents, hysteresis losses, force and torque on electrical conductors [8]. In this review, some of the FEA applications pertaining to induction machine design are presented, from which techniques for BDFM analyses can be derived.

Recent trends in machine design reflect a drive toward high efficiency machines and high output power ASDs using squirrel cage motors [9]. Both of these trends affect the fundamental design of the squirrel cage rotor. To increase the machine efficiency, the rotor losses must be reduced by optimizing the rotor bars for the application under consideration. For some applications, like ASD, the rotor bars must be designed to also minimize harmonic losses. In addition to optimizing the rotor electrically, its mechanical integrity should also be considered. For example, the effect of the ventilation system, thermally induced forces, centrifugal, and transient forces must be addressed [9].

A design method for rotor bars using finite element analysis is presented in the literature [10,11]. This approach evaluates bar resistance and inductance using a one slot rotor geometry with appropriate boundary conditions. It is applicable to closed, semi-closed, and open slots.

Once a finite element solution is obtained, the bar resistance is evaluated using the Joule losses per unit length [10]. For closed slots, bar inductance is evaluated by
summing up slot, bridge, and airgap leakages and differential inductances [10]. For open or semi-open slots bar inductance is evaluated as the difference between the total and magnetizing inductances [11]. This design method has the potential to become a fast and easy tool for rotor bar design. However, because of the required special boundary conditions (BC), this method cannot become an office desk tool without the appropriate user interface, which often requires access to the FE code.

Other FEA applications include methods of steady state and transient performance analysis of cage induction motors [12]. The method of evaluating the equivalent circuit parameters in [12] is similar to the techniques used in [10,11] to evaluate rotor bar resistance and inductance. Belmans proposes a different technique for evaluating equivalent circuit parameters in [13]. He evaluates the parameters from the complex power associated with one pole pitch:

\[ S = P + jQ = \sum (A*J) \]  

(1.1)

where,

- \( S \) = total complex power
- \( P \) = real power
- \( Q \) = reactive power
- \( A \) = vector potential
- \( J \) = current density.

A method of interfacing finite element analysis with the induction machine equivalent circuit is presented in [14]. FEA can also be an effective tool for model
check. In [15], an equivalent model to analyze the effect of high frequency harmonic currents on the rotor was developed and compared with FEA predictions.

This thesis and a recent paper [17] use commercial FEA software [16] to study rotor bar shapes for high frequency brushless doubly-fed alternators. Since it is not possible to modify the code, the techniques proposed in [10,11] for evaluating bar resistance and inductance cannot be used. A modified "Belmans" method for a linear magnetic circuit was subsequently developed.

In light of the FEA potential, a design study for the BDFM rotor bars is proposed. The BDFM suffers from high rotor losses partly because of the high rotor current frequency. Unlike a conventional induction machine, which has low rotor current frequency in steady state operation, the grid connected BDFM rotor exhibits frequencies between 15 and 60Hz in steady-state operation. In [17], we compare the effect of deep, semi-open round, and fully open rectangular bars on the overall performance of a high speed BDFM alternator system. In addition to the FEA approach of designing rotor bars for the BDFM, an equivalent circuit method [18] and a Grapho-Visual method [19-21] are examined.

1.3 BDFM Characteristics

The BDFM as shown in Figure 1.1 consists of two sets of stator windings and a unique, cage type rotor with nested loops. The stator windings consist of a power winding which supplies most of the machine power, and a control winding which supplies a fraction of the machine power through a power conditioning unit.
The prototype BDFM systems used for this thesis have two-pole control windings and six-pole power windings. Unlike the squirrel cage rotor which has rings to short rotor bars on both ends, the BDFM rotor has a ring to short all the rotor bars only on one end while at the other end the bars are selectively shorted together to form distinct loops. The number of loop groupings or rotor nests is determined by the sum of the pole-pairs of the power and control windings:

$$\text{Number of Nests} = P_p + P_c$$  \hspace{1cm} (1.2)

where,

\begin{align*}
P_p & = \text{pole-pairs of power winding} \\
P_c & = \text{pole-pairs of control winding.}
\end{align*}
In response to the two stator winding fields of different frequency and possibly different sequence, two rotor fields are induced in the rotor. If these rotor fields are locked together, a synchronism condition is achieved, which relates mechanical rotor speed, $f_{r,m}$ with stator frequencies and pole pair numbers:

$$f_{r,m} = \frac{f_p \pm f_c}{P_p + P_c}$$  \hspace{1cm} (1.3)$$

where the indices $p$ and $c$ refer to power and control winding, respectively. The "$+/-$" in Eqn. (1.3) refers to the control winding phase sequence which can be co-rotational (+) or contra-rotational (−) with the power winding sequence.

The electrical frequency of rotor currents in the synchronism condition can be related to the remaining system frequencies as [17]:

$$f_{r,el} = f_p - P_p f_{r,m} = \mp f_c + P_c f_{r,m}$$  \hspace{1cm} (1.4)$$

From this, the following relative slips can be derived:

power winding to rotor slip

$$s_p = \frac{f_p - P_p f_{r,m}}{f_p}$$  \hspace{1cm} (1.5)$$

control winding to rotor slip

$$s_c = \frac{\mp f_c}{\mp f_c + P_c f_{r,m}}$$  \hspace{1cm} (1.6)$$

and
power winding to control winding slip

\[ s_{pc} = s_p s_c \]  

Equations (1.3-1.7) can be used to establish possible rotor frequency variations for which rotor bar shapes need to be optimized.

For example, using the six/two-pole system in a 60 Hz adjustable speed drive with 0-900 r/min speed range leads to rotor frequencies between 15 and 60 Hz, respectively. Thus, rotor design needs to be optimized for a much higher steady state frequency range than conventional induction machines, both in terms of \( I^2R \) loss as well as core loss. This is even more true for the high speed alternator described in chapter 3, for which the experimental prototypes were designed. It exhibits rotor current frequencies of between 20 and 100Hz in steady state operation.

Results of two BDFM applications will be considered throughout the thesis - the grid connected BDFM system and the BDFM alternator system. The grid connected machine has its power winding connected to the utility grid (fixed voltage and frequency) while its control winding is connected to a power converter. The alternator machine has its power winding connected to a bridge rectifier which feeds a battery, while its control winding is connected to a power converter.

1.4 Finite Element Application

Finite element analysis is a numerical method that is widely used to solve many engineering problems, especially since the advent of cheap computing power. As
computers become more powerful and inexpensive, finite element techniques will be
utilized for machine design as PSPICE is widely utilized for circuit design. In light of
the popularity of FE techniques and the availability of FEA software packages, it is
important for the user to understand the essentials of the method in order to critically
evaluate FE solutions.

There are two basic approaches to generate finite element models, namely, the
Ritz method which uses the functional associated with the differential equations and the
Galerkin method which uses the weak form of the differential equations directly [22].
Upon selecting either the Ritz or the Galerkin method, the following seven-step [22]
procedure will complete the finite element method.

(1) Discretization. As the name finite element implies, the solution space has to be
subdivided into smaller subspaces. For example, a two-dimensional problem
region can be subdivided into small triangles.

(2) Interpolation. The solution at the nodes (points where the elements meet) has to be
interpolated over the space between the ends of an element to obtain a solution
everywhere in the element. Depending on the order and complexity of the
problem, linear, quadratic or higher order polynomial interpolations can be
utilized.

(3) Elemental formulation. Each element has to be expressed in terms of the functional,
for the Ritz method, or in terms of the weak formulation, for the Galerkin
method.

(4) Assembly. Upon defining each element, all the elements in the problem space are
related to form some kind of stiffness matrix.

(5) Constraints. The boundary conditions are incorporated into the problem formulation.

(6) Solution. At this stage the equations are solved for the unknown parameter.

(7) Computation of derived variables. Once the unknown parameter in the differential equation is solved, other variables can be extracted from the solution via post-processor. For example, if the vector potential (A) was solved for initially, the flux density can easily be extracted from the vector potential.

Because of the time involved in developing finite element code, a commercial finite element software package [16] was used for the work presented in this thesis.
2.1 Introduction

The squirrel cage design provides for one of the most robust electric machine rotors. The simple construction of parallel bars shorted on both ends with rings makes the rotor cheap, reliable, and robust. Over the years, the basic structure has not changed much, however, the bar shapes have been optimized quite well for various induction machine applications.

![Figure 2.1 Induction Machine Torque-Speed Curves [23].](image-url)

The torque-speed curves for several classes of induction motors are shown in Figure 2.1 [23]. Each class has a distinct torque-speed characteristics because of its
rotor bar shapes. For example, the class D motor has a double cage rotor bar. The double cage bar is designed to have high resistance at high slip by reducing the effective area of the bar to the small area of the top portion of the bar and low resistance at low slip by increasing the effective area of the rotor bar to include the bottom section of the bar.

Induction machine rotor optimization involves understanding of its mechanical, thermal, and electrical characteristics. However, the work presented in this thesis examines only the electrical characteristics of the rotor and, in particular, the effect of different rotor bar shapes on rotor performance. In order to study the effect of different bar shapes on the rotor performance, design criteria need to be established.

2.2 Rotor Design Criteria

It is essential to have a clear idea of the desired machine performance such as its efficiency, torque-speed characteristics, current and voltage requirements, and the application for which it's being designed for.

Assuming that the stator structure and windings are appropriately designed for the required power, current and voltage levels, the desired rotor resistance and inductance characteristics as a function of slip frequency need to be evaluated and matched with appropriate rotor bar geometry. This task requires a difficult balance of conflicting machine characteristics. For example, to achieve a high motor starting torque, the rotor resistance must be high; on the other hand, high rotor resistance increases the $I^2R$ losses in steady state operation.
To meet the desired rotor design criteria, three procedures will be employed, namely, equivalent circuit, 'Grapho-Visual', and finite element method. The equivalent circuit method will provide the required rotor resistance and inductance for a given torque-speed characteristics. Application of the 'Grapho-Visual' method will provide a method of translating the resistance and inductance obtained into rotor bar shapes. Finally, the finite element method will be utilized to verify and optimize the torque-speed performance of the resulting motor with the new bar design. Also finite element analysis will be used to examine core saturation, bar current density distribution, and other salient bar features.

2.2.1 Equivalent Circuit Method

The equivalent circuit method (ECM) is a well established method for analyzing the steady state performance of induction machines. A typical per phase equivalent circuit [24] is shown in Figure 2.2.

![Figure 2.2 Induction Machine Steady-State Equivalent Circuit [24].](image-url)
From the equivalent circuit, the following equations are derived [26]:

\[ \dot{V}_{la} = \hat{V}_1 \frac{jX_\phi}{R_1 + j(X_1 + X_\phi)} \]  
(2.1)

\[ R_{e1} + jX_{e1} = (R_1 + jX_1) \parallel jX_\phi \]  
(2.2)

\[ T = \frac{1}{\omega_s} \frac{q_1 V_{la}^2 (R_2/s)}{(R_{e1} + R_2/s)^2 + (X_{e1} + X_2)^2} \]  
(2.3)

\[ T_{\text{max}} = \frac{1}{\omega_s} \frac{0.5q_1 V_{la}^2}{R_{e1} + \sqrt{R_{e1}^2 + (X_{e1} + X_2)^2}} \]  
(2.4)

\[ S_{\text{maxT}} = \frac{R_2}{\sqrt{R_{e1}^2 + (X_{e1} + X_2)^2}} \]  
(2.5)

Where

\[ \omega_s = \frac{4\pi f}{\text{poles}} \]  
(2.6)

The torque-speed curve shown in Figure 2.3 [24] is obtained from Eqn. (2.3) assuming constant machine parameters. The resulting curves when the rotor resistance is varied is shown in Figure 2.4 [24]. Notice that the maximum torque is independent of the rotor resistance \( R_2 \) as Eqn.(2.4) indicates while the corresponding slip \( S_{\text{max}} \) is proportional to \( R_2 \).
Figure 2.3 Induction Machine Torque-Speed Curve [24].

Figure 2.4 Torque-Speed Curves for Various Rotor Resistance Values [24].
The equivalent circuit and its associated torque-speed equations provide a good method of evaluating the effect of rotor resistance on the machine torque-speed characteristics. The limitation of the EC method is that it addresses neither the effect of rotor bar shapes on bar resistance and inductance, nor the associated skin effect and current distribution. While approximate solutions can be obtained using EC method, the following two methods will provide an insight into overcoming these limitations.

2.2.2 Grapho-Visual Method

This is a method that optimizes machine performance and provides a desired torque-speed curve for squirrel cage induction machines by shaping the rotor bars. It is based on the analytical methods of calculating slot leakage and skin effect. As references [19-21] show, the resulting equations from this analysis are complex and nonlinear.

The method simplifies these equations and establishes a visually oriented method of linking bar segments with their effect on torque-speed characteristics. Parts of the bar which change bar resistance and inductance are cut away to improve torque [21].

A segmented bar with depth of penetration curves and torque-speed curves are shown in Figure 2.5 [19-21]. The depth of penetration curves show the effective depth of the bar with respect to slip for bar resistance \( (H_{pr}) \) and reactance \( (H_{pr}) \); the torque-speed curves show the bar characteristics before and after bar segmentation. Each bar segment has a special effect on the motor performance. The top narrow segment determines the resistance of the bar at startup; the segment below it, between the \( H_{pr} \) and
$H_p$ curves, determines the motor start-up current which can be limited by increasing the area of the segment. The following segment (e-h) determines how much the torque should increase to meet load requirement by how much of it is cut out. As the figure shows, by cutting out the dotted section of segment (e-h), the new torque-speed curve (curve 37) improved enough to satisfy the required load torque (curve 35). The last segment is most effective during steady-state operation where small bar resistance is desired in order to reduce operating speed bar $I^2R$ loss. By increasing the area of this region, the overall bar resistance at low slips can be reduced considerably. Of course, issues like saturation have to be considered to determine the optimum area of this segment.

This method can be quite effective if properly interfaced with the equivalent circuit method and the following finite element method.

### 2.2.3 Finite Element Method

As introduced in Chapter 1, finite element analysis is an excellent tool for verifying the performance of various bar geometries and providing information on current distribution, flux distribution, and saturation, among others.

By implementing FE design procedure presented by Belmans [13], the predicted torque-speed characteristics of different induction motor rotor bar geometries will be examined in Chapter 4. Finite element application to machine design will be covered in detail in the next two chapters, with an emphasis on the BDFM.
Figure 2.5 Rotor Bar Segmentation Principle [19].
CHAPTER 3

FINITE ELEMENT DESIGN PROCEDURE FOR THE BDFM

3.1 Introduction

In steady state operation, squirrel-cage induction machine rotor current frequency is generally less than 10% of the supply frequency fed from the power grid. However, many applications require adjustable frequency sources, hence, power converters, which introduce harmonics, are utilized. Depending on the converter topology [25] utilized, the harmonics introduced into the stator winding of an induction machine can be very high.

The BDFM also exhibits high frequency rotor currents. As explained in detail in Chapter 1, the BDFM rotor current frequency is in the rage of 15-60Hz for the grid connected motor and 20-100Hz for the alternator. Compared with the IM steady-state slip frequency of 3-5Hz, these frequencies can indeed be considered as a "high frequency."

This chapter will examine the BDFM prototype machines used for testing the various prototype rotors, the finite element techniques implemented to design the rotors, and the general characteristics of the BDFM using the FE techniques.

3.2 High Speed Alternator System

The prototypes discussed in chapter 4 are designed for a high speed alternator system intended for automotive applications. As illustrated in Fig. 3.1, the six-pole
power winding is connected to a bridge diode rectifier, while the control winding is fed through a PWM inverter from the battery dc bus. The rating of the inverter needs to be kept low to allow for competitive system cost and to enable integration in a smart power package. Through appropriate design (as discussed in chapter 4) and control [5], the alternator system attempts to improve upon the efficiencies and power ratings achievable with conventional claw-pole or Lundell alternators. A new BDF alternator with twelve-pole power winding, four-pole control winding, and eight-nest rotor will be examined in Chapter 5.

![Figure 3.1 Brushless Doubly-Fed Alternator.](image)

The characteristics of the doubly-fed system require careful design of the machine for optimum performance. The diode rectifier forces near unity displacement power factor on the power winding, requiring magnetization through the control
winding. Minimizing converter rating thus calls for reduced magnetizing requirements. Selecting power and control windings fields to be co-rotational allows for generation through the antiparallel inverter diodes. This feature is used to select an optimum excitation frequency which minimizes overall I^2R loss and core loss while keeping the inverter current low [5]. For a properly designed stator system, the optimum condition uses the inverter exclusively for magnetization at the rated loading condition.

Since the power winding output is rectified, frequency variations are acceptable. Thus, in accordance with Eqn.(1.2), rotor electrical frequency can be reduced by increasing control winding frequency. Since reactive drop is proportional to frequency, this slip-lowering measure is limited by the available dc link voltage. Proper implementation of these control philosophies requires judicious selection of rotor parameters. Following a brief review of finite element analysis and its applicability to the problem at hand, rotor designs for the alternator are discussed in the next chapter.

3.3 Finite Element Assisted Basic BDFM Design

Finite Element (FE) analysis techniques have been successfully used for some time in the design of induction, reluctance and permanent magnet machines. Neglecting end effects, these machines can easily be investigated using two-dimensional FE analysis. Application of these techniques to the BDFM is difficult due to the following considerations:

(1) By nature of the nested loop rotor structure, i.e. the absence of a solid end ring on one side, the BDFM analysis problem is three-dimensional in nature.
(2) The doubly-fed characteristics always require the consideration of two frequencies at any time. For true representation, the frequency relations expressed in Eqns. (1.1-1.5) need to be enforced.

Despite these restrictions, a commercially available two-dimensional FE package [16] has been successfully utilized in estimating BDFM performance characteristics.

The machine design procedure follows these steps:

(1) Analyze individual bar geometry in terms of resistance and inductance. Bar resistance can readily be evaluated using Joule losses per unit length, while bar inductance can be determined by established FE procedures for open [10] and closed slots [11]. While FE analysis is used in this thesis, analytical techniques are also applicable [8].

(2) Separately investigate six-pole and two-pole induction machine characteristics assuming a squirrel cage connection of the bars analyzed in step (1). As discussed in [13], torque-frequency characteristics are best obtained using rotor loss, i.e.

\[ T_e = \frac{P_{\text{rotor}}}{SO} \]  

(3) Analyze the loop characteristics of the BDFM rotor by setting appropriate symmetrical boundary conditions enabling loop currents which are equal in magnitude but opposite in direction in the loop bars. This allows for
determination of current distribution and torque contributions associated with the individual loops. This design step is required to investigate mutual interactions between bars and address the variations in stator/rotor coupling factors for the different values of rotor loop spans.

(4) Interface the two-dimensional FE analysis with a state variable machine model [26] which appropriately represents the rotor bar connections. This necessarily involves the whole machine rather than a section or pole pitch as in induction machine analysis [14].

Figures 3.2 and 3.3 illustrate the result of step (4) with a flux plot and airgap flux magnitude at three different rotor positions.

![Figure 3.2 BDFM Flux Plot.](image)

Stator excitation in Figs. 3.2 and 3.3 is at 60 Hz for the six-pole and 3 Hz for the two-pole, leading to a rotor frequency of 17.25 Hz.
Figure 3.3 BDFM Airgap Flux Density Magnitude.
(a) $\theta_r = 146^\circ$; (b) $\theta_r = 164^\circ$; (c) $\theta_r = 179^\circ$. 
The four-pole structure of airgap flux is evident as is the pulsating nature of the poles due to 90° phase displacements of currents in adjacent nests. This verifies the analytical results in [27]. Note that the slot ripple due to the open slots is exaggerated by the discrete nodes of the FE method and by the fully-open slots. This will be more attenuated in the actual machine. Of course, true representation requires a 3-D approach, but the 2-D approximation has been successfully used in designing prototypes.

The following chapter addresses the application of this design procedure to the high speed alternator.

### 3.3.1 BDFM Analysis Using Induction Machine Characteristics

As stated in the previous section, the doubly-fed nature of the BDFM which requires two sources with different frequencies, poses a difficulty in modeling it with the 2D finite element software. This led to a simplifying assumption which will be examined in the next chapter. It is assumed that the rotor bars can be optimized by reducing the BDFM to an induction machine with pole numbers equal to the power winding pole numbers (6) and examining the 6-pole induction machine torque-speed characteristics for various rotor bar geometries since most of the BDFM power is processed by the power winding.

The following steps are taken to model an induction machine with finite element software:

1. The full machine geometry is created and meshed with the Meshmaker module [16].

An example of this is shown Fig. 3.4.
2. The meshed geometry is loaded into the Eddy module [16] and setup to be solved at a single source current frequency. Each object is given an attribute as shown in Table 3.1. Permeability of 6000 is used for the stator and rotor iron, and the rotor bars are assigned the conductivity of 2.53E+7 for aluminum. For stator windings, 100 Amp-turns peak per phase is also assumed.

The peak value and phase shift must be specified for each current source. Table 3.2 shows how the stator source currents for the 6-pole machine are specified. Since the model is a current forced one, the total ampere-turns are forced in each stator slot.
3. The default (Neuman) boundary condition is accepted for all the inside boundaries, and on the outer surface, the vector potential (A) is set to zero.

To speed up the solution process, the above 6-pole induction motor setup can be modeled by a single pole (one sixth) geometry due to symmetry.

**Table 3.1 Eddy Problem Setup Parameters.**

<table>
<thead>
<tr>
<th>Objects</th>
<th>Attributes</th>
<th>Current Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>Permeability = 6000</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conductivity = 0.0</td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stator Conductors</td>
<td>Permeability = 1.0</td>
<td>Yes. See Table 3.2.</td>
</tr>
<tr>
<td></td>
<td>Conductivity = 2.53E+7</td>
<td></td>
</tr>
<tr>
<td>Rotor Conductors</td>
<td>Permeability = 1.0</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conductivity = 2.53E+7</td>
<td></td>
</tr>
<tr>
<td>Airgap</td>
<td>Permeability = 1.0</td>
<td>No</td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Shaft</td>
<td>Permeability = 1.0</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conductivity = 0.0</td>
<td></td>
</tr>
</tbody>
</table>

4. Once the problem is setup as stated above, it is solved for various slip frequencies of the current sources. Then the torque for each slip frequency is calculated from the rotor losses.
Table 3.2 Six-Pole Stator Winding Layout.

|   | a  | c' | c' | b  | b  | a' | a' | c  | c  | b' | b' | a  | a  | c' | c' | b  | b  | a' |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| X | .  | X  | X  | .  | .  | X  | X  | .  | .  | X  | X  | .  | .  | X  | X  | .  | .  |
| a' | c | c | b' | b' | a | a | c' | c' | b | b | a' | a' | c | c | b | b | a' |
| 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| . | X | X | . | . | X | X | . | . | X | X | . | . | X | X | . | . | X |

where,

- $\text{MMF}_a = 100\cos(\omega t)$
- $\text{MMF}_{a'} = 100\cos(\omega t - 180^\circ)$
- $\text{MMF}_b = 100\cos(\omega t - 120^\circ)$
- $\text{MMF}_{b'} = 100\cos(\omega t + 60^\circ)$
- $\text{MMF}_c = 100\cos(\omega t - 240^\circ)$
- $\text{MMF}_{c'} = 100\cos(\omega t - 60^\circ)$
3.3.2 Finite Element Based Modeling of Doubly-Fed Characteristics

Another method of modeling the BDFM is proposed in this section. The method presented in the previous section attempted to model the BDFM as an induction motor with pole numbers equal to the pole numbers of the power winding of the BDFM. As will be shown in the next chapter, this method has limitations and could even mislead. The new method attempts to obtain the torque-speed characteristics of the BDFM due to only the cage bars of the BDFM rotor. Since the rotor nested loops cannot be modeled with the 2D finite element software, it is hoped that sufficient information regarding the behavior of the BDFM can be learned from the BDFM rotor with cage bars only.

The analysis procedure for the new method is similar to the one outlined in section 3.3.1 for the analysis of the six-pole induction motor. The torque-speed characteristics are obtained by superimposing the instantaneous torques due to the power winding and the control winding which are excited with current sources of the same frequency. The frequency of excitation is that of the electric rotor current frequency found in the BDFM rotor during the synchronous operation. Two separate cases are solved for each rotor current frequency: 1) exciting the control winding alone at the rotor current frequency, 2) exciting the power winding alone at the rotor current frequency. Then the respective vector potential solutions are added to obtain the combined flux plots. Similarly, the respective current densities are added vectorially and used to calculate the BDFM electric torque. This technique will be examined in Chapter 5.
3.3.3 3-D Simulation of the BDFM

Because of the nested structure of the rotor, the BDFM finite element problem is a three-dimensional one. The 3-D finite element software that is to be used for the BDFM has same limitations as the 2-D software in terms of being able to set up two sources of different frequencies. However, the method described in Section 3.3.2 is well suited for the 3-D finite element analysis of the BDFM. Figs. 3.5 and 3.6 show CAD generated BDFM stator and rotor geometries, respectively.

Figure 3.5 3-D BDFM Stator Geometry.
Figure 3.6 3-D BDFM Rotor Geometry.
CHAPTER 4

BDFM ALTERNATOR ROTOR OPTIMIZATION - PHASE I

4.1 Introduction

In this chapter, the Brushless Doubly-Fed Alternator (BDFA) rotor is designed using the finite element design procedures outlined in chapter 3.

4.2 Alternator Rotor Design

The alternator was built in an existing four-pole induction motor frame. Stator laminations are designed for high voltage, 60 Hz operation. Core loss will increase for the high frequency (200-400 Hz) alternator; this effect is compounded by heat damage during the rewind process. Nevertheless, the stator can serve as benchmark for the subsequent rotor designs. Details on the low voltage six-pole and two-pole stator winding designs are listed in the appendix.

The original 48 slot rotor of the induction machine was remanufactured to a four-nest BDFM configuration. The rotor slots are closed and of a deep bar geometry representative of a Nema class B design. Number one copper round bars were placed in the top portion of the deep bar rotor slots. Bar shapes and flux for a six-pole equivalent induction machine [cf. design step (2)] in section 3.3 are illustrated in Fig. 4.1. The Figure shows the flux distribution at 5, 30, and 60Hz slip frequencies ($f_s$). As illustrated in Fig. 4.1c, the leakage flux increases with frequency.

The skin depth effect can be seen from the current density distribution in the 4th bar from the right as shown in Fig. 4.1 at 5, 30, and 60Hz slip frequencies as shown
Figure 4.1 Six-Pole Current-Forced IM Flux Plot (round bar, deep slot)
(a) $f_s = 5\text{Hz}$, (b) $f_s = 30\text{Hz}$, (c) $f_s = 60\text{Hz}$.
in Fig. 4.2. The current density in a bar is expected to increase with increase in slip frequency. However, as Fig. 4.2 shows, the current density at 60Hz is lower than the current density at 30Hz slip frequency. This is due to the instantaneous movement of the airgap field as shown in Fig. 4.1 with respect to the chosen bar.

![Figure 4.2 Six-Pole Current-Forced IM Middle Rotor Bar Current Density Distribution (round bar, deep slot).](image)

The magnitude of the airgap flux density which verifies the six-pole nature of the IM is shown in Fig. 4.3. The six-pole induction motor torque-speed curve shown in Fig. 4.4 illustrates that at high frequency operation, the alternator torque per amp characteristics will be satisfactory. Reaching the high torque, low slip range would require excessive two-pole frequencies not attainable with the inverter voltage available.

Similarly, an induction motor with rotor bars that fill the deep bar slots is examined. The flux plots, current density, airgap flux density, and torque-speed curve
Figure 4.3 Six-Pole Current-Forced IM Airgap Flux Density (round bar, deep slot).

Figure 4.4 Six-Pole Current-Forced IM Torque-Speed Curve (round bar, deep slot).
are shown in Figs. 4.5a-c, 4.6, 4.7, and 4.8 respectively. The torque-speed curve for the

Figure 4.5 Six-Pole Current-Forced IM Flux Plot (deep bar, deep slot)  
(a) $f_s = 5\text{Hz}$, (b) $f_s = 30\text{Hz}$, (c) $f_s = 60\text{Hz}$. 
6-pole induction motor with the deep bar slot rotor as shown in Figs 4.8 illustrates that at high frequency operation, the alternator torque per amp characteristic will not be satisfactory. Reaching the high torque, low slip range would require excessive two-pole frequencies not attainable with the inverter voltage available. The induction machine laminations available used relatively thick 24 gauge material with the attendant core loss at the high operating frequencies.

These considerations led to the development of a custom prototype rotor. The initial design attempted the use of a simple round bar in a semi-open slot similar to a Nema class D geometry. In order to provide for better bar utilization in the nested loop structure [28], the number of bars was reduced to 32 while increasing the bar cross-

![Graph](image)

**Figure 4.6** Six-Pole Current-Forced IM Middle Rotor Bar Current Density Distribution (deep bar, deep slot).
Figure 4.7 Six-Pole Current-Forced IM Airgap Flux Density (deep bar, deep slot).

Figure 4.8 Six-Pole Current-Forced IM Torque-Speed Curve (deep bar, deep slot).
sectional area. Figs. 4.9-4.12 again show flux distribution, current density distribution.

Figure 4.9 Six-Pole Current-Forced IM Flux Plot (round bar, semi-open slot)
(a) $f_s = 5\text{Hz}$, (b) $f_s = 30\text{Hz}$, (c) $f_s = 60\text{Hz}$. 
Figure 4.10 Six-Pole Current-Forced IM Middle Rotor Bar Current Density Distribution (round bar, semi-open slot).

Figure 4.11 Six-Pole Current-Forced IM Airgap Flux Density (round bar, semi-open slot).
airgap flux density, and an equivalent six-pole torque-speed characteristic. Comparison with Fig. 4.8 illustrates improved torque per amp performance at all but low frequencies. It should be noted that from an induction machine point of view, a deep bar or double cage structure will be even more effective at boosting torque at high frequencies. However, torque is not the only concern as converter utilization characteristics also require minimization of total reactive power. Also, bar performance in the nested loop structure needs to be optimized, which is not addressed by the characteristics of Figs. 4.8 and 4.12.

In order to evaluate the round bar design, rotor laminations were laser cut using 26 gauge M36 steel with C3 coating for better interlaminar insulation and improved core loss characteristic. The rotor was manufactured using 5 gauge copper wire; Fig. 4.13
shows a section of the lamination, and Fig. 4.14 illustrates the completed rotor along with parts used for an alternative structure.

Figure 4.13 Experimental Lamination - Round Slot.

Figure 4.14 Rotor Parts and Assembled Prototype Rotor.
Laboratory testing of both the converted induction machine rotor as well as the round bar rotor verified the projected performance improvement. Fig. 4.15 illustrates line-to-shaft efficiencies for both configurations. While the original closed slot rotor has a relatively flat efficiency-speed characteristic due to low windage loss, overall performance is unacceptably low. The manufactured rotor shows marked improvement with some degradation at high speeds due to increased windage. Fig. 4.15 also includes the efficiency characteristic of an off-the-shelf claw pole alternator. The doubly-fed system shows improved performance at high speeds; the degradation at low speeds is due to the limit imposed on the inverter rating. Appropriate stator and inverter redesign can shift the efficiency characteristic in order to improve low speed performance.

Figure 4.15 Alternator Efficiency Comparison ($I_a = 15A$)
(a) Doubly-fed, original slots;
(b) Doubly-fed, round slots;
(c) Commercial claw-pole alternator.
While the round bar rotor bettered machine performance significantly, further improvement is possible. As outlined in design step (3), the nested loop structure requires special consideration in order to assure appropriate current distribution and torque contribution by each loop. Fig. 4.16 illustrates the flux characteristic for single stator coil excitation. In order to improve upon the resulting current distribution, fully open rotor slots as illustrated in Fig. 4.17 were considered. Flux distribution is further improved by omitting one slot and leaving an iron bridge at the center of each nest.

Figure 4.16 Loop Characteristic Flux Plot.
Table I illustrates the differences in current distribution between inner and outer loops for the different rotor geometries.

### Table 4.1 Experimental Rotor Current Distributions.

<table>
<thead>
<tr>
<th>Bar Shape</th>
<th>Induced Current Ratio (outer loop/inner loop)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 Hz</td>
</tr>
<tr>
<td>semi-open, round</td>
<td>2.0</td>
</tr>
<tr>
<td>fully open, rectangular</td>
<td>2.2</td>
</tr>
</tbody>
</table>

While higher frequencies still cause a current shift to the outer loops, the effect
has been attenuated somewhat. The rectangular bar geometry also has the advantage of reducing overall machine reactive power as illustrated in Fig. 4.18. For a given alternator output current level, a decrease in the magnetizing requirement allows for a reduction of control winding and inverter rating.

![Figure 4.18 Machine Reactive Power Ratio (Fully open, rectangular slot to semi-open, round slot).](image)

Using laser cut laminations and rectangular copper bar stock, a prototype rotor was built and tested. Despite the fully open slots, mechanical integrity was excellent and the rotor was successfully operated at speeds exceeding 6000 r/min. The rectangular slots did not improve upon the round bar efficiency shown in Fig. 4.15. However, for the inverter constructed for the round bar machine, the new rotor was able to increase maximum dc output current by approximately 30%. Thus, the low inductance rotor serves to improve converter utilization.
CHAPTER 5
BDFM ALTERNATOR ROTOR OPTIMIZATION - PHASE II

5.1 Introduction

The brushless doubly-fed alternator rotor was designed in Chapter 4 using a 2-D finite element package. Various rotor bar geometries were examined and compared based on their torque-speed performance, core saturation, bar current density distribution, etc. It was found that the torque-speed curves for the 6-pole induction machine simplification of the BDFM were inadequate and a bit misleading because the desired overall torque increase over high slip range for the 6-pole induction machine does not translate into torque-speed improvement for the BDFM. This is why the original alternator rotor had the highest overall magnitude of induction motor torque but worst BDFM rotor performance.

This chapter will examine the effect that a variation in BDFM rotor resistance has on its performance utilizing the BDFM steady-state model. Also, a new way of examining the BDFM rotor performance with the 2-D finite element software as described in Section 3.3.2 will be utilized to study the performance of a 12/4-pole alternator.

5.2 Effect of Rotor Resistance

In order to design a suitable rotor for a machine, one has to understand the effect that a variation in rotor resistance and reactance has on machine performance.
As discussed in Chapter 2, understanding the effect of rotor resistance on squirrel cage induction motors is straight-forward. From its equivalent circuit, we find the torque equation which shows a clear relationship between rotor resistance and torque. A similar approach can be taken to examine the BDFM. However, the BDFM torque equation as given in Li’s thesis [29], is expressed in terms of the currents. Hence, it is necessary to examine numerically the effect of rotor resistance on the torque. Using a computer program that solves the BDFM torque from the steady-state equations for the grid-connected machine [4], the torque for various rotor resistances are obtained as shown in Fig. 5.1. The overall torque improves as the resistance decreases. This is contrary to what is expected for induction machines. Though the computer program

![Figure 5.1 Effect of Rotor Resistance on the BDFM Torque.](image)
program used the steady-state equations derived for the grid-connected BDFM, it can be surmised that this result to be applicable to the BDFM alternator.

5.3 Twelve/Four-Pole Alternator Design

The accumulation of new knowledge about the behavior of the BDFM and the need to design a marketable alternator led to the design of a compact 12-pole power winding and 4-pole control winding (and eight rotor nest) alternator. Because of the inherent improved efficiency of the alternator at higher operating voltages, it is designed for a 48 Volt system. A 12/4-pole configuration was chosen in order to operate the alternator at higher frequencies and hence reduce the frame size.

The rotor bars were chosen such that the rotor resistance is as small as possible (using largest possible bars) without compromising on the ease of manufacturability. The rotor resistance was further reduced by doubling the size of the cage bars compared to the size of the inner loops. The drawings of the laser-cut stator and rotor laminations are shown in the Appendix, along with the alternator specifications.

Applying the FE technique discussed in section 3.3.2 to the new alternator, flux plots are obtained. Figs. 5.2, 5.3 and 5.4 show the flux plots of current forced 12-pole, 4-pole, and combined 12 and 4-pole windings respectively. All three cases were current forced with 200 Ampere-turns and rotor current frequency of 22Hz.

The Eddy solutions of the 12/4-pole FE model provide information on magnitude of flux density in the core, expected structure of the electromagnetic poles, and torque-speed characteristics of the BDFM. By superimposing the 12-pole and 4-pole current
forced induction machine FE solutions, the BDFM torque due to the cage bars can be evaluated.

Preliminary laboratory tests of the 12/4-pole alternator as a 12 Volt system showed promising results. Even though it was designed for a 48 Volt system, an increase in efficiency of 5-10%, at higher loads (I_{out} = 15 - 20A), over the existing 12V alternator was observed.

![12-Pole Flux Plot - Eddy Current Solution](image)

**Figure 5.2** 12-Pole Flux Plot - Eddy Current Solution (200A total 12-pole current, 22Hz rotor frequency).
Figure 5.3 4-Pole Flux Plot - Eddy Current Solution
(200A total 4-pole current, 22Hz rotor frequency).

Figure 5.4 Doubly-Fed Flux Plot - Superposition.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

It has been shown that two-dimensional FE analysis in combination with geometrical considerations and interface with a detailed model can be a valuable tool in the analysis of nested loop rotor structures which are characteristic of brushless doubly-fed machines.

The doubly-fed characteristic requires adjustment to the design procedures used for conventional, singly-fed induction machines. In the alternator system under consideration, the design needs to maximize power winding output current at low control winding rating while maintaining good efficiency performance.

Using the design tools and criteria discussed, relatively simple and readily manufactured rotor slot geometries were investigated both numerically and experimentally. Improvement of power winding torque per amp characteristic and overall reactive power requirement led to a prototype alternator system which shows better efficiency characteristics than a conventional claw-pole high speed alternator, as illustrated in Fig. 4.6.

While the results shown are encouraging, further improvement is possible. Future considerations should address more complicated geometries to provide yet better high frequency operation. Also, work to date has been limited to equal bar shapes for every loop. Table 4.1 illustrates the uneven current distribution within the loops. A grading of bar size within the loops of one nest or pole should be investigated as a
possibility of improving current distribution and torque production. The effect of the nested rotor loops should be examined using 3-D finite element analysis. Saturation of the stator and rotor cores also need to be investigated further, taking into account the nonlinearity of the lamination materials.

Even though preliminary laboratory tests of the 12/4-pole alternator are encouraging, further evaluations are needed. Finally, the stator and rotor configurations need to be matched in order to reduce slot harmonics and noise.
BIBLIOGRAPHY


APPENDIX
ALTERNATOR SPECIFICATIONS

6/4-POLE ALTERNATOR SPECIFICATIONS

System Requirements

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<th>Requirement</th>
<th>Specification</th>
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<tr>
<td>speed range</td>
<td>2000-6000 r/min</td>
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<td>nominal voltage</td>
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<td>maximum output current</td>
<td>40 A dc</td>
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Machine Specifications

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<th>Specification</th>
<th>Details</th>
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</thead>
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<td>stator slots</td>
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</tr>
<tr>
<td>power winding</td>
<td>6 poles, double layer, 4 slot coil span, 1 turn per coil</td>
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<td>control winding</td>
<td>2 poles, double layer, 12 slot coil span, 3 turns per coil</td>
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<td>original rotor design</td>
<td>48 slots (closed, class B), 24 gauge laminations</td>
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<tr>
<td>prototype 1 rotor</td>
<td>32 slots (semi-open, class D equivalent), 26 gauge M36-C3 laminations</td>
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<td>airgap</td>
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<td>diameter at airgap</td>
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Pictures of the laser-cut laminations are shown in Chapter 4.

12/4-POLE ALTERNATOR SPECIFICATIONS

System Requirements

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<td>nominal voltage</td>
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<tr>
<td>maximum output current</td>
<td>70 A dc</td>
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Machine Specifications

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</thead>
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<td>power winding</td>
<td>12 poles, single layer, 3 slot coil span, 3 turn per coil</td>
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<tr>
<td>rotor</td>
<td>24 slots (semi-open, class D equivalent), 26 gauge M36-C3 laminations</td>
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airgap 0.4 mm
diameter at airgap 104.8 mm

Figure A.1 Stator Lamination of 48V dc Alternator.
Figure A.2 Rotor Lamination of 48V dc Alternator.