Design of a Low-Cost and Efficient Integrated Starter-Alternator

J. Colton, D. Patterson, J. Hudgins

Department of Electrical Engineering, University of Nebraska-Lincoln
209N Walter Scott Engineering Center, Lincoln, NE 68588 USA
(Telephone: +1 402 472 3771, E-mail: jcolton@bigred.unl.edu)

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Abstract

This paper details the design and construction of a low-cost electric machine to perform efficiently as both a starter and alternator. In addition to efficiency, considerations are made with regards to safety, size, manufacturability and cost. The design for this machine is chosen to be a single-sided axial flux with surface-mount permanent magnet excitation fitted with single-layer non-overlapping windings (NOW). The design aspects will be presented and an accounting of the design procedures will be described where appropriate.

1 Introduction

The growing onboard energy demand in vehicles is currently fueling a need for alternators with higher power capabilities and more efficient performance. This need is even more evident as the prominence of hybrid-electric vehicles escalates and the price of oil continues to rise. With proper design considerations for the machine and control electronics, these higher power capacity alternators can also be used to cold-crank the combustion engine at startup. The aim of this paper is to address some of these important options in reference to the actual machine design, with emphases on topology and winding selection.

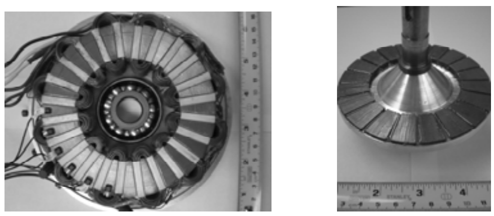
Much research energy has been devoted to the comparison of axial-flux (AF) and radial-flux (RF) machines. The results of these comparisons are not always forthright due to the sheer number of variables involved in the design of a machine. However, it has been accepted that AF machines are a competitive alternative to RF machines in terms of power (and torque) density if the number of poles is high enough and the axial length is sufficiently short [6,13-15,17]. Thus AF may be a more suitable machine topology in situations where materials cost and physical space must be limited, as in the integrated starter-alternator application.

Machines which employ NOW are quickly replacing those with traditional winding schemes in numerous applications. The use of NOW results in shorter end-turns, and therefore, a decrease in both copper costs and conduction losses, provided that the winding factor is sufficiently close to one [2,7,10-12,14]. Advantages are also achieved, especially with single-layer (SL) NOW, in terms of manufacturing because coil placement is easier and it is possible to construct the stator modularly [7,10-12,19]. Additional gains are inherently achievable regarding the cogging torque and fault tolerance capability of the machine [2,4,7,10-12].

The machine detailed in this paper has been designed in conjunction with the 2007 Future Energy Challenge (FEC) competition, which is organized biennially by IEEE. The design requirements will be given and then the bases for the particular design choices will be addressed and validated. Finally, some performance aspects of this particular machine will be analyzed and discussed.

2 Design Specifications

The 2007 FEC challenge was to develop a 1kW, 3000rpm integrated starter-alternator which can provide 30Nm of stand-still torque for a limited time period. A description of the machine specifications is provided here, while justification of the features will be address subsequently.



(a) **(b)**

Fig. 1. Photograph of machine (a) stator and (b) rotor.

As stated previously, the chosen topology is a single-sided axial-flux machine. It has three phases and is designed with 24 slots and 20 poles; a variation on the recently popular 12-slot/10-pole NOW machine. The stator is formed from a prefabricated wound toroid where the rectangular slots have been milled out. The core is wound from 0.28mm thick, grade M4, silicon steel with an outer diameter of 110mm, an inner diameter of 66mm and a height of 25mm. A photograph of the stator following coil placement can be seen in Fig 1.

The windings for this machine are single-layer NOW with each phase consisting of four coils connected in series. Each coil is prepared with 110 turns of 20-gauge (0.8mm diameter) magnet wire. The line-to-line resistance is measured to be 2.6Ω and the phase inductance is 6mH. As a side note, the construction of this machine was completed by hand and as such, the fill factor of 51% may be improved through automation. This winding configuration yields a sinusoidal back-EMF with a machine constant of approximately 0.5V/rad/s (peak) as can be observed in Fig. 2.

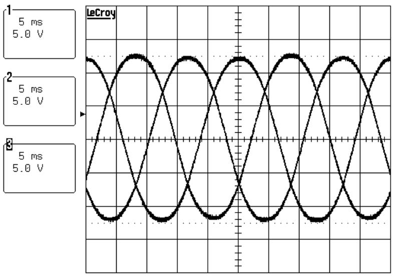
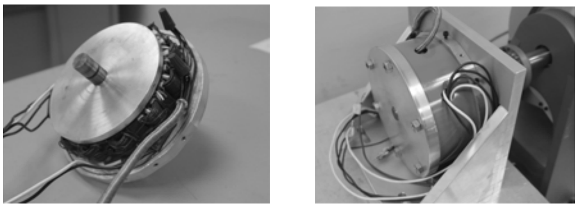


Fig. 2. Back-EMF waveforms of the machine.

The rotor magnets are composed of NdFeB (N35 quality) material and have a planar trapezoidal shape (Fig. 1). The magnet pole arc length has been established so as to minimize the cogging torque and the thickness of the magnets is designed in such a way to prevent demagnetization during maximum torque loading. This was achieved via finite element analysis (FEA) using Maxwell® 2D software from Ansoft. The rotor plate is constructed of mild steel which serves to complete the magnetic circuit. A photograph of the rotor can be seen in Fig. 1 and the fully assembled machine within its housing is shown in Fig. 3.



(a) **(b)**

Fig. 3. The fully assembled prototype machine (b) with and (a) without housing.

According to the FEC specifications, this integrated starter-alternator is to be interfaced with a 200V DC bus. However, this machine has a relatively large inductance and exhibits a large peak back-EMF at rated speed. Therefore some innovative design in the power electronics and control system has been used. This paper is intended to describe only the machine design aspects, so the drive system will not be detailed here.

3 Analysis of Design Aspects

The key design characteristics to be discussed in relation to this integrated starter-alternator application include selection of machine topology and winding configuration. In addition, some deliberation is given over to the factors influencing cogging torque and mechanical vibration. Justification of the selected design parameters is offered as a balance between both cost and performance.

3.1 Machine Topology

There has been a good deal of research and discussion comparing the benefits of AF and RF machines, and the general consensus is that the optimal machine topology is dependent upon the particular application. However, it has been shown that for a given power requirement, when compared with a RF machine, a single-sided AF machine does have a lower mass and takes up less volume when the axial length is short and the number of poles is adequately high [6,13-15,17]. Thus, the cost of materials for the AF machine will generally be lower than that for a RF machine with the same power rating. These differences become even more pronounced as the power requirements are increased up to 10kW [14]. This is important to note because although the machine in this paper is designed at a modest 1kW, modern automotive starter-alternator power requirements are on the order of 5-10kW.

The AF machine also offers several manufacturing advantages over a RF machine. As a consequence of the AF slot geometry, the phase coils are planar which makes it very simple to form the coils around an external bobbin and then slide them onto the teeth. Additionally, a magnet retention mechanism which does not interfere with the flux paths in the machine (a simple lip around the outer radius of the rotor) can be placed on an AF rotor to protect against the effects of centrifugal forces.

The three major topologies for an AF machine are: single-sided, dual-rotor or dual-stator designs. For the starter-alternator application, the single-sided design was chosen because it is the most cost effective in terms of materials and ease of assembly for a given performance requirement. However, one concern which is often expressed with regards to a single-sided AF machine is the fact that the entire thrust between the rotor and stator must be borne by a single bearing structure. This phenomenon does not generally occur for the dual-stator or dual-rotor topologies because although some mechanical imbalance must be designed for, the symmetry in these layouts can be exploited. The magnitude of this axial force for the single-sided design can be approximated according to [15]

$$F = \frac{\alpha_m S_{gap} B_{gap}^2}{2\mu_0} \tag{1}$$

where
- S_{gap} is the airgap surface area.
- B_{gap} is the flux density in the airgap.
- α_m is the percentage of airgap surface area adjacent to magnets.

For the specific machine detailed in this paper, the attractive force between the rotor and stator due to the magnets is approximately 3kN. Standard design deep-groove ball-bearings are able to handle this axial load with a generous safety margin, although it is possible to oversize the bearing to ensure quality lifetime performance. For the prototype machine described in Section 2, angular contact bearings were used.

3.2 Winding Selection

The use of NOW in lieu of traditional winding schemes has become prevalent in recent years because of the benefits in terms of copper losses, fault-tolerance and manufacturability [2,4,7,10-12,14,19]. Machines with particular combinations of slot/pole numbers can be designed with a single-layer (SL) winding in which the phase coils are placed around alternating teeth instead of around every tooth as in a double-layer (DL) scheme (Fig. 4). Of course, there are trade-offs to be considered.

(a) **(b)**

Fig. 4. Coil geometry for (a) single-layer and (b) double-layer winding schemes for an axial flux machine (top view).

It has been recognized that a result of employing a NOW scheme is a higher harmonic content, especially sub-harmonics, in the winding M.M.F distribution when compared with that of a traditional winding layout [2-4,10-12,]. Clearly, this is true for both SL and DL arrangements; however, the harmonic content between these two layouts does differ. The analytical Fourier decomposition of the winding M.M.F. harmonics for a three-phase 12-slot/10-pole machine is shown in Fig. 5 for both SL and DL windings. The assumption for the comparison is that the total number of turns per phase, N, and the electric loading is invariant during the transition from the DL to SL scheme.

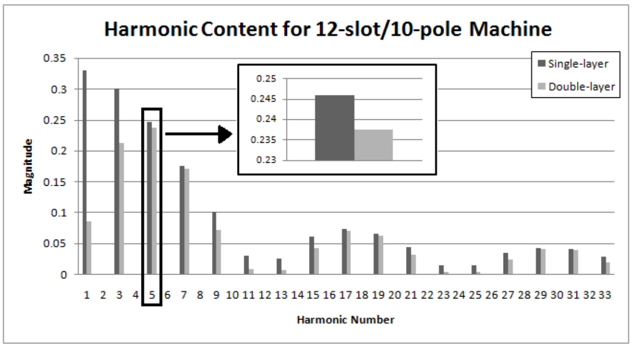


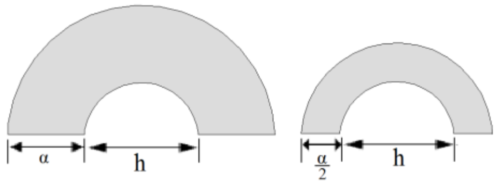
Fig. 5. Analytical Fourier decomposition results for harmonic comparisons between single and double-layer NOW for a 12-slot/10-pole machine.

This same analysis was also performed for 12-slot/14-pole, 12-slot/22-pole, 18-slot/22-pole and 24slot/22-pole machines. In all cases except for the 18-slot/22-pole machine, the magnitude of the main (torque producing) harmonic is increased by 3.5% for the SL winding. These results are in accord with those reported in [2].

As has been addressed in [2-4,10-12] and can be observed in Fig. 5, the SL winding scheme increases the magnitudes of nearly all of the M.M.F. components, especially the subharmonics. These harmonics circulate asynchronously with the rotor; hence, there are more substantial alternating fields in the rotor structure and an increase in losses there [3]. It is possible to restrict these losses by certain methods, segmenting the magnets for instance; however these techniques have manufacturing costs associated with them for limited benefits in performance.

Another matter when choosing between SL and DL windings is the difference in the end-turn geometries. When a machine is transformed from a DL to a SL winding, the volume of copper in the end-turns is increased. Fig. 6 shows the end-turn geometry for these two schemes in an axial flux machine. The assumptions made in the ensuing analysis are as follows:

- The curvature at the outer radius of the machine is neglected.
- The outer end-turn has a semicircular surface area and the inner end-turns are neglected.
- The slot width is α and the tooth width at the outer radius of the machine is h.



(a) **(b)**

Fig. 6. Winding end-turn geometry for (a) single-layer and (b) double-layer winding schemes in an axial flux machine.

The surface area of the end-turns for an individual SL and DL coil are then given by equations (2) and (3) respectively.

$$A_s = \frac{1}{2}\pi\left[\left(\alpha + h/2\right)^2 - \left(h/2\right)^2\right] \quad (2)$$

$$A_d = \frac{1}{2}\pi\left[\left(\alpha/2 + h/2\right)^2 - \left(h/2\right)^2\right] \quad (3)$$

Assuming that the number of phase coils in a SL winding is N_s, the total end-turn surface area for a SL winding is N_sA_s while that of the DL winding is $2N_sA_d$. The ratio of (2) to (3) can be written as a function of (α/h), i.e. the ratio of tooth width to slot width at the outer radius of the machine, as

$$\frac{A_s}{A_d} = \frac{2\left(\alpha/h\right)+2}{\left(\alpha/h\right)+2} \quad (4)$$

which is depicted in Fig. 7 for a range of values. For the particular machine detailed in Section 2, α = 5.6mm and h = 8.8mm. These values give a 24% increase in end-turn surface area as a result of the transformation from DL to SL.

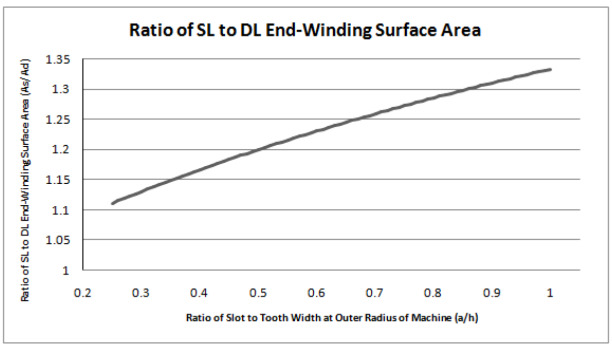


Fig. 7. Graph showing the ratio of SL to DL end-turn winding surface areas for various slot/tooth width ratios. This quantifies the increase in end-turn copper that results from a transformation from DL to SL NOW.

In summary, the SL winding scheme offers an increase in magnitude for the torque producing harmonic when compared with that of a DL arrangement; however, the rotor losses and copper end-turn volume are increased in response. The other benefits for a SL winding layout include increased fault tolerance and manufacturing benefits [4]. Thus, the SL winding arrangement was selected for this starter-alternator application.

3.3 Cogging Torque and Mechanical Vibration

The machine for this application is designed with rectangular slots, which is well known to increase the cogging torque of a machine in comparison with the use of partially closed slots. However, the ease of manufacturing and reduced cost of the open slot configuration far outweigh this drawback because it is possible to manage the cogging torque by selecting an appropriate magnet pole-arc to pole-pitch ratio and adopting a suitable relationship between the number of stator slots and rotor poles[1,5,10-12,18].

A machine designed with a NOW configuration inherently presents a lower cogging torque in comparison with a traditional winding scheme, where the number of slots per pole is an integer [1,2,11,18]. This is because the cogging component associated with an individual magnet is out of phase with those of the other magnets and therefore the total cogging torque is reduced due to the partial cancellation of the individual components.

Traditional techniques and FEA have been utilized to determine the optimal magnet pole-arc for minimization of cogging torque while not degrading the total torque output capability of the prototype machine describe in Section 2. The FEA simulated cogging torque of the machine over a rotor rotation of a single pole-pitch is shown in Fig. 8. Note that the expected six periods of cogging torque is indistinguishable due to the noise resulting from the FEA computations. The simulation was completed using 2D FEA on a portion of a RF machine model with a radius of 100m. This allowed for more rapid prototyping because a 3D model of the machine was not necessary.

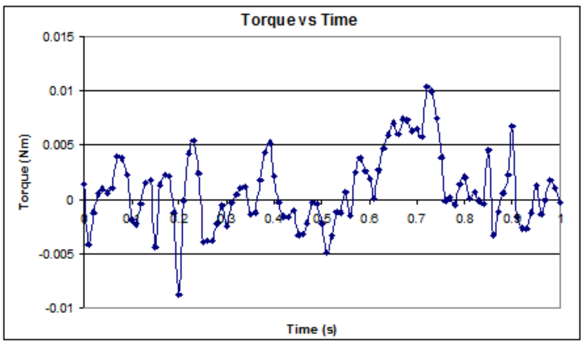
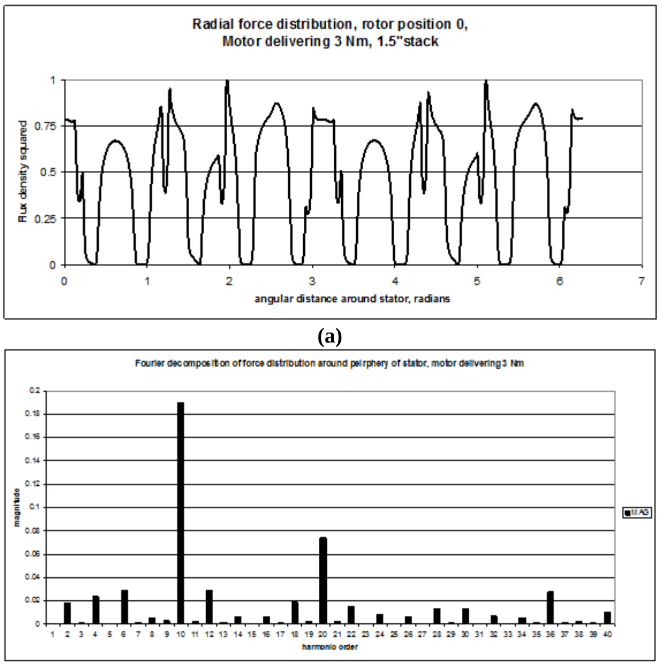


Fig. 8. FEA estimation of the cogging torque of the prototype machine over one pole pitch (speed of rotation is 1 pole-pitch per second).

Another important consideration for the design of a machine is the mechanical vibration characteristics. FEA was used to determine the radial flux density of a RF 10-pole/12-slot machine with the presence of armature current. The quantity of interest is the radial force, so Fig. 9 shows a plot of the radial flux density squared and also its harmonic decomposition.



(a)

(b)

Fig. 9. (a) Radial force distribution for a 12-slot/10-pole RF machine and (b) harmonic decomposition of that force distribution.

Using methods described in [18], it has been determined that the natural modes of vibration for the 4th-order harmonic and upwards occur at frequencies much higher than any excitation frequency for this application; however, the shaft speed which will excite the 2nd-order mode is very near to 3000rpm. This analysis is relevant for the RF machine, but it is the authors' understanding that the natural frequencies for vibration modes in an AF machine are much higher. However, further mechanical analysis is necessary to confirm this.

4 Performance

The no-load (spinning) losses for the machine described in Section 2 have been measured and are shown in Fig. 10. These losses were measured by spinning the machine using a separate motor (no load connected) with torque being measured via an in-line torque transducer.

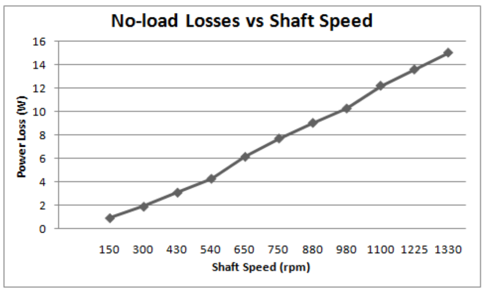


Fig. 10. Spinning losses versus shaft speed for prototype machine.

When running the machine as a starter, the torque requirement is set at 30Nm for 3-5 seconds. If the machine is operating in 6-step mode at 30Nm for 5 seconds, the total power dissipation is calculated at 4.1kW. Assuming the heat is contained entirely in the 555g of copper, the temperature rise of the coils is evaluated to be 97^{o}C, which is well within typical expectations. Thus, maximum loading can then be applied repeatedly with minimal time between heat soaks.

Because the available laboratory facilities are small but growing, it has not been possible to fully characterize the machine at rated speed or maximum loading. However, the performance of the machine can be deduced from FEA with reasonable accuracy. At rated power and speed, the conduction loss calculated at room temperature is 26.3W and the spinning loss extrapolated from Fig. 10 is ~40W. Eddy-current losses in the rotor are 18W (via FEA), which gives an overall efficiency of 91.6%. Taking into account heating in the copper (to 80^{o}C), the efficiency reduces to 90.7%.

5 Conclusion

This paper has described the machine design and construction of a low-cost and efficient integrated starter-alternator, which was part of the 2007 FEC competition. The goal was to explore some of the options in designing a machine to perform as both a starter and alternator, especially in terms of machine topology and winding configurations. The options were analyzed with respect to both performance and monetary cost and resulted in selection of a single-sided AF machine with SL NOW for the integrated starter-alternator application. Work is currently being done to apply these design concepts to a higher power (~8kW) machine for the same application.

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