

Foil Field Lundell Alternator with Rotating Power Electronics

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Abstract— The power requirements of automotive alternators are increasing significantly due to the introduction of new vehicle electrical loads. We aim to improve alternator power density with the use of a foil field winding in the Lundell or claw-pole alternator. Foil field windings are shown to provide higher conductor packing factors than conventional wire wound fields (e.g. 73% as opposed to 64% for a typical wire wound design) and offer improved thermal transfer properties. These advantages are demonstrated to enable significant increases in field ampere turns and achievable alternator output power. However, realizing these advantages requires a new field excitation circuit that can deliver high field current at a low voltage, without exceeding the limited current ratings of alternator brushes.

Index Terms—AC generators, alternators, synchronous generators, voltage control, power electronics, DC-DC power conversion

I. INTRODUCTION

The output power and power density requirements of automotive alternators are increasing significantly due to the proliferation of vehicle electrical loads [1]-[3]. This challenge is stimulating new research into the design of automotive generators, ranging from improvements to conventional Lundell alternator designs [4]-[7] to alternative machine implementations [8]-[13]. This paper demonstrates the use of power electronics placed on the alternator rotor, in combination with minor machine redesign, to achieve significant improvements in Lundell alternator power and power density. The proposed design approach is treated in detail, and is validated in a prototype system based on a commercial Lundell alternator.

At the load matched condition, the output power of a Lundell alternator is proportional to the number of field ampere turns squared [14]-[16]. Our aim is to achieve an increase in output power by increasing the number of field ampere turns through design modifications that maintain the field winding temperature rise. As will be shown, achieving this goal motivates the introduction of power electronics on the rotating field of the alternator to provide voltage and current transformation.

Section II of the paper explores the tradeoffs between wire and foil field windings in Lundell alternators. It is demonstrated that substantial improvements in field ampere turns can be realized with a foil winding, but that field power must be delivered at higher current and lower voltage to realize these improvements. Section III of the paper presents the design of a rotating dc/dc converter that provides the necessary voltage transformation that enables delivering power to the rotating field winding without exceeding the current limitations of conventional alternator brushes. Section IV presents the design and experimental evaluation of a prototype alternator realizing the proposed strategy. Finally, Section V concludes the paper.

II. FOIL FIELD WINDING

Currently, the field winding of an automotive Lundell alternator consists of round copper wire with a packing factor near 0.6 [16]-[17]. For the same number of turns and winding area, the higher the packing factor, the larger each wire can be, and therefore, the lower the resistance of the field winding. The lower resistance results in a corresponding increase in field current for a given heat flux or temperature rise. One way of increasing the packing factor involves replacing the round wire field winding with a foil winding. There are several advantages to doing this: Foil packs more tightly so the geometric packing factor will be higher. In addition, a foil winding has better thermal heat transfer (lower thermal resistance to the cooling path) than round wire.

A plot comparing round wire and foil packing factors is shown in Fig. 1 for an example Lundell field winding, assuming constant insulation thicknesses. The insulation thickness for the foil winding of 1 mil (25.4 μm) is currently the minimum thickness readily available commercially, while the wire winding insulation thickness is based on conventional practice. Below a certain number of field turns, the foil winding packing factor is higher than that of wire. A packing factor exceeding 0.7 is readily achievable using a foil winding, and still higher packing factors may be practical. This improvement leads directly to an increase in field ampere turns at constant heat flux. Moreover, the lower

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thermal resistance of a foil winding allows for higher heat flux (and ampere turns) at a specified rotor winding temperature rise.

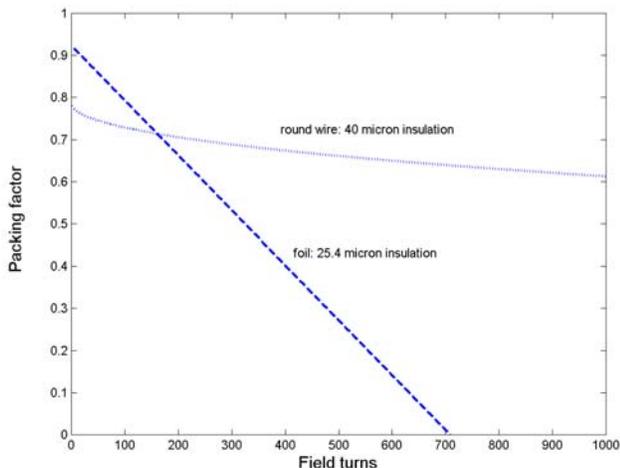


Fig. 1. Packing factor for foil and round wire versus number of field turns (constant insulation thickness). This calculation is done for a slot width of $W_s=26$ mm, a slot height of $H_s = 18$ mm, square packing of round wire ($k_f = \pi/4$) and typical insulation thicknesses as indicated in the plot.

In order to achieve an improvement in power output by increasing the field excitation, an existing alternator (OE Plus 7776-10-8-N 130 ampere) was modified by replacing the alternator's round wire field winding (440 turns of approximately 40 mil diameter copper wire with a packing factor of 0.64) with copper foil (Alphacore [Bridgeport, Connecticut] 5 mil foil with 1 mil insulation) where 90 turns of copper foil filled the bobbin. To obtain good measured resistance ratios, the two windings were connected in series and driven from a dc supply and the voltages across each winding were measured. Repeated measurements showed that the ratio of winding resistances is

$$\frac{R_{fround}}{R_{ffoil}} = 27.43 \quad (1)$$

Therefore, the ratio of packing factors is

$$\frac{k_{pffoil}}{k_{pfround}} = \left(\frac{N_{ffoil}}{N_{fround}} \right)^2 \frac{R_{fround}}{R_{ffoil}} = 1.15 \quad (2)$$

demonstrating a 15% improvement in packing factor by using copper foil.

As described in section IV, further measurements can be made to determine the field excitations at which the winding temperatures are the same at steady state, which is the criterion to be used in comparing output power. Since copper foil has somewhat better thermal properties than round wire (because of easy heat transfer across a winding layer), the effective thermal resistance to ambient may be lower, and therefore allowing higher field excitation for a given maximum temperature (beyond equivalent copper losses or heat flux).

A key challenge in realizing such a design is to develop

field circuitry that enables the use of a foil field winding. The foil winding provides more ampere-turns than a conventional wire winding when fewer turns are used at significantly higher currents. Thus, a higher current through the winding (at a lower winding voltage) is needed to achieve the desired improvement in field ampere turns. The higher packing factor relative to round wire allows us to increase the number of ampere turns relative to round wire, leading to an even higher current. This high current requirement poses a challenge, since the current-carrying capacity of conventional alternator brushes (through which the field current passes) is quite limited. Moreover, the losses and efficiency penalties of brush contacts become severe at low voltage and high current.

The higher field current required for a foil winding can be achieved in several ways. Since the brushes limit the allowed field current, one way would be to use larger brushes to allow for more current. This approach, however, is still likely to yield higher brush loss and wear, given practical contact areas. A second way is to eliminate the brushes and transfer power to the rotor through some other means (e.g. via contactless power transfer methods) [13],[16]. A third approach, explored here, retains the brushes while providing dc-dc conversion on the rotor to provide larger currents to the field winding.

This paper presents the design, construction and testing of a foil-field alternator with a dc-dc converter on the rotor. The packing factor of the foil wound alternator is higher at a lower number of turns. Fewer field turns require more amperes to produce the same or more ampere turns. The converter's function is to create a step down in voltage and an increase in current to the field winding. High current is provided to the foil-wound field while a much lower current passes through the brushes.

III. ROTATING DC-DC CONVERTER

The approach utilized here is to place a buck converter on the alternator rotor to transform the (relatively) low current (at high voltage) passed through the brushes to the high current (at low voltage) required by the foil field winding. For the prototype developed, a transformation ratio of approximately 5 is desired. Moreover, although it is possible to keep the voltage regulator on the stationary side and have the converter on the rotating side maintain a constant conversion ratio, it is potentially more efficient (and more elegant) to eliminate the voltage regulator on the stator and control the converter on the rotating side such that it performs both the regulation and transformation functions. Fig. 2 shows a simplified schematic of the prototype rotating dc-dc converter. The rotating converter is functionally similar to the buck chopper circuit used in conventional field regulators, but employs a Schottky diode to reduce conduction loss at low output voltage. While we recognize that use of a synchronous buck converter [18],[19] would have substantial

merit in this application, a more conventional buck design (with a Schottky diode) was employed in the prototype for experimental simplicity. The active switch position in the converter was selected to simplify the drive circuitry, as is done in conventional (stationary) voltage regulators [17]. The converter operates at a fixed switching frequency of 19 kHz under duty ratio control.

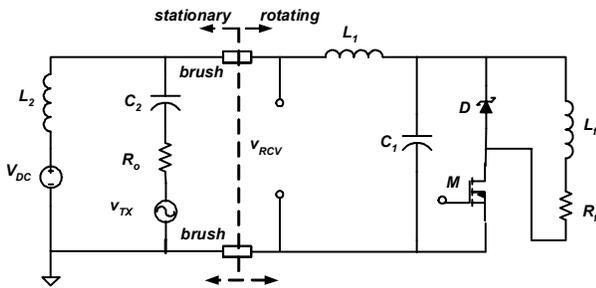


Fig. 2. Circuit topology with DC/DC converter on rotor

To regulate the alternator output voltage, feedback information from the (stationary) alternator output is communicated to the (rotating) dc-dc converter for regulation of the field. In the prototype developed here, this information is communicated in the form of a commanded duty ratio for the dc-dc converter. A number of means could be selected to communicate this information, including via short-range wireless transmission (e.g. Bluetooth), through an additional sliding (brushed) contact, or across the power contacts with high-frequency line-carrier communication. In the design presented here, communication of duty ratio information is achieved using line carrier transmission. The control signal is encoded by modulating the frequency of a high-frequency sinusoid, which is injected onto the voltage bus on the stationary side (v_{tx} in Fig. 2). The signal is then transmitted through the brushes and on to the rotating side where a receiver picks up the signal (v_{rcv} in Fig. 2), and demodulates it.

Fig. 3 shows the alternator control system, including the FM line-carrier communications system used to transmit control information from the stationary side, through the brushes, to the dc-dc converter on the rotating side. Error amplifier A_1 produces a PID compensated duty ratio command for the rotating converter based on the difference between the alternator output voltage and a reference voltage. The duty ratio command signal is converted directly to a frequency-modulated (FM) ac signal. The frequency of the transmitted signal is set to be a linear function of the desired duty ratio in the range of 153 kHz to 167 kHz. This ac signal is buffered by A_2 and fed through the brushes to the rotating converter. On the rotor, an FM demodulator recovers the compensated error signal. The received signal is then used to create a pulse-width modulated gate signal used to drive the MOSFET. Since duty ratio varies only slowly, the phase-locked loop (PLL) of the FM demodulator can easily track the

desired signal. A lowpass filter composed of L_1 and C_1 is designed to filter out switching ripple from the switching currents that could otherwise corrupt the received modulated signal.

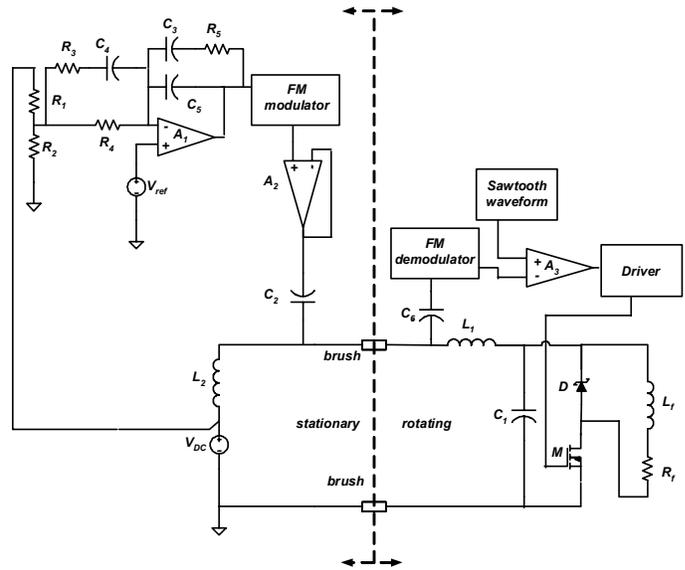


Fig. 3. Alternator voltage controller (error amplifier), FM communications circuit, and rotating converter driving circuit for controlling the alternator output.

For the selection of the switching frequency (19 kHz) and filter components, several factors had to be considered. It is desirable for the switching frequency to be high enough to minimize the size of the passive components such as L_1 and C_1 but not too large that the switching losses become considerable. The switching current, which can be viewed as noise from the viewpoint of the control signal being communicated, is a rectangular wave whose spectrum consists of samples of a sinc function that decay at higher frequencies. This decay is desirable because it assures that the noise will be small if we pick our communication frequency high enough. The switching frequency of 19 kHz was selected and the frequency range of the modulated signals was from 152 kHz and 167 kHz so that this range would fall between two harmonics (8th and 9th) of the noise from the switching currents, which would isolate the frequency range of the modulated signal from the noise harmonics. Since the noise harmonics decrease with frequency (noise spectrum decays as a sinc) and in addition, the filter (composed of L_1 and C_1) attenuates these harmonics, the noise is not a concern in the vicinity of the frequency range used. The input filter is composed of L_1 that is used to block AC ripple from the noise source, and C_1 that absorbs it.

V. RESULTS

A. Experimental Results

To demonstrate the proposed approach, a foil-field rotor has been developed for an OE Plus 14 V, 130 A alternator (7776-10-8-N). A 5 mil copper with 1 mil insulation (kapton) foil winding (90 turns) is wound on the original bobbin, yielding a 15% improvement in packing factor over the regular field winding. With refined sizing and winding of the copper foil, substantial further improvements in packing factor are anticipated to be possible. The DC/DC converter described in the previous section, together with the filter and the communications receiver circuit, is mounted directly on the rotor as shown in Fig. 4. The converter and communications circuit is mounted in interstitial space between blades of one of the two rotor-mounted centrifugal fans. An associated controller, transmitter, and filter unit is mounted on the stationary side, in place of the conventional regulator. The rotor with the converter was then placed inside the stator and the rest of the alternator case was assembled. The external circuit containing the FM modulator was connected to wires leading to the brushes. The alternator was then bolted onto the stand and connected to a drive motor via a toothed belt.



Fig. 4. Pressed rotor claws with foil field winding and rotating dc-dc converter.

Testing was conducted for idle speed operation (1500 rpm) at constant duty ratio (run open-loop) and 13 V output to enable a comparison with the published specifications for the stock alternator. At non-steady-state thermal conditions a maximum field current for the modified alternator of 33.1 amperes was obtained, yielding a 44% increase in ampere turns over that of the stock alternator (approximately 2068 ampere turns). Note that idle speed is not the worst case operating point from a temperature standpoint [20],[21], so some improvement at idle speed could be sustainable.

To determine the maximum achievable output power

under “manufacturer nominal” conditions, the tests were made at idle speed (alternator speed of 1500 rpm). The maximum output current was approximately 78.6 A at approximately 32 A of field current as shown in Fig. 5. The average output power obtained is 1048 W (output voltage of 13.34 V). The quoted nominal output power of the alternator is 70 A at idle speed and 13 V output (such that the regulator generates full field current). The quoted output power is then 910 W. From experiments on a stock alternator, the maximum output power at idle speed obtained was 964 W at ambient temperature (73 A at 13.2 V). Therefore, the maximum output power increased by 8.7% under nominal conditions when the enhanced foil wound alternator was used. The input power to the field winding was also measured for the conventional and modified system. The electrical input power to the enhanced foil field winding circuit was 168.6 W (12.64 A at 13.34 V). The electrical input power to the round wire field winding circuit was 61.4 W (4.7 A at 13 V). It is anticipated that adoption of synchronous rectification in the buck converter would eliminate much of this difference.

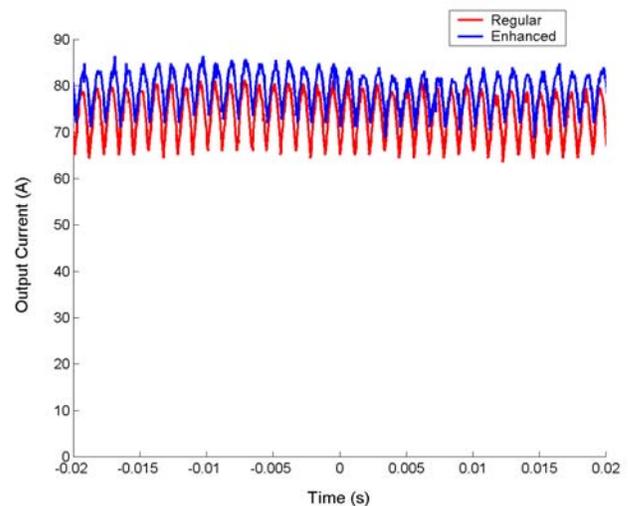


Fig. 5. Comparison of maximum average output current obtained (average of 78.6 A for enhanced, 73 A for regular) at approximately 32 A of field current

The achievable output power of the conventional and modified alternators were also compared at thermal steady state. The round-wire field was tested at full-field conditions, while the foil field was tested with an ampere turn excitation yielding the same increase in rotor winding temperature over ambient as the round wire field winding (in thermal steady state). The improved thermal properties of the foil winding over the round wire winding are exploited in this test. Equivalent temperature rise performance was established by measuring the relative resistance increases of the rotor windings [16].

The existing Lundell alternator was run at full field current (13 V output and idle speed of 1500 rpm) until thermal steady state and the percentage increase in resistance

was found to be 26.1% (2.53 Ω increasing to 3.19 Ω in steady state). Therefore, comparisons for output power are to be made at a field current where the foil winding resistance increases by the same percentage, thus insuring equivalent field winding temperatures. The initial resistance of the foil field winding was measured to be 0.13 Ω under ambient conditions. The modified alternator was run at the same operating conditions (approximately 13 V output voltage and idle speed) and the field current was increased (by increasing the duty ratio) until the percentage increase in field resistance measured (measured through a hole in the alternator case) was approximately 26%. The foil resistance was measured to be approximately 0.165 Ω . The field current was approximately 30 A based on previous duty ratio and input current versus field current experiments. The output current was measured and was found to be 71.3 A as illustrated in Fig. 6. The corresponding output power was 940 W in thermal steady state, as compared to an output power of the conventional alternator of 819 W (63 A at 13 V). Therefore, the percentage increase in thermal steady state output power while maintaining the same winding temperature in both round wire and foil wound windings is 15 %. Thermal models and measurements of Lundell alternators suggest that such an increase in alternator power has an acceptable thermal impact on the stator (at idle speed) [20]. Further experiments and measurement details may be found in [16].

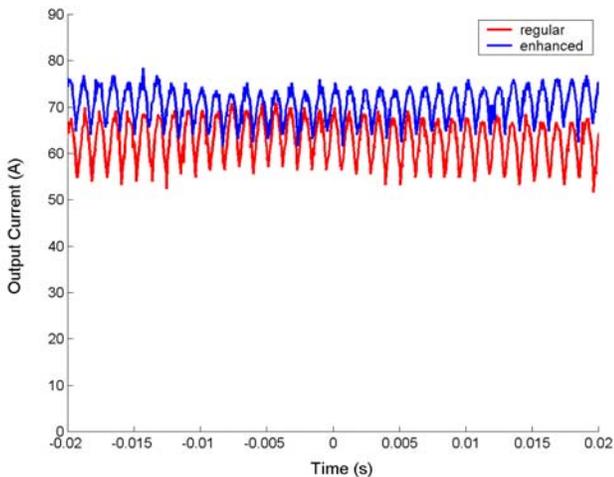


Fig. 6. Comparison of output current at thermal steady state, same winding temperature (average of 71.3 A for modified alternator; 63.0 A for stock alternator).

For an equivalent rotor temperature rise, an approximately 30% increase in field ampere turns is achieved in the modified alternator over the stock alternator. This yielded an approximately 15% increase in alternator power capability without redesign (excepting the foil field winding). With suitable redesign of the alternator to take advantage of the improved ampere turns, substantially higher performance should be achievable. In order to fully utilize the increase in ampere turns, the alternator stator can be redesigned to

accommodate the increased flux, which can otherwise result in more stressful thermal and saturation conditions. The armature winding heat flux can be decreased by increasing the stator slot depths and armature wire size. Saturation in the stator can be lessened by increasing the air gap and the back iron thickness. If more field ampere turns are to be used, the air gap can be increased proportionately while maintaining the air gap flux density and decreasing the armature reactance, and therefore still achieving an increase in output power while not saturating the alternator any further. It is anticipated that redesigning the alternator to accommodate the improved field capability would yield substantially more than the demonstrated 15% improvement in power.

B. Future Development

Several directions for further development of this general strategy are apparent. The first is adoption of synchronous rectification on the rotating converter, which would reduce field circuit loss and increase achievable output power. Efficient synchronous rectification (enabled by recent developments for electronic systems applications) also affords the possibility of higher step down conversion ratios and consequent improvements in packing factor. Moreover this could also be used as a means for rapid field deexcitation under fault conditions [16] (e.g. by using the MOSFET body diode drop to facilitate rapid deexcitation).

A further direction is simplification of the hardware used for communication of the duty ratio command. This circuitry occupied much of the volume and cost of the rotating hardware. One possibility is to exploit a higher degree of integration of the communications system. An alternative approach is to only use the rotating converter for voltage transformation, and to use a separate converter on the stator to provide regulation.

A third fruitful development direction is the use of thinner insulation and more aggressive packing for the rotating field winding. Given the low turn-to-turn blocking requirements of the foil insulation, much thinner insulation is certainly feasibly if not readily available on the market.

A final direction is reoptimization of the stator design to take full advantage of the high ampere turns made possible by the foil field winding. Means for achieving such reoptimization are outlined in [16], for example.

VII. CONCLUSION

This paper presents the design, construction, and testing of a Lundell alternator having a foil field winding and a rotating dc-dc converter. Copper foil is used as the field winding to improve packing factor and allow for a higher field ampere turn excitation at equivalent thermal conditions. The rotating dc-dc converter provides a step down in voltage and a step up in current that is necessary for effective use of the foil field

winding. The dc-dc converter is also used to provide alternator output control, and line-carrier frequency modulation is used to communicate control information to the dc-dc converter. This paper demonstrates the efficacy of the proposed approach for achieving improvements in alternator power. An increase of 30% in field ampere turns and 15% in output power is achieved at equivalent rotor thermal conditions. Further redesign of the alternator will allow much better utilization of the increase in ampere turns to substantially increase output power.

VIII. ACKNOWLEDGEMENT

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