Applications of Power Electronics in Automotive Power Generation

David J. Perreault, Thomas A. Keim, Jeffrey H. Lang, Leandro M. Lorilla

Laboratory for Electromagnetic and Electronic Systems
Massachusetts Institute of Technology
M.I.T. Rm. 10-171, 77 Massachusetts Ave.
Cambridge MA 02139 USA

Abstract: This paper focuses on the use of switched-mode power electronics to enhance the power, efficiency, and transient performance of Lundell alternators. The application of power electronics in conjunction with both the alternator field and armature are explored. It is shown that the combination of a foil field winding and improved field control electronics enable substantial improvements in field packing factor and alternator output power. Likewise, application of switched-mode rectification with a redesigned armature and appropriate controls enable improved alternator power and efficiency. The application and limitation of power electronics to enhance transient performance and load dump suppression are also overviewed.

Keywords: Lundell Alternator, Claw-Pole Alternator, Switched-Mode Rectifier, Semi-Bridge Rectifier, Boost Rectifier, Brushless Alternator, Brushless Exciter, Contactless Power Transfer.

1. Introduction

The evolution of automotive electrical systems is creating a demand for generators providing unprecedented levels of performance. Important characteristics of future alternators include higher power and power density, improved efficiency, higher temperature operation, and better transient response (e.g., load dump suppression.) Meeting these challenges has motivated a variety of research into automotive alternator design in recent years (e.g., [1-18]).

This paper considers the use of switched-mode power electronics to realize improved performance in automotive alternators. We focus on the Lundell, or claw-pole, alternator [19] because of its almost universal use in automotive applications, and because recent work suggests that this class of machine is suitable for meeting emerging performance requirements [15-17]. The use of power electronics to enhance the characteristics of both the field and armature is discussed, and an overview of some recent experimental results in this area is presented.

The paper is organized as follows: Section 2 examines the use of improved switch-mode power electronics to enhance the performance associated with the alternator field. It is demonstrated that a foil field winding coupled with appropriate power electronics enable greatly increased field packing factor and available field ampere turns, with a consequent benefit in performance. The use and limitations of "fast field de-excitation" to improve load-dump transient response is also explored. Section 3 examines the redesign of the alternator armature (stator) in conjunction with use of switched-mode power electronics to improve performance. Tradeoffs between the complexity of the power electronics and control system and achievable performance are reviewed.   Finally, Section 4 concludes the paper.

2. Alternator Field

As illustrated in Fig. 1, the field of a conventional brushed Lundell alternator is a rotating "fishing reel" winding pressed between the rotor claws and fed from the stationary frame via brushes and slip rings [19].   In this section we consider means of constructing and driving the field winding to achieve increased power and faster transient response.

2.1 Alternator Field Construction

Conventional field windings are implemented as carefully-packed round-wire windings with copper packing factors in the vicinity of 0.6 [17-19]. An alternative to this approach is to wind the field with a copper foil winding [17,18]. Foil windings provide the opportunity to achieve much higher packing factors than are possible with round-wire windings.
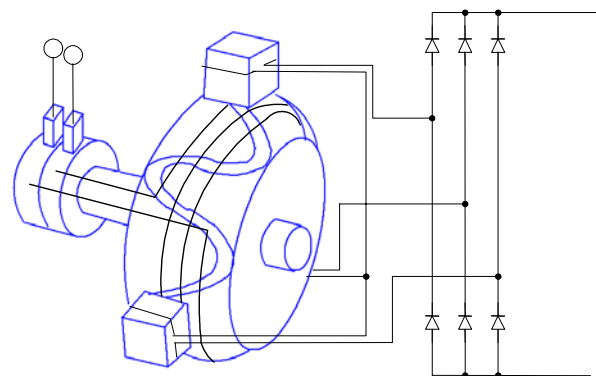

Figure 1: Structure of the brushed Lundell alternator.

Moreover, a spiral-wound foil winding provides a more direct heat transfer path for cooling the winding. Both of these effects contribute to higher achievable field ampere turns with a foil winding. Because alternator output power is ideally related to the square of ampere turns, adoption of a foil-wound design can yield significantly higher achievable output power.

As illustrated in Fig. 2, foil windings can achieve significantly higher packing factors than wire windings (yielding higher allowable ampere-turns), but only do so with far fewer turns operating at much higher current levels. Direct replacement of a wire-wound field with a high-packing-factor foil-wound field is not possible because of the current limitations of the brushes that transfer power from the stationary frame. Achieving the performance benefits of a foil winding thus necessitates some means of bypassing this limitation; power electronic conversion is an effective means of doing so [17, 18].

2.2 Rotating dc-dc Converter

One means of delivering power to a foil field winding without exceeding the brush current ratings is to place a dc-dc power converter on the rotor. The dc-dc converter transforms the high-voltage, low-current power delivered across the brushes to the low-voltage, high current required by the foil field winding. It can be implemented as a buck converter or synchronous buck converter, for example. The converter can be operated at fixed duty ratio (i.e., as a "dc transformer") with regulation implemented on the stator side. Alternatively, if means are provided to transfer control information to the rotating frame, this converter can also be used to implement field control.
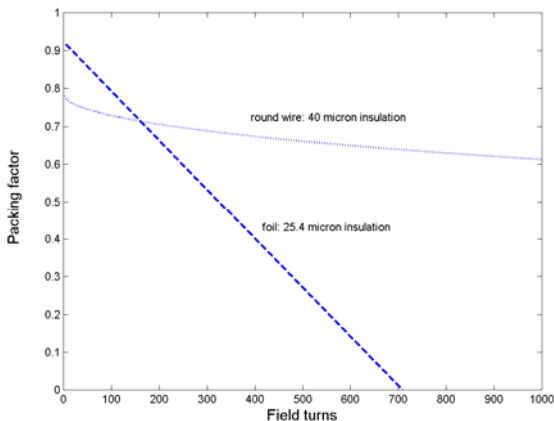

Figure 2: Theoretical comparison of packing factor for foil and square-packed round-wire field windings [17,18]. The comparison is for a bobbin width of 26 mm, a bobbin height of 18 mm and for indicated insulation thicknesses.
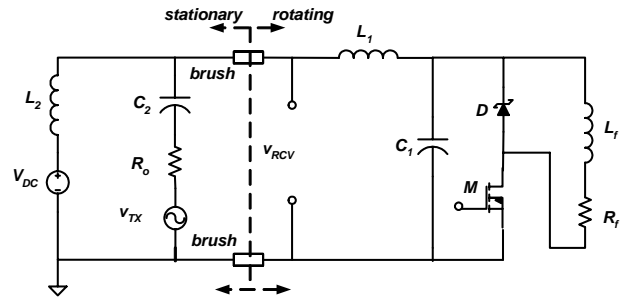

Figure 3: Simplified power and control circuit of a rotating dc-dc converter for a foil-field alternator [17,18].

A foil-field alternator with a rotating dc-dc converter has recently been demonstrated in [17,18]. The alternator (based on OE Plus model 7776-10-8-N) uses a foil field winding (90 turns of 5 mil copper foil with 1 mil insulation, packing factor ~0.74) in place of the standard wire winding (440 turns of ~40 mil diameter insulated copper wire, packing factor ~0.64). This modification thus presents a significant improvement in copper packing factor and thermal path, but requires a step down in field voltage by approximately a factor of five.

A simplified schematic of the rotating converter and control circuit is shown in Fig. 3. For experimental simplicity, the circuit uses a buck–type topology, with the converter and control circuit mounted against one rotor claw. Control information is transferred from the stator to the rotating converter across the brushes using a small frequency-modulated signal. The control signal is injected on the stationary side, transmitted across the brushes, and read on the rotating side. A photograph of the foil-field rotor and dc-dc converter system is shown in Fig. 4.

The foil-wound design with dc-dc converter was found to enable approximately a 30% increase in

Figure 4: Foil-wound rotor and rotating dc-dc converter [17,18].
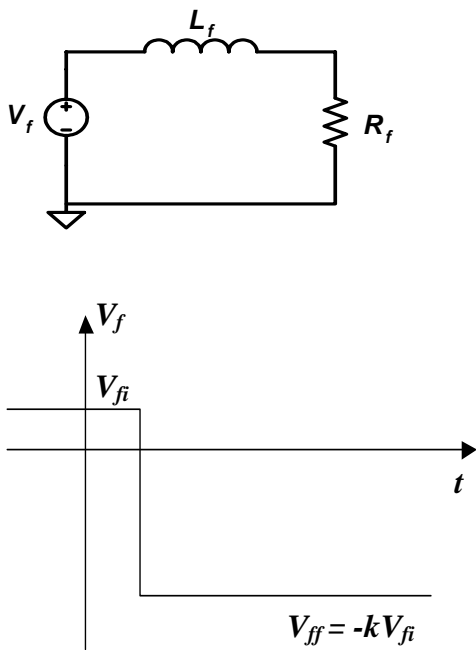
$$V_{ff} = -kV_{fi}$$

Figure 5: Simplified model of fast field de-excitation.

field ampere turns over the stock alternator for the same field temperature rise at idle speed. This provided an increase of 15% in alternator power at idle speed (a sustainable increase given the stator thermal profile vs. speed of typical Lundell alternators [13,14].) This improvement was achieved in the absence of any modification to the electromagnetic design of the machine. Substantially larger improvements in output power could be achieved if the stator were redesigned to take advantage of the increase in field ampere turns.

It should be noted that the size and cost of the required rotating power electronics can be extremely small: The conventional buck design used in the prototype could be replaced with a highly integrated synchronous buck power stage, thus leveraging technology from the high-volume portable electronics market. Likewise, implementing the control on the stator or utilization of an improved communications scheme would be of great benefit, as most of the volume and cost of the prototype rotating converter was due to the circuitry for communications. Nevertheless, the design demonstrates the potential to achieve significant improvements in performance with this approach.

2.3 Brushless Power Transfer

An alternative means of transferring power to a rotating foil field winding without the current limitation of brushes is via contactless power transfer using a rotating transformer. Brushless exciters have long

been applied to large machines, and have also been explored for automotive applications [6,17]. Use of such an approach eliminates the current delivery limitations of conventional brushes, and also eliminates brush wear as a failure mechanism.

In [17], for example, a contactless power transfer system based on a rotating transformer is demonstrated that has sufficient power and current delivery capability to supply a foil field winding. In this system, an inverter drives a rectifier on the rotor via a coreless printed-circuit-board transformer with a rotating secondary. Power control is achieved via frequency modulation over a range of 100 to 400 kHz. The transformer design concept is similar to other coreless printed transformers [20], albeit with a rotating secondary printed on a different circuit board. The transformer is simply implemented as a pair of planar spiral coils (I.D. 32 mm, O.D. 54.6 mm) printed in 4 oz copper on a pair of circular circuit boards (primary 4 turns, 2.5 mm track width, secondary 2 turns, 5 mm track width). The printed circuit board transformer is designed to be mounted axially (around the shaft) with the primary on the stator and the secondary on the rotor, separated by a 0.64 mm gap.

The system of [17] demonstrates contactless power delivery to a foil field winding using a simple, inexpensive coreless magnetic structure. The demonstrated power delivery is sufficient to provide a 50% increase in ampere-turns over a conventional wire-wound design, exceeding that needed due to thermal constraints. While significant further development of this technique would be needed for commercial deployment, it is clear that a foil field winding with brushless power transfer is a feasible design strategy.

2.4 Load Dump Control: Fast Field De-Excitation

An undesirable characteristic of Lundell alternators is the severe "load dump" voltage transient that can occur when a load (especially the battery) drawing high current is disconnected from the alternator [22-31]. This transient has a significant impact on the design of automotive electronics since it can impose a substantial overvoltage on the system lasting hundreds of milliseconds.

Some form of voltage clamp is often used at the alternator output to limit the magnitude of the load dump transient. (Alternator diodes are often designed for avalanche for this precise purpose.) The clamp must absorb the excess alternator power during a load dump until the alternator field controller can reduce the machine back voltage. Conventional "buck-type" field regulators [19] effectively short circuit the alternator field (through a diode) during the transient, such that the transient lasts several
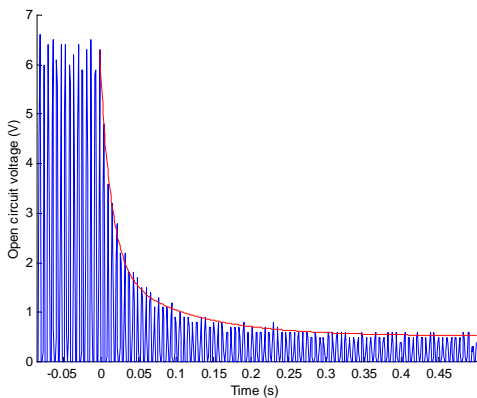
Figure 6: Experimental measurement of the open circuit stator voltage response of an alternator (phase-to-neutral voltage, positive half of waveform only) to nearly instantaneous removal of field current at t=0. Results are for a Motorcraft 14 V, 140 A alternator, speed = 1840 rpm, initial field current = 1 A.

field winding time constants (typical field time constants are in the range of 100-200 milliseconds). This leads to a relatively large energy absorption requirement for the clamp circuitry which grows more onerous with increasing alternator power rating.

A well-known means of reducing the load dump duration is to use more sophisticated field control power electronics that can apply a reverse voltage to the field, thereby actively driving field current downwards (e.g., [30]). Clearly, a range of field control circuit topologies exist that can realize such fast field de-excitation (e.g., see [17,30].) In this paper we consider the performance and limitations of such fast de-excitation techniques.

A highly simplified model of fast de-excitation is shown in Fig. 5. The field is simply represented as a series connection of an inductor and a resistor (rotor eddy currents, loading by the armature and other effects are ignored in this model). The field is de-excited by switching the field voltage from its initial positive value V_{fi} to some negative value V_{ff} that is a factor k times as large in magnitude. This simplified model yields a de-excitation time t_Z (to zero current) of approximately [17]:

$$ t_z = \frac{L_f}{R_f} \ln\left(\frac{k+1}{k} \right) \quad , \quad k \geq 0 \qquad [1] $$

where k is the ratio of the magnitude of the reverse voltage to the initial voltage. k=0 corresponds to the usual case of short circuiting the field, resulting in an exponential current decay to zero (in infinite time, with three time constants sufficient for practical purposes). Based on this model, having a larger k results in a shorter de-excitation time, but requires

the ability to apply larger reverse voltages to the field.

Based on the above model, the benefit of ever faster de-excitation for reducing the energy requirements of the load-dump clamp may seem clear. However, the simplified model leading to equation [1] formally only holds when the field decay process is sufficiently slow that rotor eddy currents are not important. A practical consideration that is not widely appreciated is the effect of rotor eddy currents on the duration of the load dump transient. If, for example, one instantaneously removes the field current (in an attempt to instantly drive the field flux to zero), eddy currents will be induced in the rotor poles that reject this flux change. Consequently the speed voltage seen by the armature will no longer be proportional to the field current, but will reflect a contribution induced by the eddy currents. The decay time of rotor eddy currents can thus be an important consideration in fast de-excitation.

To illustrate the importance of this phenomenon, an experiment was carried out on a Motorcraft 14 V, 140 A alternator in which the open-circuit armature (phase-to-neutral) voltage was measured while the field current was driven nearly instantly to zero (in 200 µs) using a resonant circuit. The results of this experiment, which was carried out at an initial field current of 1 A and an alternator speed of 1840 rpm, are illustrated in Fig. 6. As can be inferred from these results, eddy currents prevent instantaneous reduction of the voltage down to levels determined by remanent magnetization, and the transient still lasts more than 50 ms.

Detailed fitting of the data of Fig. 6 reveals dominant time constants of 100 ms and 15 ms [17], and suggests that even with the instantaneous removal of field current, recovery from a practical load dump transient can require several tens of milliseconds. Meeting this response time without large reverse voltages (*k* values) or achieving still faster response requires field circuits that can drive controlled negative current in the field to more rapidly counteract the eddy current effects. Higher-order rotor circuit models suitable for capturing eddy current effects, example field control circuits providing bidirectional current and voltage, and sample experimental and simulation results of fast field control may be found in [17]. It may be concluded that improved field control power electronics can enhance alternator transient response (e.g., to better manage fault conditions such as load dump), but must be designed to account for rotor eddy current effects.

3. Alternator Armature

The previous section showed that changes in the field design along with application of improved field control power electronics can benefit the performance of the Lundell alternator. Here we consider the design of the armature in conjunction with improved power electronics to achieve increased alternator performance.

3.1 Changes in Electromagnetic Design

One family of productive ways to change an automotive alternator to obtain more output is changes to the stator electromagnetic design. For example, one recently-introduced class of alternators achieves increased output power through substantially higher copper packing factor in the stator slots [5]. Among other benefits, this "segmented conductor" technology permits an increase in stator copper packing factor from ~0.45 to ~0.7, thereby decreasing stator resistance.

Another possibility is to increase the depth of the stator slots. Increasing the depth of the stator slots, and then filling those slots with the same number of turns of larger cross section wire also has the effect of decreasing the stator resistance. If the copper packing factor in the new, deeper, slots is the same as that in the original unmodified stator, the stator resistance at constant temperature goes down as the ratio of the square of the old slot depth to the new slot depth.

Reduction in stator resistance is an important contribution to efficiency, but its value in increasing alternator output varies depending on the circumstances. With a diode bridge rectifier, any change in output requires an increase in current because the output voltage is regulated to a fixed value. The internal resistive voltage is much less significant than the internal reactive voltage in determining the current which flows to the load [32,12]. So if no other changes are made to the machine, the increase in output power which results from a reduction in stator resistance can be quite modest over much of the operating range unless improvements in stator inductance are also achieved.

On the other hand, any change to the machine which allows for the possibility of more speed-induced voltage, without an increase in stator inductance, will tend to cause a nearly proportional increase in current deliverable to the stator. In this instance, a reduction in stator resistance may be required to take advantage of this improvement without causing the machine to overheat.

Reducing stator resistance by increasing slot depth has the important disadvantages that the volume and mass of iron in the machine goes up. This results in a larger machine diameter, larger mass, more iron loss, and larger cost. Additionally, the slot leakage contribution to armature inductance is also increased. If this last change is significant with respect to other contributions to armature inductance, the entire benefit may be lost. Reducing stator resistance by increasing copper packing factor (as in [5]) has none of these disadvantages.

3.2 Changes in the Rectifier

Advances in power electronics make it possible to greatly improve Lundell alternator performance. Here we consider a variety of strategies through which improved performance can be achieved through changes in the rectifier coupled with design of the machine.

Synchronous Rectification

Conceptually the simplest change is the adoption of synchronous rectification. With synchronous rectification, the rectifier diodes are substituted with active switches having a lower on-state voltage drop [33-35]. The switches are controlled to achieve the same function as the diodes they replace (fully on when forward biased, fully blocking when back biased.) In practice, MOSFETs represent the only class of solid state power switching device which is widely used for synchronous rectification.

The benefit of synchronous rectification depends strongly on the application. The reduction in heat load on the diode plate can be a large fraction of the value required with a diode rectifier. In a case where this cooling requirement is exceptionally difficult to achieve, synchronous rectification can offer a solution. Other than that, the benefits of synchronous rectification are similar to those for reducing stator resistance. The contribution to efficiency can easily be important. Because diodes tend to be a constant voltage drop even at low current, their loss tends to be a constant fraction of output power, independent of the level of output power. With synchronous rectification, the forward voltage drop in the switch tends to be lower than with a diode even at full current, and at part load, the forward drop tends to fall, so efficiency at part load is helped even more than efficiency at full load.

As with a resistive voltage drop, the voltage drop in a rectifier tends to be in quadrature with the element of impedance which is most influential in limiting the current deliverable to the load. As a result, synchronous rectification tends to have only limited capability to increase output power (e.g., see [35]).

Full Active Bridge Techniques; Vector Control

While synchronous rectification has definite benefits, it is unlikely that many applications will substitute MOSFETs for diodes for the benefits of synchronous rectification alone. Automotive rectifier diodes are a highly developed product, extremely well adapted to their use. They are simple and inexpensive to produce, relative to any three-terminal power device, they are capable of operating at high temperatures, and their packaging has been demonstrated to be robust across the entire range of automotive working and storage environments. While MOSFETs may be fully acceptable as automobile components, they fall short of alternator rectifier diodes in all the three dimensions listed above. (While their packaging may in fact be robust in the automotive underhood environment, this fact has not been demonstrated with billions of part-years of service, as has been the case with the diodes.) Additionally, MOSFETs require gate drivers, and gate drivers require power supplies, including level-shifted power supplies. So the cost of substituting a full active bridge for a diode bridge is substantial.

Once this transformation in the power circuit has been accomplished, very large benefits in system performance can be achieved at relatively limited incremental cost. Because active switches (i.e. the MOSFETs) can interrupt current without waiting for a current zero, they have the capability to shift the phase of the alternator's internal ac current with respect to the speed-induced voltage. This ability can be exploited in many ways, and different branches of the motion control community have developed different terminology to describe the relatively limited range of really effective techniques. The ultimate limit may be the method often called vector control. In this technique, the armature (in this case stator) current vector, (in a phase space representation of the machine's operation), is controlled to be always at or near 90 electrical degrees away from the field (in this case rotor) flux vector. This condition achieves maximum torque per unit of current, and thus represents a very efficient operating point.
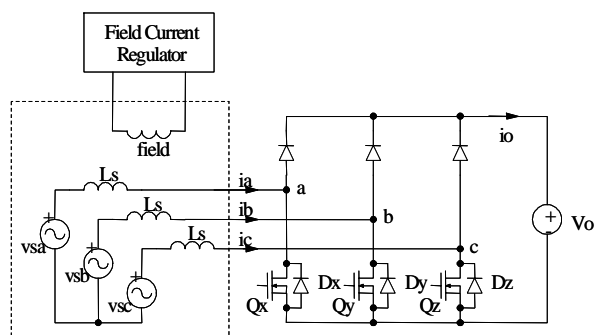
It is possible with this technique to get three, or four, or more times as much power from the same mass and volume of iron and copper as it is with simple diode rectification. And with a full active bridge, motor operation is as easily achieved as generator operation, potentially allowing the alternator to assume the function of the starter, and to aid the engine in propulsion of the vehicle.

Vector control requires no additional power switching elements in the circuit schematic, compared to synchronous rectification. What it does require is substantially more complex decision making in the control of the switches. These more complicated decisions require more information. In particular, it is necessary to know rotor angle, either directly from a sensor or indirectly through a state estimator, which itself requires sensor inputs and data processing.

Vector control over a range of speeds may also suggest that the windings of the stator be different from those used with a diode rectifier or synchronous rectification. Vector control may also require that the device ratings of the power MOSFETs be higher than if synchronous rectification is the only function.

So selection of a full active bridge opens up a large number of design choices not possible with diode rectification. Much, but not all, of the incremental cost is incurred when the choice is made to use active switches. Automotive designers can thus make a whole range of operating choices, ranging from synchronous rectification at the simplest to vector control at the other extreme. Once the cost to use an active bridge has been accepted, small increments of additional performance can be achieved at relatively small increments of additional cost.

As an aside, no matter how much additional performance is specified, it almost always will make sense to achieve the benefits of synchronous rectification when an active circuit is used. In this sense, the control concept is a simple one. Whenever the MOSFET is biased so that the intrinsic body diode would conduct, the controller should energize the gate of the MOSFET, so that the main channel conducts in parallel with the body diode, shunting away most of the current and reducing the voltage drop across the device.

Switched-Mode Rectification

If motor operation is not required, the use of a switched-mode rectifier such as a semi-bridge rectifier (or "partial active bridge") merits consideration. The semi-bridge switched-mode rectifier of Fig. 7 has been employed in a variety of applications, including automotive power generation (e.g., [5,10-13]).

Figure 7: Semi-bridge switched-mode rectifier.

When combined with an appropriate control strategy and armature design, a semi-bridge rectifier enables substantial improvements in power and efficiency at a much lower cost than that required to implement a full active bridge. For example, in [12] it is demonstrated that an alternator with the circuit of Fig. 7 can deliver 1.9 times as much power over a drive cycle from the same mass of iron and copper, while at the same time *reducing* the losses in the machine (thus providing substantial efficiency benefits.) An efficiency-optimizing controller is also presented that can provide improvements in alternator efficiency at partial-load conditions as well (down to light load). This is achieved by taking advantage of the reduction in armature turns needed in a boost-rectified design.

Other benefits are achieved with this simplified structure as well. The circuit replaces diodes with MOSFETs only on the bottom side of the rectifier bridge. This substitution costs less than half as much as a full bridge substitution, because the MOSFETs in Fig. 7 can be driven by a ground-reference gate driver. No level-shifted power supply is required to implement this circuit. Further, the control strategy described in [12] is extremely simple: the only input required is engine speed; a variable which is already sensed for other purposes.

The design and control strategy introduced in [12] does not result in any increase in alternator output at idle speed. The same circuit can be used with a slightly more elaborate control law to achieve enhanced performance at idle speed. In [13] Rivas et. al. demonstrate a 10% improvement in idle power at reduced loss (and higher efficiency), and a 15% improvement in idle output power within machine thermal limits. Substantial further improvements in idle-speed power capability are likely to become possible in conjunction with stator winding techniques such as described in [5], which improve the stator time constant. The control law is only slightly more complicated than that described in [12], and the only additional sensing information required is voltages internal to the rectifier, which can be sensed at very low cost.

Transient Control

It should also be recognized that either full bridge or switched-mode rectifier power electronics can be utilized to achieve greatly increased transient control bandwidth (e.g., to address load dump). Switched-mode power electronics can respond on the time scale of a switching period (e.g., 10 microseconds), rather than being constrained by the rotor characteristics. As a simple example, by gating the MOSFETs of Fig. 7 on while the field is ramped down during a load transient, the transient voltage can be entirely suppressed at the output. An experimental example of load dump suppression

using a switched-mode rectifier is illustrated in [12], in which the transient response at the alternator output is reduced down to approximately 100 µs. The higher bandwidth offered by switched-mode conversion also enables other features, such as high-bandwidth energy management.

Summary

Changes to the stator of an automotive alternator, relative to today's design practices, can deliver substantially improved machine performance. Changes to the stator winding alone can deliver some benefits, but are most valuable to exploit the capabilities made available by other changes to the alternator, especially changes which produce more field excitation and/or changes to the rectifier.

Until recently, changes to the rectifier have been considered too expensive to be commercially viable. However, the tremendous developments in low-voltage power MOSFETs, passive components, and packaging methods for high-volume electronics applications are rapidly changing this situation. A number of alternative design choices are available with respect to the rectifier, offering a wide range of possible performance enhancements, including improvements to power and power density, efficiency, and transient suppression. These choices present different cost and performance options which may be exploited to meet emerging demands.

5. Conclusion

The evolution of automotive electrical systems is creating a demand for generators providing unprecedented levels of efficiency and power density. This paper overviews emerging opportunities in the use of switching power electronics to enhance the power, efficiency, and transient performance of Lundell alternators. The application of power electronics in conjunction with both the alternator field and armature are described. It is shown that the combination of a foil field winding and improved field control electronics enable substantial improvements in field packing factor and alternator output power. Likewise, the application of switched-mode power electronics with a redesigned armature can provide a range of improvements to power and efficiency. The application and limitation of power electronics to enhance transient performance and load dump suppression are also demonstrated. The design and control methods described here, in conjunction with continuous improvements in power semiconductor devices and passive components, promise future alternators having greatly enhanced performance.

6. Acknowledgement

7. References

[1] G. Henneberger: "*Improvement of the output performance of the claw-pole alternators by additional permanent magnets*," International Conference on Electric Machines (ICEM) '94, Paris, France, 1994.

[2] M. Naidu, M. Boules, and R. Henry: "*A High Efficiency, High Power Generation System for Automobiles*," 1995 IEEE Industry Applications Society Annual Meeting, 1995, pp. 709-716.

[3] F. Liang, J. Miller, and S. Zarei: "*A Control Scheme to Maximize Output Power of a Synchronous Alternator in a Vehicle Electrical Power Generation System*," 1996 IEEE Industry Applications Society Annual Meeting, October 1996, pp. 830-835.

[4] F. Liang, J. Miller, X. Xu: "*A Vehicle Electrical Power Generation System with Improved Output Power and Efficiency*," IEEE Transactions on Industry Applications, Vol. 35, No. 6, Nov./Dec. 1999, pp. 1341-1346.

[5] H. Ishikawa, A. Umeda, and M. Kohmura: "*Development of a More Efficient and Higher Power Generation Technology for Future Electrical Systems*," SAE Paper 2000-01-C081, 2000 International Congress on Transportation Electronics (Convergence 2000), Detroit, MI, Oct. 2000.

[6] A.L. Julian and G. Oriti: "*New Brushless Alternator for Automotive Applications*," 2001 IEEE Industry Applications Society Annual Meeting, Sept./Oct. 2001, pp. 443 – 448.

[7] I. Boldea, S. Scridon, and L. Tutelea: "*BEGA- A biaxial excitation generator for automobiles*," Proceedings of the 7th International OPTIM Conference, Brasov, Romania, May 10-11, 2000.

[8] F.B. Reiter Jr., K. Rajashekara, and R.J. Krefta: "*Salient Pole Generators for Belt-Driven Automotive Alternator Applications*," 2001 IEEE Industry Applications Society Annual Meeting, 2001, pp. 437-442.

[9] S. Scridon, I. Boldea, L. Tutelea, F. Blaabjerg, and A.E. Richie: "*BEGA - A Biaxial Excitation Generator for Automobiles: Comprehensive Characterization and Test Results*," IEEE Transactions on Industry Applications, Vol. 41, No. 4, July-Aug. 2005, pp. 935 – 944.

[10] W.L. Soong and N. Ertugrul: "*Inverterless High-Power Interior Permanent-Magnet Automotive Alternator*," IEEE Transactions on Industry Applications, Vol. 40, No. 4, July-Aug. 2004, pp. 1083 – 1091.

[11] C.-Z. Liaw, D.M. Whaley, W.L. Soong, and N. Ertugrul: "*Investigation of Inverterless Control of Interior Permanent-Magnet Alternators*," IEEE Transactions on Industry Applications, Vol. 42, No. 2, March/April 2006, pp. 536-544.

[12] D.J. Perreault and V. Caliskan: "*Automotive Power Generation and Control*," IEEE Transactions on Power Electronics, Vol. 19, No. 3, May 2004, pp. 618-630.

[13] J.M. Rivas, D.J. Perreault, and T.A. Keim: "*Performance Improvement in Alternators with Switched-Mode Rectifiers*," IEEE Transactions on Energy Conversion, Vol. 19, No. 3, Sept. 2004, pp. 561-568.

[14] S.C. Tang, T.A. Keim, and D.J. Perreault: "*Thermal Modeling of Lundell Alternators*," IEEE Transactions on Energy Conversion, Vol. 20, No. 1, March 2005, pp. 25-36.

[15] L.M. Lorilla, T.A. Keim, J.H. Lang, and D.J. Perreault: "*Topologies for Future Automotive Generators, Part I: Modeling and Analytics*," 2005 Vehicle Power and Propulsion Conference, Chicago, IL, Sept. 2005.

[16] L.M. Lorilla, T.A. Keim, J.H. Lang, and D.J. Perreault: "*Topologies for Future Automotive Generators, Part II: Optimization*," 2005 Vehicle Power and Propulsion Conference (VPP), Chicago, IL, Sept. 2005.

[17] L.M. Lorilla: "*Enhanced Next Generation Alternator*," Ph.D. Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, September, 2005.

[18] L.M. Lorilla, T.A. Keim, J.H. Lang, and D.J. Perreault: "*Foil Field Lundell Alternator with Rotating Power Electronics*," 2006 IEEE Power Electronics Specialists Conference, Jeju, Korea, June 2006, (in press).

[19] *Automotive Electric / Electronic Systems, 2nd Ed.*, Robert Bosch GmbH, Stuttgart, 1999, pp. 304 - 349.

[20] S.C. Tang, S.Y. Hui, H. Chung: "*Coreless Planar Printed-Circuit-Board (PCB) Transformers - A Fundamental Concept for Signal and Energy Transfer*," IEEE Transactions on Power Electronics, Vol. 15, No. 5, Sept. 2000, pp. 931-941.

[21] S.C. Tang, S.Y.R. Hui, and H. Chung: "*Characterization of Coreless Printed Circuit Board (PCB) Transformers*," IEEE Transactions on Power Electronics, Nov. 2000, pp. 746-752.

[22] D.J. Perreault, K.K. Afridi, and I.A. Khan: "*Automotive Applications of Power Electronics*," in The Power Electronics Handbook, M.H. Rashid, Ed., Academic Press, 2001, pp. 791-813.

[23] SAE EMI Standards Committee (1995): "*Immunity to Conducted Transients on Power Leads,*" SAE Standard J1113/11, in "*SAE Handbook,*" Society of Automotive Engineers, Warrendale, PA, 1999.

[24] J.R. Morgan: "*Transients in the Automotive Electrical System,*" 1973 Vehicular Technology Conference, Cleveland, OH, pp.1-10.

[25] S. Yamamoto, O. Ozeki, T. Yamanaka, and H. Kondo: "*Electrical Environmental Characteristics for Automotive Electronic Systems*," IEEE Transactions on Vehicular Technology, Vol. VT-32, No. 2, May 1983, pp. 151-157.

[26] S. Korn: "*Automobiles Need Transient Voltage Suppression,*" Power Conversion and Intelligent Motion, Vol. 15, No. 2, Feb. 1989, pp. 28-31.

[27] T. Elfland, M. Manternach, A. Marshall, and J. Mings: "*The Load Dump,*" 1990 IEEE Workshop on Electronic Applications in Transportation, pp. 73-78.

[28] J.D. Dimech: "*Standardized Automotive Load Dump Testing,*" 1991 IEEE International Symposium on Electromagnetic Compatibility, 1991, pp. 355-359.

[29] P. Le Bars: "*42 V Load Dump Transient and Centralised Active Supression*," Passenger Car Electrical Architecture IEE Seminar, London, UK, 2000, pp. 4/1-4/3.

[30] C.S. Namuduri, B.V. Murty, and M.G. Reynolds: "*Load Dump Transient Control of a 42V Automotive Generator,*" 2004 IEEE Power Electronics Specialists Conference, Aachen, Germany, 2004, pp. 389-394.

[31] Z.J. Shen, S.P. Robb, F.Y. Rob, M. Fuchs, D. Berels, and K. Hampton, "*Load Dump Protection in 42 V Automotive Electrical Distribution Systems,* 2001 IEEE Applied Power Electronics Conference, 2001, pp. 289-295.

[32] V. Caliskan, D.J. Perreault, T.M. Jahns, and J.G. Kassakian: "*Analysis of Three-Phase Rectifiers with Constant-Voltage Loads*," IEEE Transactions on Circuits and Systems – I, Vol. 50, No. 9, Sept. 2003, pp. 1220-1226.

[33] M.W. Smith and K. Owyang: "*Improving the Efficiency of Low Output Voltage Switched-Mode Converters with Synchronous Rectification,*" Proceedings of Powercon7, 1980, pp. H4-1 – H4-13.

[34] G. Stojcic and C. Nguyen: "*MOSFET Synchronous Rectifiers for Isolated, Board-Mounted DC-DC Converters*", International Telecommunications Energy Conference, 2000, pp. 258-266.

[35] S. Rees and U. Ammann, "*A Smart Synchronous Rectifier for 12 V Automobile Alternators,*" 2003 IEEE Power Electronics Specialists Conference, 2003, pp. 1516-1521.

8. Glossary

SMR Switched-Mode Rectifier

PCB Printed Circuit Board