

# A New Design for Automotive Alternators

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## ABSTRACT

This paper introduces a new design for alternator systems that provides dramatic increases in peak and average power output from a conventional Lundell alternator, along with substantial improvements in efficiency. Experimental results demonstrate these capability improvements. Additional performance and functionality improvements of particular value for high-voltage (*e.g.*, 42 V) alternators are also demonstrated. Tight load-dump transient suppression can be achieved using this new design and the alternator system can be used to implement jump charging (the charging of the high-voltage system battery from a low-voltage source). Dual-output extensions of the technique (*e.g.*, 42/14 V) are also introduced. The new technology preserves the simplicity and low cost of conventional alternator designs, and can be implemented within the existing manufacturing infrastructure.

## INTRODUCTION

The electrical power requirements in automobiles have been rising rapidly for many years and are expected to continue to rise (Fig. 1). This trend is driven by the replacement of engine-driven loads with electrically-powered versions, and by the introduction of a wide range of new functionality in vehicles. The continuous increase in power requirements is pushing the limits of conventional automotive power generation and control technology, and is motivating the development of both higher-power and higher-voltage electrical systems and components [1,2].

One consequence of the dramatic rise in electrical power requirements is that the inherent power limitations of the conventional Lundell alternator are rapidly being approached. This is a serious problem due to the large investment in manufacturing infrastructure for this type of alternator and the relatively high cost of other machine types. The move towards dual- and high-voltage electrical systems (*e.g.*, 42 V systems) also poses a challenge for future alternators. Specifically, practical implementation of 42 V electrical systems will require

much tighter transient control (*e.g.*, for load dump) than is presently achieved in the Lundell alternator.

Here we introduce a new design for automotive alternators that utilizes the conventional Lundell machine but incorporates a simple switched mode rectifier along with a special load-matching control technique. The new design allows much higher levels of output power and efficiency to be achieved as compared to conventional designs while retaining low cost and simplicity of structure and control. It is ideal for supplying anticipated new loads, such as electromechanical engine valves, that have a large, speed-dependent power requirement. Furthermore, the approach provides additional performance and functionality improvements that are of central importance for future 42 V systems, including tight transient control and the ability to jump charge the 42 V battery from a low-voltage source.

We first consider the characteristics and limitations of conventional Lundell alternators. A new alternator design incorporating a simple switched-mode rectifier and load matching control technique is then introduced. This leads to an experimental evaluation of the new design, including power output, losses, and efficiency. Next, the implications of the new design for dual- and

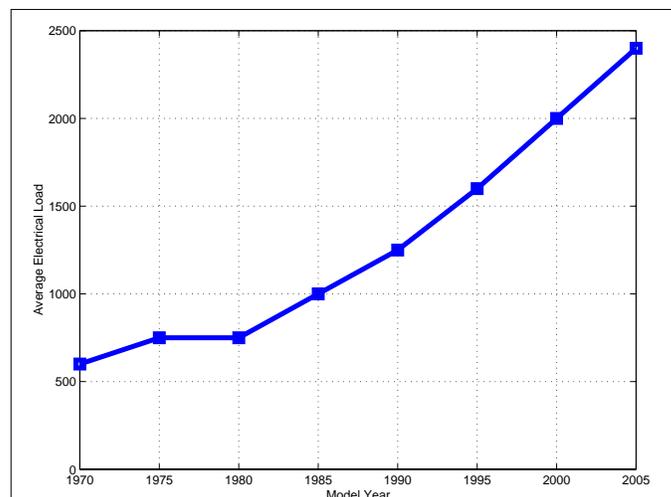


Figure 1: Automobile electrical power requirements [1].

high-voltage alternators are considered, and the transient control and jump-charging features of the new design are validated. We conclude with a summary and overall assessment of the new technology.

## THE LUNDELL ALTERNATOR

The Lundell, or Claw-Pole, alternator is a wound-field synchronous machine in which the rotor comprises a pair of stamped pole pieces (“claw poles”) secured around a cylindrical field winding (Fig. 2). The field winding is driven from the stator via a pair of slip rings. The stator is wound in a three-phase configuration and a full-bridge diode rectifier is traditionally used at the machine output. The alternator system output voltage is controlled by regulating the field current. A relatively long field time constant and a high armature leakage reactance are characteristic of this type of alternator and tend to dominate its electrical performance.

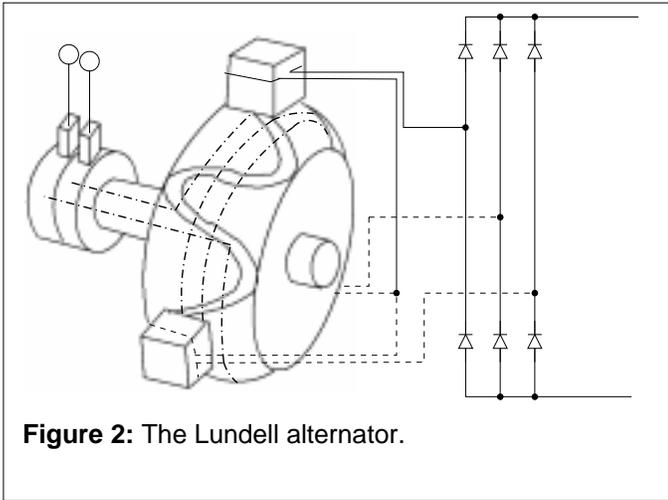


Figure 2: The Lundell alternator.

### A SIMPLE ALTERNATOR ELECTRICAL MODEL

Figure 3 shows a simple electrical model for the conventional Lundell alternator system. The field current  $i_f$  of the machine is determined by the field current regulator which applies a pulse-width modulated voltage across the field winding. Average field current is determined by the field winding resistance and the average voltage applied by the regulator. Changes in field current occur with an  $L/R$  field winding time constant that is typically on the order of 100 ms or more. It is this long time constant that dominates the transient performance of the alternator.

The armature is modeled as a Y-connected set of sinusoidal three-phase back emf voltages  $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$  and leakage inductances  $L_s$ . The electrical frequency  $\omega$  is proportional to the mechanical speed  $\omega_m$  and the number of machine poles. The magnitude of the back emf voltages is proportional to both frequency and field current:

$$V_s = k \omega i_f$$

A diode bridge rectifies the ac machine output into a constant voltage source  $V_o$  representing the battery and associated loads. This simple model captures many of the important characteristics of the Lundell alternator while remaining analytically tractable [3,4].

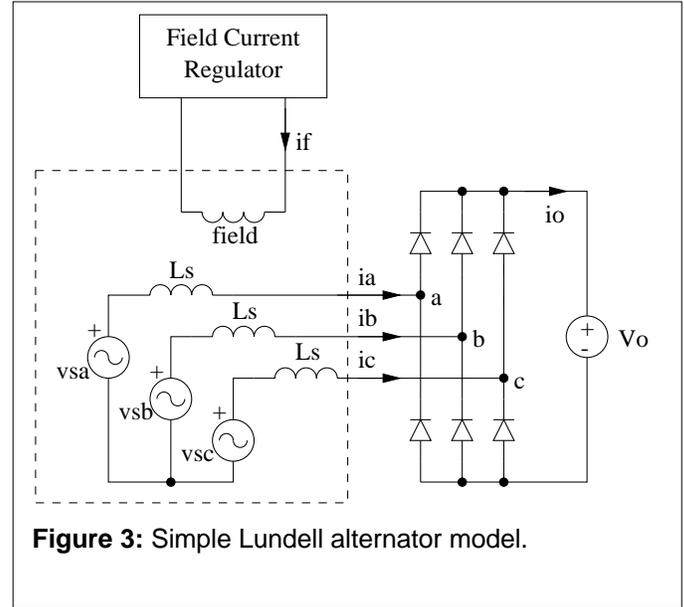
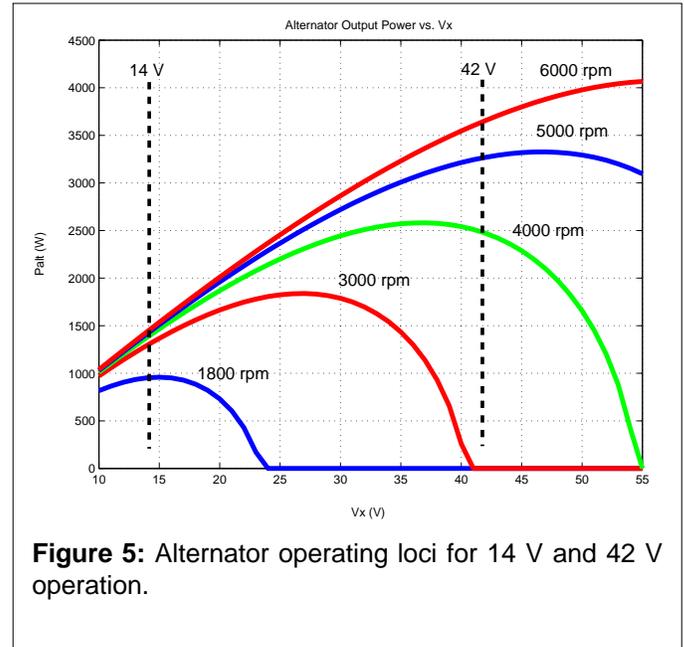
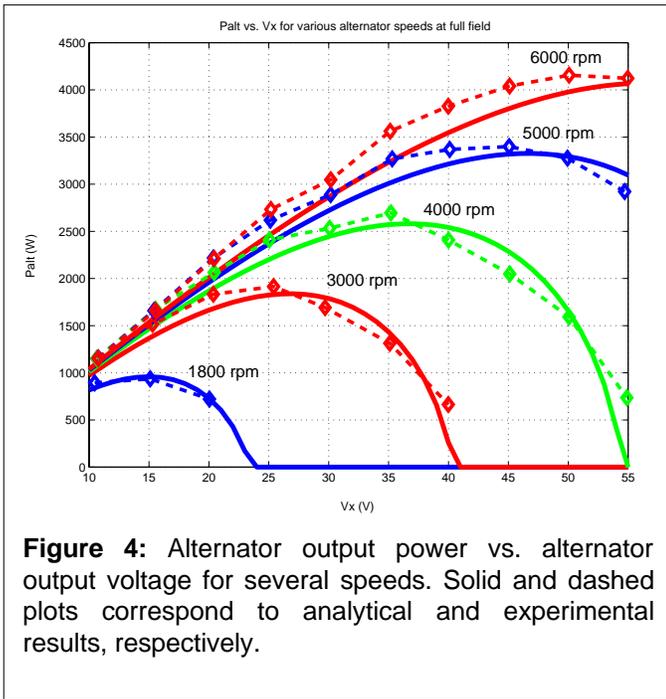


Figure 3: Simple Lundell alternator model.

### ALTERNATOR ELECTRICAL BEHAVIOR

Figure 4 shows the output power versus output voltage of a conventional 14 V alternator at constant (full) field current, parametric in alternator speed. 1800 rpm corresponds to idle speed and 6000 rpm corresponds to cruising speed. The solid lines show analytical predictions of alternator behavior based on the above electrical model, while the dashed lines and markers represent actual data from a Ford alternator. As can be seen, for any given speed there is a substantial variation in output power capability with output voltage. At each speed there is an output voltage above which the output current (and hence output power) become zero. This voltage corresponds to the peak of the line-to-line back emf voltage, above which the diodes in Fig. 3 will not conduct. At each speed there is also a single output voltage at which maximum output power is achieved, and this output voltage is substantially below the line-to-line back emf voltage magnitude.

The observed alternator behavior can be traced to the large armature leakage inductances of the Lundell machine. Significant voltage drops occur across the leakage inductances when current is drawn from the machine, and these drops increase with increasing output current and operating speed. Consequently, the Lundell alternator exhibits heavy load regulation (droop in the output voltage with increasing current). For example,



in a typical automotive alternator, back voltages in excess of 80 V may be necessary to source rated current into a 14 V output at high speed. An appropriate dc-side model for the alternator system is thus a large open-circuit voltage in series with a large speed- and current-dependent output impedance. The output power characteristics of Fig. 4 may thus be understood in terms of the maximum power transfer theorem for a source with output impedance. In short, the high armature leakage inductance results in a large dc-side output impedance, and causes the power deliverable by the alternator at a given speed to be maximized only for a single “load-matched” output voltage.

Consider the operational characteristics of the alternator system described by Fig. 4. The analytical curves, repeated in Fig. 5, represent operation at full field current; power can be reduced below the values shown by reducing the field current. If the alternator is used at the designed output voltage of 14 V, then the output power capability as a function of speed is represented by the intersection of the vertical 14 V locus and curves of Fig. 5. The alternator delivers its maximum idle speed power near the 14 V design voltage. At higher speeds and 14 V output the alternator delivers more power (up to about 1500 W at 6000 rpm), but does not achieve the maximum power possible if voltage were varied because of the way the power-voltage relationship changes with speed. At 42 V output and 6000 rpm, for example, the alternator can deliver over 3500 W. Nevertheless, this alternator could not usually be used in a 42 V system, because at 42 V output and lower speeds the output power drops off rapidly, with no power generation at idle. Thus, the need to generate sufficient power at low speed

means that the peak power capability of the machine is not achieved at higher speeds.

As described above, an alternator with the power vs. voltage curves of Fig. 5 is well suited to an output voltage of 14 V, but is not suitable for a higher voltage such as 42 V. If one wanted to operate at 42 V, one could rewind the stator with three times as many turns of wire having a third the cross-sectional area. As described in [4], this would have the effect of stretching the horizontal axis in Fig. 5 such that all the curves would peak with the same output power at 3 times the voltage (e.g. with the 1800 rpm curve peaking near 42 V). Thus, to first order, the output power capability of an alternator does not depend on the output voltage for which it is designed since the stator may be rewound to provide the same power characteristics vs. speed at any other fixed output voltage.

## THE LOAD MATCHING CONCEPT

As described above, for speeds above idle the conventional Lundell alternator cannot achieve the maximum power possible because the fixed output voltage is not matched to the alternator characteristic at these speeds. Here we introduce a new design and control approach that allows the maximum load-matched power to be attained at all speeds. The new alternator system utilizes both field control and a simple switched-mode rectifier to achieve substantially higher power and performance than conventional systems, particularly at speeds above idle. High power is achieved by utilizing the switched-mode rectifier as a second control handle to properly match the constant-voltage load to the alternator. This is done *without increasing alternator losses or thermal stress*.

Consider the alternator and switched-mode rectifier (SMR) shown in Fig. 6. In this system, a diode bridge is followed by a "boost switch set" comprising a controlled switch (such as a MOSFET)  $Q_x$  and a diode  $D_x$ . The switch  $Q_x$  is turned on and off at high frequency in pulse-width Modulation (PWM) with duty ratio  $d$  (with  $D_x$  turning on and off in a complementary fashion). In an averaged sense, the boost switch set acts as a dc transformer with a turns ratio controlled by the PWM duty ratio  $d$ . That is, with reference to Fig. 6(b), assuming  $i_x$  and  $v_o$  are relatively constant over a PWM cycle, we may calculate the local average value of bridge voltage  $v_x$  as:

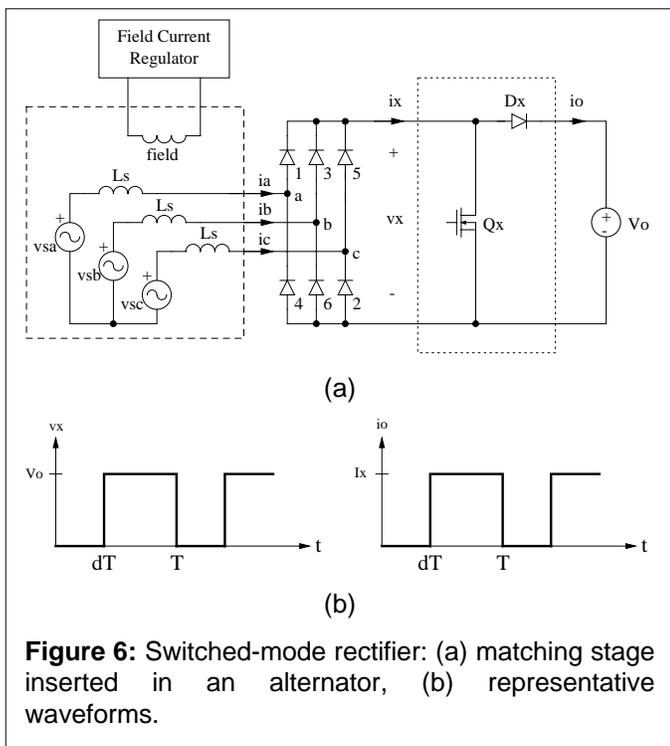
$$\langle v_x \rangle = (1-d)V_o$$

and the local average of the alternator output current  $i_o$  as:

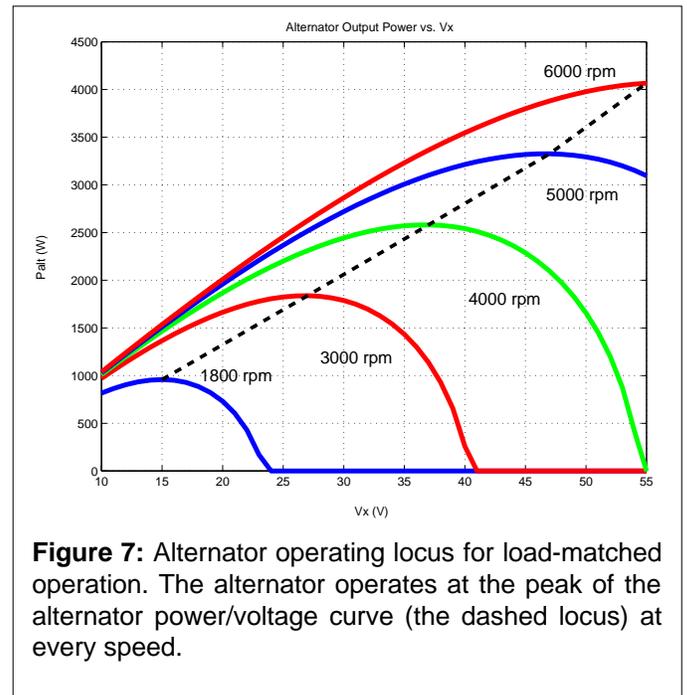
$$\langle i_o \rangle = (1-d)I_x$$

By controlling the duty ratio  $d$ , one can vary the average voltage at the output of the bridge,  $v_x$ , to any value below the output voltage of the alternator system,  $v_o$ .

In this system, the attainable output power of the alternator is a function of the bridge voltage  $v_x$  rather than the output voltage  $v_o$ . By adjusting the duty ratio  $d$ , the alternator can generate up to its maximum power as speed varies, while supplying a constant output voltage,  $v_o$ , (of 42 V, for example). As illustrated in Fig. 7, this operating mode allows much more power to be drawn from the machine at most speeds than is achievable with a diode rectifier supplying a fixed output voltage (Fig. 5).



**Figure 6:** Switched-mode rectifier: (a) matching stage inserted in an alternator, (b) representative waveforms.



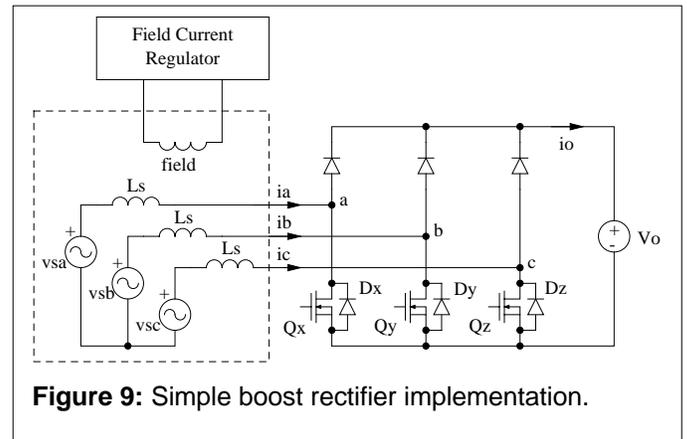
**Figure 7:** Alternator operating locus for load-matched operation. The alternator operates at the peak of the alternator power/voltage curve (the dashed locus) at every speed.

(An important exception to this improvement is at idle, where performance of the new design is identical to that of the conventional design.) What makes the improvement in output power possible is that the switched-mode rectifier provides the necessary controlled voltage transformation to match the constant-voltage load to the alternator as speed varies. This load matching is most simply achieved by appropriately controlling the SMR duty ratio as a function of alternator speed. The output power can be efficiently regulated to values below the achievable maximum with field control. Examining Figs. 4, 5 and 7, we see that while this particular machine is suited for use at 14 V output with a diode rectifier, with the boost-type SMR and load-matching control it is better suited to a higher output voltage (e.g., 42 V, or optimally, 50-55 V). This is because the bridge voltage  $v_x$  must be the same or less than the actual output voltage. Figure 8 shows the output power capability (at full field) for this (theoretical) machine characteristic as a function of alternator speed for different operating conditions. Utilized with a diode rectifier at its optimized voltage of 14 V, the machine is capable of generating approximately 1 kW at idle (1800 rpm alternator / 600 rpm engine), increasing up to approximately 1.5 kW at cruising speed (6000 rpm alternator / 2000 rpm engine). Operating with the new SMR load-matching technique at its (approximately optimal) voltage of 50 V output, the machine is capable of similar performance at idle, but its power capability increases to 4 kW at cruising speed! This improvement in power capability at speeds above idle is not fundamentally due to the change in output voltage, since to first order the machine can be rewound to operate at any voltage with the same power capability. Rather, the improvement results from using the additional degree of control freedom provided by the SMR to achieve load matching across the speed range.

## EXPERIMENTAL EVALUATION

The new design and control algorithms described above have the potential for dramatically increasing the output power capability of automotive alternators. Here we present an experimental evaluation and assessment of this new approach, including an examination of peak and average power capability, losses and efficiency, and manufacturing implications.

The experimental setup incorporates a standard Lundell alternator driven by a computer-controlled variable speed drive. The internal rectifier assembly of the alternator is bypassed, and the machine phases are directly connected to an external switched-mode rectifier of the type illustrated in Fig. 9. For some experiments, the internal alternator field current regulator is bypassed and a specified field current (within alternator specifications) is supplied from an external power supply. In this case an electronic load is used to set the output voltage level.



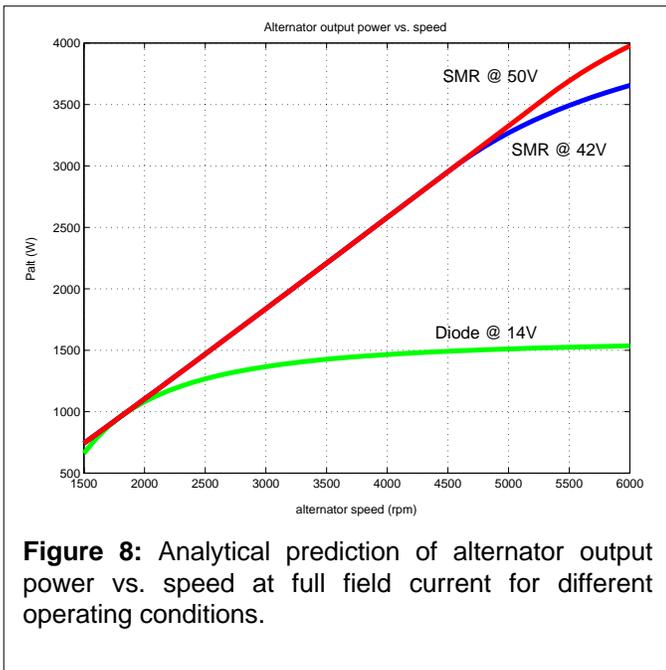
**Figure 9:** Simple boost rectifier implementation.

## OUTPUT POWER CAPABILITY

The alternator and switched-mode rectifier were tested across a range of speeds and output voltages with both diode rectification ( $d = 0$ ) and with the load-matched operating condition illustrated in Fig. 7. As described in [4], load-matched operation is easily achieved by making the complement of the duty ratio ( $d'$ ) proportional to alternator speed and field current:

$$d' = 1 - d = \left( \frac{\sqrt{2}\pi k}{4 V_o} \right) i_f \omega$$

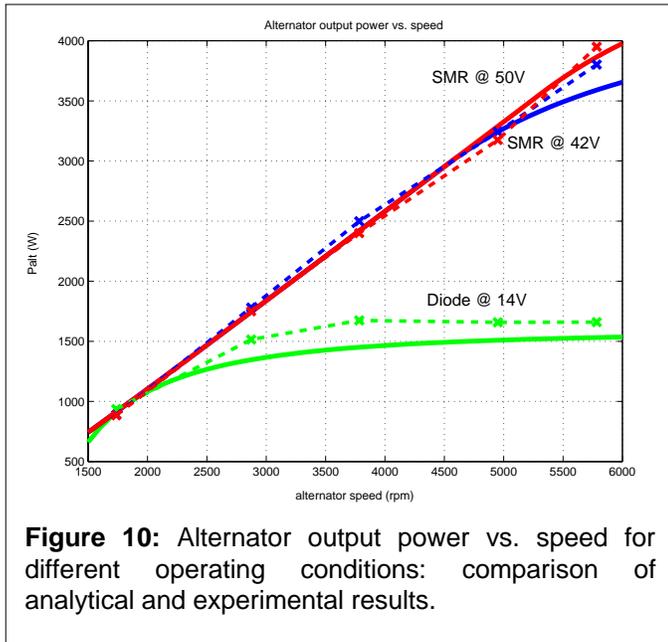
The dashed curves and markers in Fig. 10 show the measured alternator output power at full field for three cases: diode rectification at 14 V and load-matched operation at 42 V and 50 V. (50 V is of interest because it is approximately optimal for the experimental machine's characteristic with boost SMR load matching.) The solid



**Figure 8:** Analytical prediction of alternator output power vs. speed at full field current for different operating conditions.

It should be noted that switched-mode rectifiers are often used to attain high-power-factor conversion in line applications [6,7], and are also sometimes used with alternators [8,9]. In cases where the back voltages are on the same order or lower than the desired output voltage and the machine inductances are relatively small, a boost rectifier (e.g., Fig. 6) can be used to control the output voltage or current while simultaneously drawing power from the machine at high power factor [8,9]. This is *not* the case considered here, however, as an optimized Lundell alternator has back voltages that considerably exceed the desired output voltage, along with relatively large leakage reactances. What distinguishes the approach here is that field control remains the primary means of regulating output voltage; the SMR is used instead as a second control handle to match the load to the machine for high-power, high-efficiency performance.

An alternative SMR topology of particular advantage in this application is illustrated in Fig. 9 [4,7,9]. In this case, the boost stage has been incorporated directly into the bridge, saving a device drop as compared to the circuit of Fig. 6; in other regards the operational characteristics are the same. The three ground-referenced switches  $Q_x$ ,  $Q_y$ , and  $Q_z$  are gated on and off together with duty ratio  $d$ , resulting in the same operating characteristics as the system of Fig. 6. (With a slight degree of additional control the active devices can also be used to provide synchronous rectification, further reducing conduction losses.) This topology is particularly simple and inexpensive to implement, and represents only a slight structural change from the diode rectifier in use today. Finally, it should be noted that other SMR topologies, such as those described in [4,7], can also be used for load matching of alternators.



**Figure 10:** Alternator output power vs. speed for different operating conditions: comparison of analytical and experimental results.

lines are the analytical curves from Fig. 8 and are repeated for the sake of comparison.

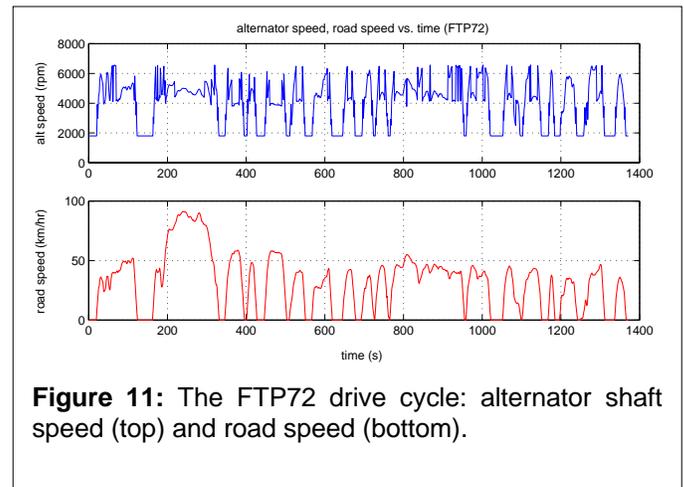
As can be seen from the figure, when operated conventionally (with diode rectification at 14 V), the alternator can generate about 1 kW at idle, increasing up to approximately 1.6 kW at cruising speed (6000 rpm). With the new SMR load-matching design at output voltages of 42 and 50 V the alternator power capability increases nearly linearly from the same value at idle up to about 4 kW at cruising speed. This represents a 250% increase in peak output power capability over the conventional approach, and validates the analytical predictions of the previous section. Again, it should be stressed that the dramatic improvement in output power capability is *not* due to the increase in output voltage, since the alternator can be rewound for the system to perform similarly at an output voltage of 14 V. Instead, it is due to the use of the switched-mode rectifier to achieve load matching over the whole speed range.

### DRIVE CYCLE PERFORMANCE

Substantial increases in alternator output power can be achieved with the new SMR load-matching technique at speeds above idle. For some automotive loads, the increasing power capability with speed is ideal. For example, the power requirement of electromechanical engine valves increases almost linearly with speed, from a small value at idle to a large value (as much as 2 kW) at cruising speed. Other types of high-power loads (*e.g.* heated windscreens) do not have a speed-dependent power requirement, and thus do not fully benefit from the increased power output capability at higher speeds.

To better characterize the average power improvement provided by the load-matching technique, we have examined the alternator power output over an FTP72

drive cycle. This drive cycle, illustrated in Fig. 11, contains idling time, city driving, and a small amount of highway-speed driving. Based on the maximum power vs. speed characteristics of Fig. 4, it was found that the average power capability of a properly-wound load-matched machine over the FTP72 cycle is approximately a factor of 1.9 higher than that of a conventional diode-rectified machine of the same size. In addition, utilizing a conventional 14 V machine (not rewound) with SMR load matching at 42 V also provides an average power capability improvement of about 1.9. These results are summarized in Table I and indicate that an alternator of a given size is capable of delivering almost twice the average power over a drive cycle if the new system design is employed.



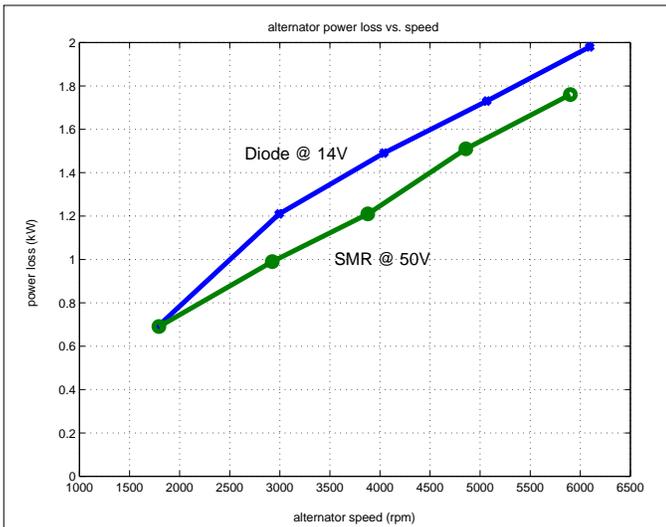
**Figure 11:** The FTP72 drive cycle: alternator shaft speed (top) and road speed (bottom).

**Table I:** Available output power over the FTP72 drive cycle for different rectifier systems. Normalized power is power relative to that with diode rectification at 14 V output.

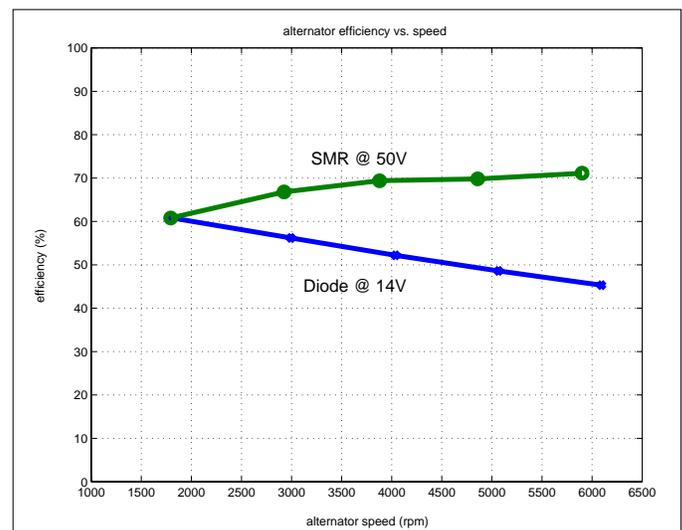
System	Avg. Power	Norm. Power
Diode (14 V)	1.31 kW	1.0
SMR (42 V)	2.51 kW	1.9
SMR (50 V)	2.54 kW	1.9

### LOSSES AND EFFICIENCY

The alternator test stand includes a dynamometer for measuring the mechanical input power to the alternator. The mechanical input power and the electrical output power of the alternator were measured and used to calculate the losses in the system. Shown in Fig. 12 are the measured power losses versus speed for full field operation of the alternator system using a diode rectifier at 14 V and SMR load matching at 50 V. The losses associated with the alternator system using SMR load



**Figure 12:** Experimentally-determined alternator losses at full field across speed for different operating modes.



**Figure 13:** Experimentally-determined alternator efficiency at full field across speed for different operating modes.

matching are less than or equal to the losses with diode rectification over the range of operating speeds. This results primarily from the fact that the new operating technique utilizes the same or lower stator winding current density than the conventional diode rectifier design at all operating speeds. It also suggests that the additional eddy current and hysteresis losses induced by the switching operation of the rectifier are not a significant factor in the design. Furthermore, given the scaling laws for rewinding the alternator and the fact that stator copper losses are the dominant loss element of concern [5], we can infer that this comparison will be valid independent of the alternator output voltages considered. Thus, we can conclude that despite its greatly increased output power capability, the new load-matched operating technique does not incur increased losses, and is actually better from a thermal design point of view.

Since the new alternator design achieves simultaneously both lower losses and increased power output, the efficiency of the system is greatly improved. The experimentally-determined mechanical input to electrical output efficiency at full field is plotted as a function of speed in Fig. 13. With the conventional diode-rectified system the efficiency starts at around 61% at idle and declines to about 45% near cruising speed. In the SMR load-matched system, the efficiency at idle speed also starts near 61% but increases to about 71% at cruising speed. This represents a dramatic improvement in the efficiency of the alternator. This degree of improved efficiency is significant from a fuel economy and environmental standpoint (on the order of a 0.5 mpg improvement for a present-day luxury car [2]), and is likely to become much more important as the average electrical loads in vehicles continue to increase and fuel economy regulations become more stringent.

## MANUFACTURING IMPLICATIONS

The Lundell alternator is a relatively inexpensive machine to manufacture, and there is a large investment in manufacturing infrastructure for it. As a result, it is almost universally used in the automobile industry. However, one consequence of the dramatic rise in automobile electrical power requirements is that the inherent power limitations of the conventional Lundell alternator are rapidly being approached [2]. This is a challenge both in terms of the cost and availability of high-power alternators for future automobiles. One benefit of the new SMR load-matched design is that it can be manufactured within the existing infrastructure. Because the new design extends the average power capability of a given size alternator by nearly a factor of two, it will be valuable for meeting the power demands on future alternators without requiring changes in machine type or replacement of the existing manufacturing infrastructure.

Manufacturing changes for implementing the new load-matched design require only the alternator rectifier and controls to be modified and the number of stator turns (and wire gauge) to be selected appropriately. As illustrated in Fig. 9, the modifications to the rectifier only necessitate the replacement of three diodes with three MOSFETs of roughly equivalent power-handling capability. The fact that the MOSFETs are ground referenced and can be driven from a common gating signal minimizes the cost impact of this modification. The only additional feedback signal required to implement the load-matching control is the alternator speed, which is readily available from the tachometer. (Field current is also valuable in some implementations [4]; this signal is also readily available.) Furthermore, the control implementation for load matching is extremely simple

and inexpensive, and does not represent a significant cost penalty [4]. Thus, the device and control changes associated with the new design are not expected to pose a significant manufacturing challenge.

To modify a conventional 14 V alternator for load-matched operation at 42 V, only the rectifier stage and controls need to be changed, and one could even conceive of manufacturing both 42 V and 14 V systems on the same production line. What may be concluded is that the new load-matched alternator design does not pose major manufacturing challenges. In fact, the design is timely for leveraging the existing manufacturing framework to meet the demands for higher-power and higher-voltage alternators in the automotive industry.

## HIGH- AND DUAL-VOLTAGE SYSTEMS

International efforts are presently underway to develop 42 V and dual 42/14 V electrical systems and components (see [2] for a review). There are a number of critical challenges to realizing practical 42 V and 42/14 V electrical systems, some of which relate directly to the charging system. Here we show how some of the most important challenges can be addressed within the framework of the new alternator design.

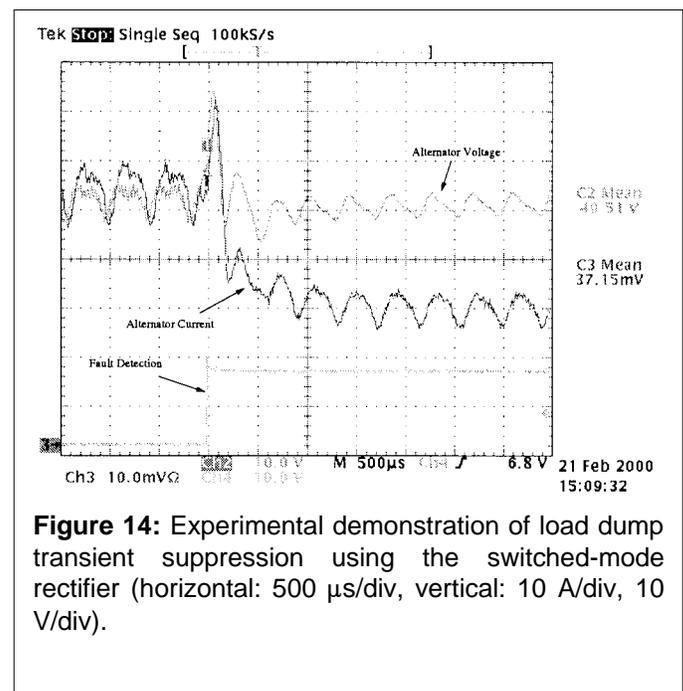
### TRANSIENT SUPPRESSION

As discussed earlier, the Lundell alternator has large stator leakage reactances. To overcome the reactive drops at high alternator current, relatively large machine back emf magnitudes are necessary. A sudden reduction of load on the alternator reduces the reactive drops and results in a large fraction of the back voltage appearing at the output of the alternator before the field current can be reduced. The resulting transient is commonly referred to as a *load dump*. In today's 14 V alternators, the load dump transient can have peak voltages of 80 V and last hundreds of milliseconds. This is a major issue in the design of automotive electrical components. In conventionally-designed 42 V alternators, the transient peak may reach *hundreds* of volts. This is considered to be unacceptable for practical 42 V systems [2], and has posed a significant challenge to their development.

Load dump transient suppression can be easily obtained with the new alternator system through proper control of the switched-mode rectifier. Once a load-dump condition (an overvoltage at the alternator output terminal) is detected, the output voltage transient can be suppressed by control of the SMR while the back emf of the machine is reduced by field control. In the simplest version of the approach, the boost switch(es) of the SMR can be turned on continuously and the field current driven down until the field current and machine currents are at an acceptable level. A more sophisticated version of the approach would adjust the pulse-width modulation of the switched-mode rectifier in concert with the field current

regulator to regulate the output voltage and suppress the transient.

Figure 14 shows the experimental results of a load dump transient test on the experimental SMR-based alternator operated at an output voltage of 50 V. The output current of the system is suddenly reduced from 50 A to 30 A (2.5 kW to 1.5 kW), thus inducing a load dump transient. Using active transient suppression control via the switched-mode rectifier, a transient having a peak overvoltage of 25 V and lasting about 100  $\mu$ s occurs. In a conventional diode rectified system the overvoltage would exceed 100 V and last hundreds of milliseconds. It should be noted that the short, low-energy transient remaining in the new system can be further clamped using a transient voltage suppressor (TVS); this is not practical with the high-energy transients in conventional systems. We thus conclude that the new alternator design can achieve tight transient control. This is of central importance for future 42 V alternators, and is also valuable for 14 V alternators.



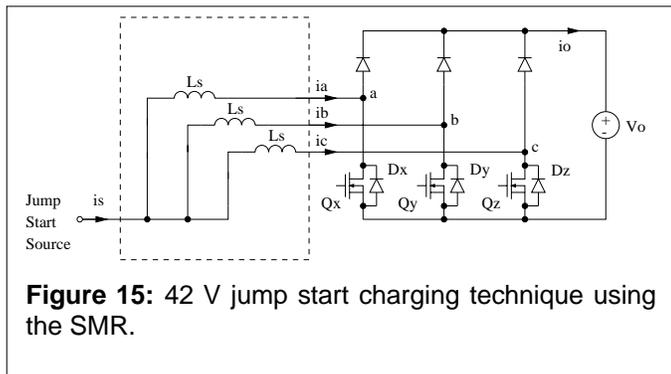
**Figure 14:** Experimental demonstration of load dump transient suppression using the switched-mode rectifier (horizontal: 500  $\mu$ s/div, vertical: 10 A/div, 10 V/div).

### JUMP START CHARGING

The lack of infrastructure for starting a 42 V vehicle with a depleted battery is another challenge to the introduction of 42 V electrical systems. Even long after the introduction of 42 V systems, most vehicles available to provide "jump start" support will have 14 V or 28 V capabilities. As a result, providing a means to charge the 42 V system battery from a 14 V or 28 V source ("jump charging") is widely considered to be a necessity for a practical 42 V vehicle. DC/DC converter-based solutions are usually considered for solving the jump-start problem, but are generally expensive. Here, we show that the

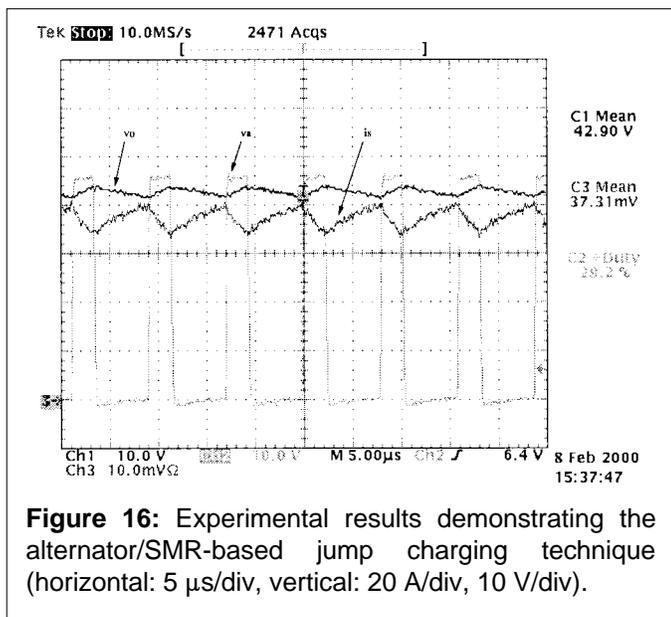
jump-charging function can be implemented at low incremental cost using the new SMR-based alternator.

A method for implementing jump charging with the new alternator system is shown in Fig. 15. In this scheme, the positive terminal of the charging source is connected to the machine neutral while the negative terminal of the charging source is connected to system ground. (Note that the machine back emf is not present since the engine/alternator in the vehicle to be jump charged is not running.) This scheme enables the switched-mode rectifier to be used in conjunction with the alternator machine inductances as a dc/dc converter to charge the high-voltage battery from the low-voltage charging source.



**Figure 15:** 42 V jump start charging technique using the SMR.

Figure 16 presents experimental results from a jump-charging test using a low voltage (14 V) source connected to the machine neutral to deliver energy at the high-voltage alternator output. The results of Fig. 16 show the prototype alternator jump-charging system delivering approximately 920 W at 43 V output from a 14 V source, with an overall efficiency of about 87%. This capability substantially exceeds the minimum necessary in practice, and is achieved without significant additional



**Figure 16:** Experimental results demonstrating the alternator/SMR-based jump charging technique (horizontal: 5  $\mu$ s/div, vertical: 20 A/div, 10 V/div).

cost. We note here that this approach may be used in dual-voltage systems where the charging source may be the low-voltage battery of the same vehicle, or it may be supplied from a different vehicle or source. It may be concluded that this new SMR alternator-based jump-charging approach allows the necessary functionality to be achieved at very little additional system cost.

## DUAL-VOLTAGE APPLICATIONS

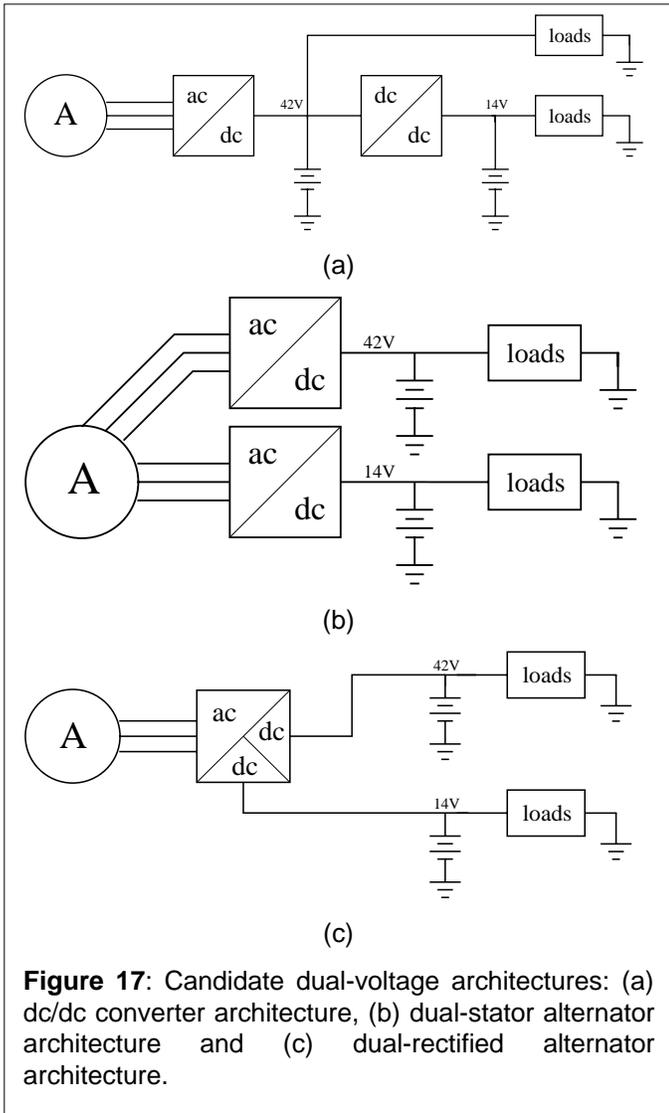
In recent years, dual-voltage electrical systems have received much attention as a means of introducing a higher-voltage supply into vehicles [1,2,10-14]. A dual-voltage electrical system (e.g., 42/14 V) provides the high-voltage supply desirable for many high-power loads, while retaining a low-voltage bus for those components which cannot be immediately redesigned for higher voltage or do not benefit from it. A variety of dual-voltage architectures are presently under consideration. The most widely considered architecture employs a high-voltage alternator and a dc/dc converter (Fig. 17(a)). Dc/dc converter-based systems feature high bandwidth control of the low-voltage bus and jump charging (if a bi-directional converter is used), but tend to suffer from the high cost of dc/dc converters. Other candidate dual-voltage architectures, illustrated in Figs. 17(b) and 17(c), rely on dual-stator alternators or dual-rectified alternators. In this section, we will introduce an extension to SMR load matching for dual-output alternators and highlight the advantageous features of the approach.

### Conventional Dual-Rectified Alternator

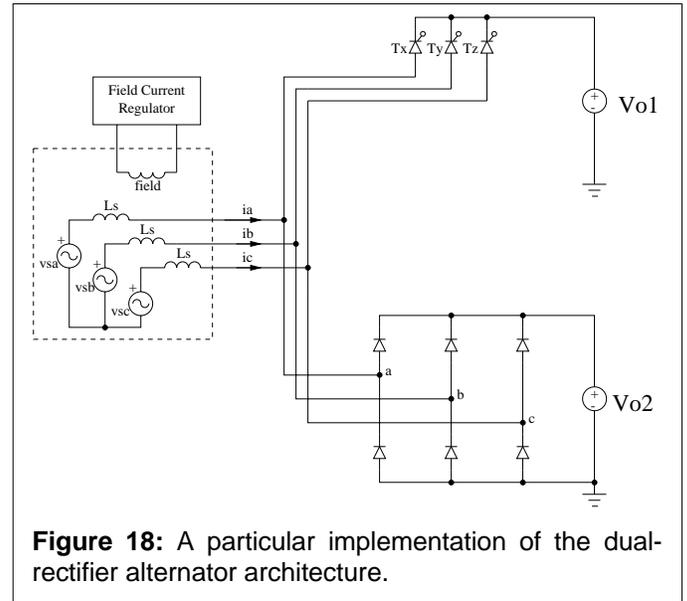
One often-considered dual-output alternator is the dual-rectified alternator illustrated in Fig. 18 [13,15-17]. The voltages  $V_{o1}$  and  $V_{o2}$  represent the low- and high-voltage batteries and loads, respectively (e.g., 14 V and 42 V). In this system, field current control is utilized to regulate the full bridge rectifier output voltage  $V_{o2}$  while phase angle control is used to regulate  $V_{o1}$ . Despite its structural simplicity, a major disadvantage of this system is that the full current of the alternator is chopped back and forth between the two outputs at a low multiple of the alternator electrical frequency. The large, low frequency ripple in the outputs necessitates the use of large filters for both buses, and dramatically increases the cost, size and weight of the rectifier system [17]. Another major disadvantage of the system of Fig. 18 is its low control bandwidth, which is limited by the large field time constant of the machine and the slow phase control of the thyristors. In addition to these shortcomings, the dual-rectified system of Fig. 18 offers no simple mechanism for jump-start charging or load dump transient suppression.

### Dual-Output SMR Load-Matched Alternator

A dual-rectified alternator system utilizing the SMR is shown in Fig. 19. In this system, three MOSFET



**Figure 17:** Candidate dual-voltage architectures: (a) dc/dc converter architecture, (b) dual-stator alternator architecture and (c) dual-rectified alternator architecture.

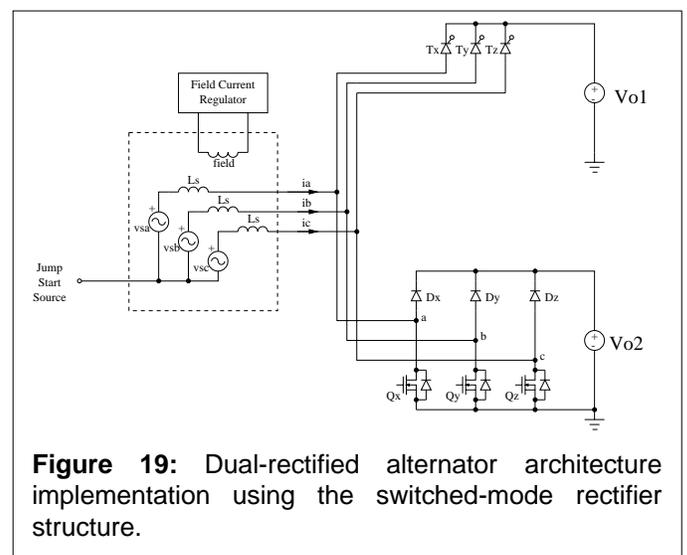


**Figure 18:** A particular implementation of the dual-rectifier alternator architecture.

improved output power capability and efficiency through load matching. By utilizing the three available control handles (MOSFET duty ratio, field current, and thyristor duty ratio), one can regulate the two output voltages and simultaneously meet the load-matching condition of the alternator. Furthermore, load-dump transient protection of both buses and jump-start charging (from the low-voltage battery or an external source) can be obtained using the techniques illustrated in the previous sections. Thus, this dual-voltage SMR-based alternator overcomes the major disadvantages of conventional dual-rectified alternators, and has great potential for inexpensive implementation of dual-voltage automotive electrical systems. Application of the new SMR-based load matching approach may be expected to provide similar benefits in other dual-rectified alternators and in dual-stator alternators.

switches replace the bottom three diodes in the conventional system. This new dual-output alternator offers substantial improvements over the conventional system of Fig. 18. In particular, the introduction of the SMR for the high voltage bus ( $V_{o2}$ ) allows the high frequency modulation of the thyristors that regulate the low voltage bus ( $V_{o1}$ ). One method of control is as follows: at the beginning of an operating cycle all MOSFETs ( $Q_x, Q_y, Q_z$ ) are turned on and stay on for a specified time. When the MOSFETs are turned off a subset of diodes ( $D_x, D_y, D_z$ ) turns on. After a specified diode conduction period, thyristors ( $T_x, T_y, T_z$ ) are fired and machine phase currents are directed through a subset of the thyristors for the remainder of the operating cycle. With this scheme, current is chopped back and forth between the two outputs at the (high) switching frequency. The high chopping frequency results in a dramatic reduction in filter size, weight, and cost. Furthermore, the achievable control bandwidth for regulating the low-voltage bus is greatly improved.

As with the SMR-based single-output alternator, the new dual-rectified SMR alternator can achieve greatly



**Figure 19:** Dual-rectified alternator architecture implementation using the switched-mode rectifier structure.

## CONCLUSION

Automobile electrical power requirements are rising rapidly, and this rise is motivating the development of both higher-power and higher-voltage electrical systems and components. The rising power requirements pose a particular challenge for alternator design because the inherent power limitations of the conventional Lundell alternator are rapidly being approached.

This paper introduced a new design for automotive alternators that incorporates a simple switched-mode rectifier and a special load-matching control technique. The new approach enables dramatic increases in output power and efficiency to be achieved as compared to conventional methods while retaining low cost and preserving the existing manufacturing infrastructure. Experimental results are provided demonstrating factors of 2.5 (peak) and 1.9 (average) increases in output power capability from a conventional Lundell machine using the new design; idle-speed performance remains unchanged. Efficiency improvements of up to 25% at high power are also demonstrated. The new design thus overcomes the power limitations of present-day Lundell alternators, and allows significant improvement in vehicle fuel economy to be achieved.

The new design approach also provides additional functionality and performance improvements of particular importance for high- and dual-voltage electrical systems. Two major challenges to the introduction of 42 V electrical systems are the need to achieve load dump transient control and the need to provide a mechanism for jump charging the high-voltage battery from a low-voltage source. It is shown that both of these functions can be readily implemented with the new alternator design. Experimental results demonstrating both the transient suppression and jump-charging features of the new design are provided. Finally, extensions of the proposed technology to dual-output (e.g. 42/14 V) alternators are described. In addition to providing the benefits that result in single-output alternators (e.g. improved output power and efficiency, transient suppression, and jump charging), it is shown that one can achieve large reductions in filter size and improvements in control bandwidth as compared to conventional implementations.

The developments described here address some of the most pressing challenges in automotive power generation and control. It is hoped that further development and adoption of these techniques will facilitate the rapid introduction of high-power and high-voltage electrical systems in automobiles.

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