Automotive Power Generation and Control

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***Abstract*—This paper describes some new developments in the application of power electronics to automotive power generation and control. A new load-matching technique is introduced that uses a simple switched-mode rectifier to achieve 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 architecture. It is also shown that 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.**

***Index Terms*—Automotive power generation, boost rectifier, dual-output extensions, jump charging, load-dump transient suppression, Lundell alternator, switched-mode rectifier.**

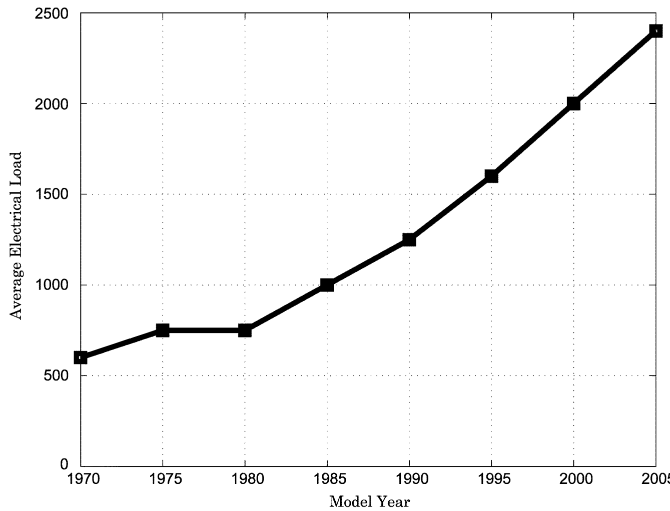

Fig. 1. Automobile electrical power requirements [1].

I. 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 toward 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 automotive electrical 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 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.

II. 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. 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. Alternator system output voltage

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(or current) is controlled by regulating the field current. A relatively long field time constant and a high armature synchronous reactance are characteristic of this type of alternator, and tend to dominate its electrical performance.

A. Simple Alternator Electrical Model

Fig. 2 shows a simple electrical model for a 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.

The armature is modeled as a Y-connected set of sinusoidal three-phase back emf voltages v_{sa}, v_{sb}, and v_{sc} and synchronous inductances L_s. The electrical frequency ω of the back emf voltages is proportional to the alternator mechanical speed ω_m and the number of machine poles p $(\omega = (p/2)\omega_m)$. The magnitude of the back emf voltages is proportional to both frequency and field current

$$V_s = k\omega i_f. \tag{1}$$

A diode bridge rectifies the ac machine outputs into a constant voltage V_o representing the battery and associated loads. As will be seen, this simple model captures many of the important characteristics of alternators while remaining analytically tractable. Other effects, such as stator resistance and mutual coupling, magnetic saturation, waveform harmonic content, etc., can also be incorporated into the model at the expense of simplicity.

B. Alternator Electrical Behavior

To characterize alternator electrical behavior we turn to the simple electrical model of Fig. 2. The constant-voltage load of the rectifier makes the analysis of the system different from the classic case of a rectifier system with a current-source (or inductive) load. Nevertheless, with reasonable approximations the behavior of this system can be described analytically [3], [4]. For example, alternator output power versus operating point can be calculated as

$$P_{\text{out}} = \frac{3V_o}{\pi} \frac{\sqrt{V_s^2 - \left(\frac{2V_o}{\pi}\right)^2}}{\omega L_s} \tag{2}$$

where V_o is the output voltage, V_s is the back emf magnitude, ω is the electrical frequency, and L_s is the armature synchronous inductance.

Fig. 3 shows the calculated output power versus output voltage of a conventional 14-V automotive alternator at constant (full) field current, parameterized by the speed of the 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) becomes zero. This voltage corresponds to the peak of the line-to-line back emf voltage, above which the diodes in Fig. 2 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. This behavior can be traced to the large armature synchronous inductances of the Lundell machine. Significant voltage drops occur across the synchronous 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 when used with a diode rectifier. For example, in a typical automotive alternator, back voltages in excess of 80 V may be needed to source rated current into a 14-V output at high speed. An appropriate dc-side model for the system is a large open circuit voltage in series with a large speed- and current-dependent output impedance. The output power versus output voltage characteristics of Fig. 3 may then be understood in terms of the maximum power transfer theorem for a source with output impedance. In short, the high armature synchronous reactance of the Lundell machine results in a large dc-side output impedance, and necessitates the use of large back-emf voltages to source rated current. This high alternator output impedance results in the power deliverable by the alternator at a given speed to be maximized only at a single "load matched" output voltage.

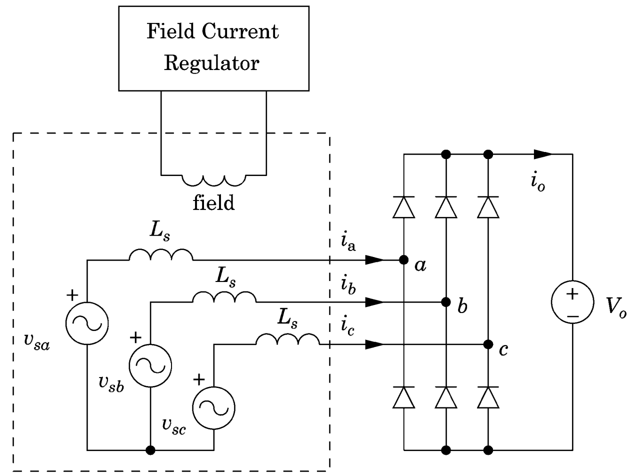

Fig. 2. Simple Lundell alternator model.

Consider the operational characteristics of the automotive alternator system described by Fig. 3. The output power versus output voltage curves of Fig. 3 are calculated for constant (full) field current and parameterized by the speed of the alternator, with 1800 rpm corresponding to idle speed and 6000 rpm corresponding to cruising speed. At any given speed and output voltage, output power can be reduced below the value shown by reducing the field current, which in turn reduces the back-emf voltage and output current. If the alternator is used at the designed output voltage of 14 V, then the output power capability across speed is represented by the vertical 14-V locus intersecting the curves of Fig. 3. 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 across voltage because of the way the voltage-power curve changes with engine 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 for a 42-V system, because at 42-V output and lower speeds the output power drops

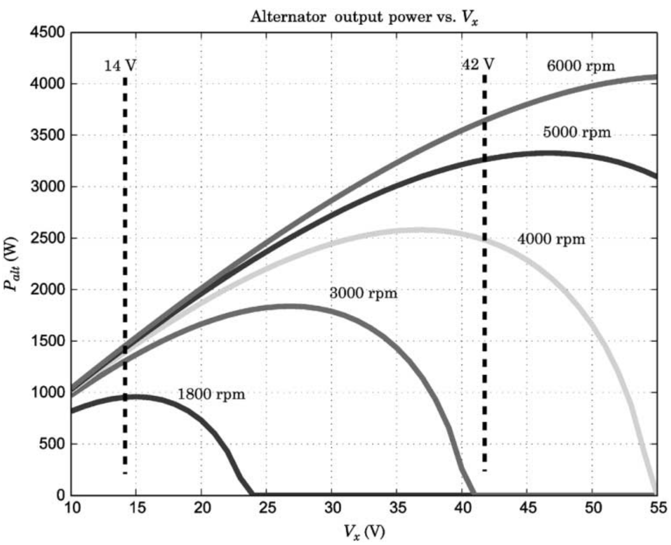

Fig. 3. Alternator operating loci for 14-V and 42-V operation.

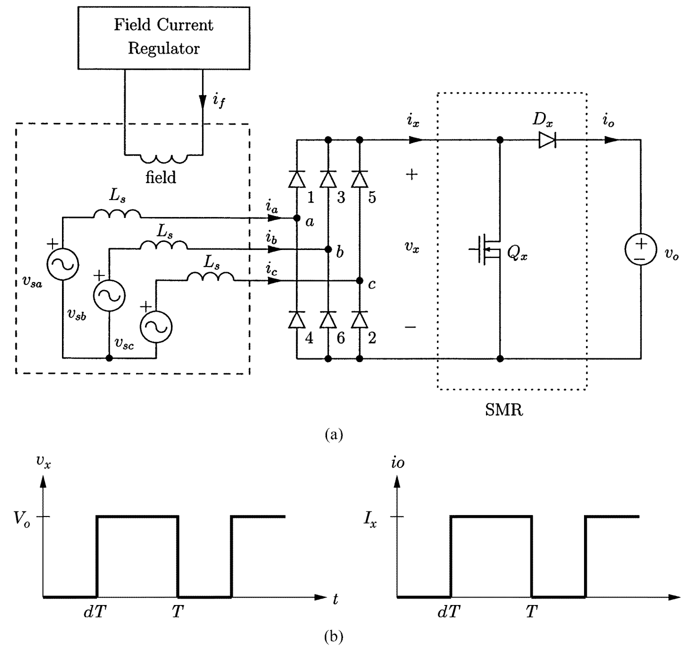

Fig. 4. Switched-mode rectifier: (a) matching stage inserted in an alternator and (b) representative waveforms.

off rapidly, with no power generation at idle speed. Thus, the need to generate sufficient power at the low speed means that the peak power capability of the machine across voltage is not achieved at higher speeds.

As described above, the output power versus output voltage curves of Fig. 3 are well-suited to an output voltage of 14 V, but not suitable for use at 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 about $1/3$ the cross-sectional area. This would have the effect of stretching the horizontal axis in Fig. 3 such that the all the curves would peak with the same output power at 3 times the output voltage (e.g., with the 1800-rpm curve peaking near 42 V)[1] . Thus, to first order, the output power capability of an alternator of a given size does not depend on the output voltage for which it is designed, since the stator may be rewound to provide the same power characteristics versus speed at any other fixed output voltage.

III. Load Matching Concept

We now introduce a new design and control approach for automotive alternators. The new alternator system utilizes both field control and a simple switched-mode rectifier to achieve substantially higher levels of power and performance than are obtained conventionally. 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.

A. SMR Load Matching

Consider the alternator and switched-mode rectifier shown in Fig. 4. 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 a pulse-width modulation (PWM) fashion with duty ratio d. The diode bridge operates in continuous conduction mode (CCM), so that the diode D_x is on when Q_x is off. The PWM operation of Q_x and D_x causes the voltage v_x to be a pulsating waveform with an average value dependent on the output voltage v_o and the duty ratio d. Neglecting device drops, and assuming v_o is relatively constant over a PWM cycle, we may calculate the local average value of v_x as

$$\langle v_x \rangle = (1-d)v_o. \tag{3}$$

Similarly, assuming the diode bridge output current i_x is approximately constant over a switching cycle, we may calculate the local average output current, i_o, of the alternator system as

$$\langle i_o \rangle = (1-d)i_x. \tag{4}$$

In an averaged sense, the boost switch set acts a dc transformer with a turns ratio controlled by the PWM duty ratio d. Because the PWM frequency is much higher than the ac frequency and the machine inductances L_s are relatively large, the alternator machine and diode bridge react to the average value of v_x almost exactly as they would to the output voltage in a conventional diode-rectified alternator. As a result, by controlling the duty ratio d, one has control over the average voltage at the output of the bridge, v_x, to any value below the true output voltage of the alternator system, v_o. The switched-mode rectifier (SMR) can thus be used as an additional control handle to extract much higher levels of performance from the alternator. For example, consider that in the present system, the maximum possible output power of the alternator at a given speed and field current is determined by the average of v_x, not by the output voltage v_o. By adjusting the duty ratio d, the alternator can generate up to its maximum power (across voltage) as speed varies, while supplying a constant output voltage, v_o, (of 50 V, for example). As illustrated in Fig. 5, this operating mode allows much more power to be drawn from the machine

[1]This may be seen by examining (1) and (2). Tripling the number of turns would raise the synchronous inductance by approximately a factor of nine and raise the back emf voltage by a factor of three. Since the output voltage is tripled the output power capability will remain unchanged.

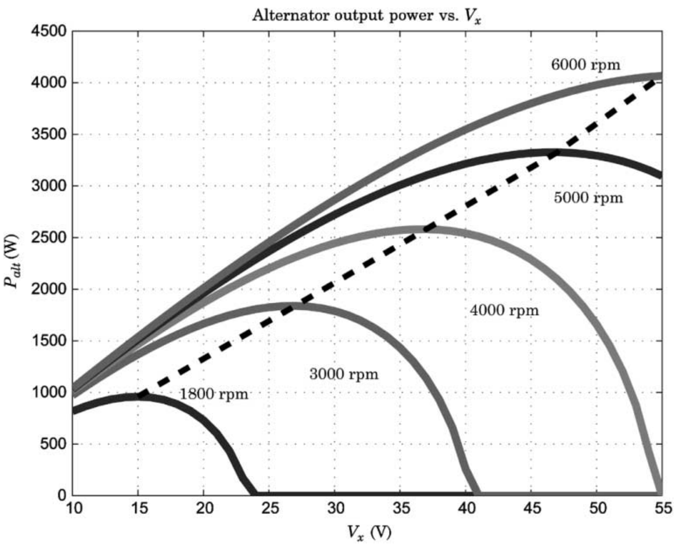

Fig. 5. Alternator operating locus for load-matched operation. The alternator operates at the peak of the alternator power/voltage curve at every speed.

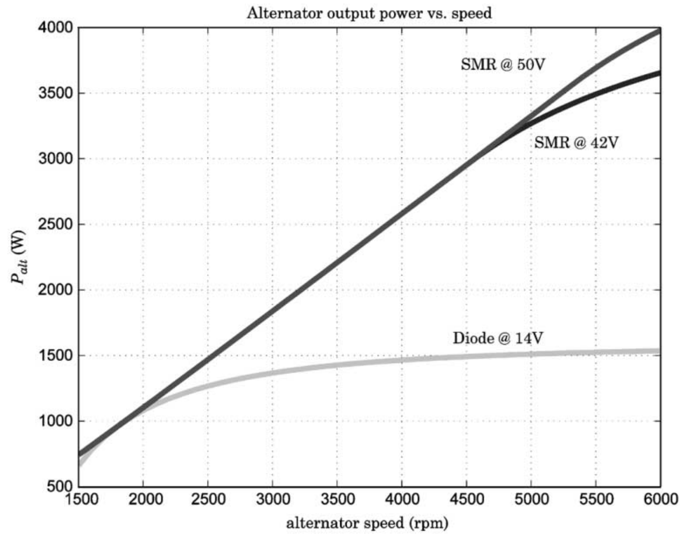

Fig. 6. Analytical prediction of alternator output power versus speed at full field current for different operating conditions.

at most speeds than is achievable with a diode rectifier supplying a fixed output voltage (Fig. 3). What makes this possible is that the switched-mode rectifier provides the necessary controlled voltage transformation to match the constant-voltage load to the alternator. 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 any value below the achievable maximum with field control.

Examining the output power versus output voltage curves of Figs. 3 and 5, we see that while this particular machine is suited for use at 14-V output with a diode rectifier, with the new SMR load-matching technique and the boost-type rectifier of Fig. 4, it is better suited to a higher output voltage (e.g., 50–55 V). Fig. 6 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), increasing up to approximately 1.5 kW at cruising speed (6000 rpm). 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 tremendous improvement in power capability 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 utilizing an additional degree of control freedom to achieve load matching across the speed range.

It should also be pointed out that a machine suitable for diode rectification at 14 V may also be directly employed at 42 V (without rewinding) by utilizing a switched-mode rectifier and the new load-matching technique. This is relevant due to the imminent introduction of 42-V automotive electrical systems which will require 42-V alternators. Operation under this condition is also illustrated in Fig. 6. For much of the speed range, load matching can be achieved at full field, and the maximum load-matched power can be achieved. Above a certain speed, the SMR duty ratio goes to zero and load matching can no longer be maintained. The machine again sees the actual (fixed) output voltage, which results in high-power operation but not as high as could be achieved under load-matched conditions. With the new approach, even present 14-V alternator designs are suitable for high-power operation at 42-V output; only the rectifier stage and controls need to be changed, and one could even conceive of manufacturing both 42-V and 14-V machines on the same production line. Thus, the load-matching approach is timely for meeting the demands of higher power and higher voltage alternators in the automotive industry.

B. Average Power Improvement

With the new SMR load-matching technique, substantial increases in alternator output power can be achieved, particularly at speeds above idle. The curves of Fig. 6 indicate that, using the load-matching technique, the alternator power capability increases almost linearly with speed between idle and cruising speed. This contrasts with the case of a conventional diode-rectified alternator in which the available output power is relatively flat over much of the speed range. For some automotive loads the improved power capability with speed is ideal. For example, the power requirement of electromechanical engine valves (a future automotive electrical load) 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. 7, contains idling time, city driving, and a small amount of highway-speed driving. Based on the maximum power versus speed characteristics of Fig. 6, it was found that the average power capability of a properly wound

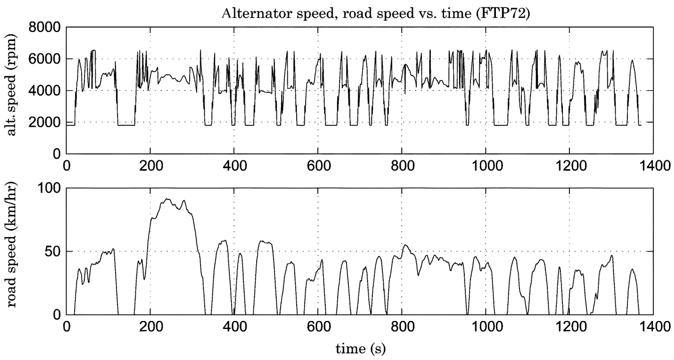

Fig. 7. FTP72 drive cycle: alternator shaft speed (top) and road speed (bottom).

TABLE I
AVAILABLE OUTPUT POWER OVER THE FTP72 DRIVE CYCLE FOR DIFFERENT RECTIFIER SYSTEMS

System	Average Power	Normalized Power
Diode rectified (14V)	1.31 kW	1.0
SMR matched (42V)	2.51 kW	1.9
SMR matched (50V)	2.54 kW	1.9

load-matched machine is approximately a factor of 1.9 higher than that of a conventional diode-rectified machine of the same size. Also, 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, summarized in Table I, indicate that a given size machine is capable of almost twice the average power output capability over a drive cycle when the new SMR load-matching technique is employed! It also means that the alternator size required to achieve a given output power requirement is roughly halved using the new technique; this represents a substantial savings in alternator size, mass, and cost.

C. Other SMR Structures

The switched-mode rectifier of Fig. 4 has been used in both continuous and discontinuous conduction modes in other contexts (see [5]–[7] for example). As applied here, this simple boost-type rectifier allows the output power capability of the alternator system to be increased by properly matching the fixed output voltage to that required by the alternator for maximum output power.

Many other simple switched-mode rectifiers can also be utilized to achieve the desired load-matching effect (Fig. 8). Note that while all of these rectifier topologies have been proposed previously (e.g., [7]), they have not been employed in the manner described here.

One boost-type switched-mode rectifier that is of particular advantage in automotive applications is shown in Fig. 8(e). In this switched-mode rectifier, the boost stage has been incorporated into the bridge, saving a device drop as compared to the circuit of Fig. 4. The operation of the rectifier in Fig. 8(e) is very similar to the operation of a standard three-phase rectifier. When a particular phase (for example, phase a) is carrying a positive current, the MOSFET and the diode of that leg form a boost switch set and are utilized in a similar manner to the MOSFET/diode combination in Fig. 4. The remaining legs (phases b and c in our example) carry the negative (return) current back to the machine. To simplify the control strategy, all three ground referenced switches Q_x, Q_y, and Q_z are gated on and off together with duty ratio d. 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 only represents a slight structural change from the diode rectifier in use today. While fundamental design and control techniques we describe here work with a wide range of SMR topologies, for simplicity we will focus on the topology of Fig. 8(e) for the remainder of the paper.

D. Alternator Control

The static control goal for the alternator system is to regulate the output voltage for load requirements from zero up to the maximum achievable power. In the proposed approach this is accomplished by properly selecting the alternator field current (or field regulator duty ratio) and SMR duty ratio as a function of output voltage and alternator speed. A unique control command exists which will produce maximum power at a given speed (i.e., full field current at the proper SMR duty ratio for load matching). For many operating points (when less than full power is required) there are multiple control combinations which will yield the desired output voltage. As a result, there is some freedom to achieve objectives in addition to increased output power capability (e.g., maximizing efficiency) in selecting a control law. The SMR duty ratio control law for achieving load matching with a boost converter is

$$1 - d = \left(\frac{\sqrt{2}\pi k}{4V_o}\right)\omega\, i_f \tag{5}$$

where i_f is the field current, ω is the alternator angular speed, k is the machine back-emf constant, and V_o is the output voltage. To achieve load matching, one thus controls the complement of the SMR duty ratio to be proportional to the field current and the alternator speed. In general, the alternator angular speed is available (from the tachometer) while the field current is easily measurable at the field regulator if desired. (Note that unlike other machine control techniques, such as field-oriented control, there is no need for position or stator current information and the control law can be implemented with simple, inexpensive circuitry.)

The simplest control approach is to use conventional field control to regulate the output voltage and select the SMR duty ratio as

$$1 - d = \left(\frac{\sqrt{2}\pi k i_{f,\max}}{4V_o}\right)\omega = C\omega \tag{6}$$

where $i_{f,\max}$ is the full field current and C is a net proportionality constant between duty ratio complement and angular speed. With this simple control law, the output voltage can be controlled from zero power up to the maximum load-matched power across speed.

A more sophisticated control approach is to again use field control to regulate the output voltage, but to set the SMR duty ratio (or its complement) using the actual instantaneous field current (which can be easily measured at the field regulator) as

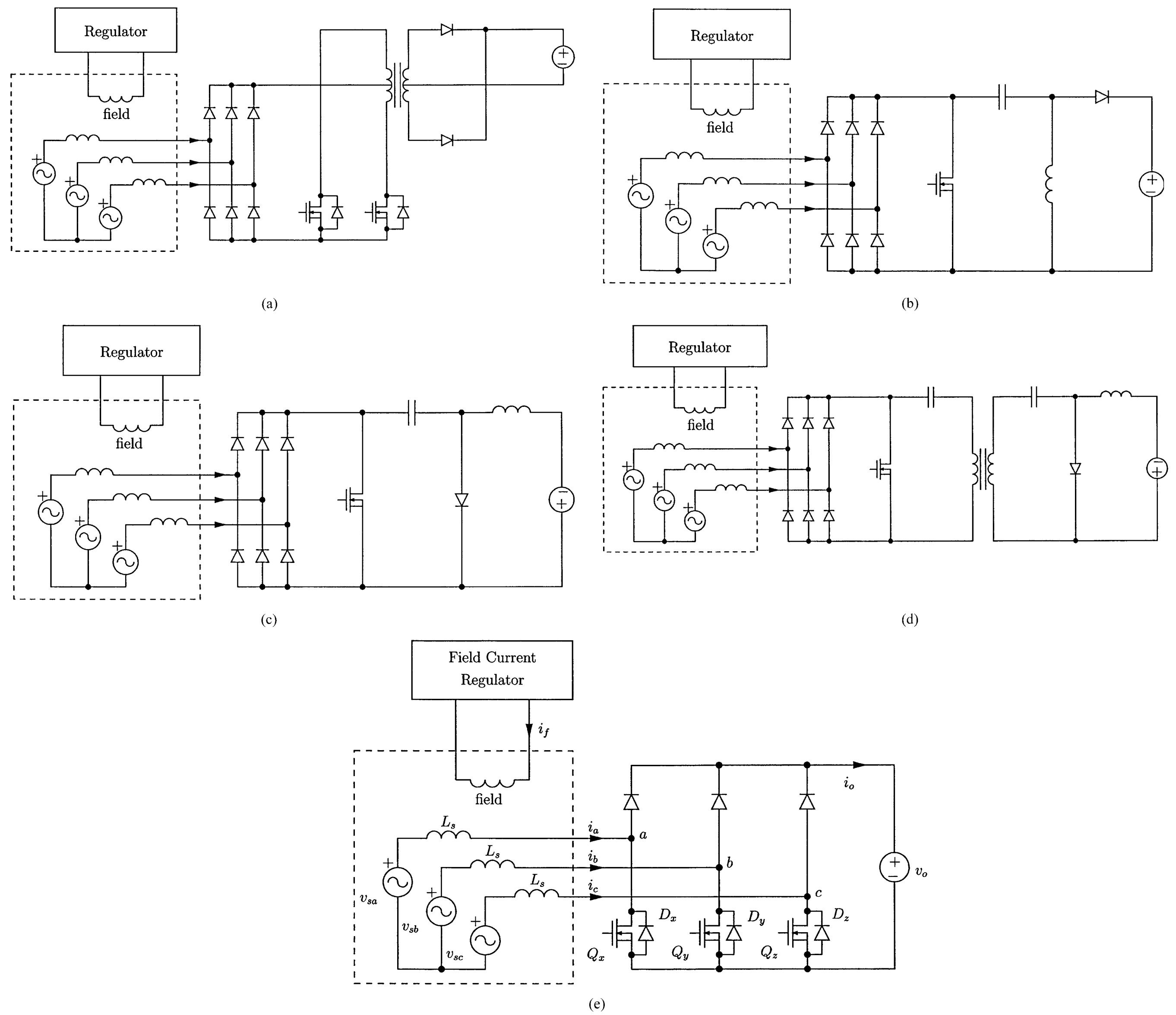

Fig. 8. Various switched-mode rectifier implementations: (a) push-pull, (b) SEPIC and (c) Cuk, (d) isolated Cuk, and (e) boost semi-bridge.

per (5). In addition to allowing the output voltage to be properly regulated over the full power range, this control law also ensures that load matching is achieved at all operating points.

In conventional automotive alternators, the conduction losses in the stator windings and the semiconductor devices represent a dominant portion of the alternator losses. In this case, if one wants to maximize the alternator efficiency over all load conditions, one should choose the alternator control law such that the alternator system always generates the needed output power utilizing the lowest stator and device currents possible. This is done by controlling the SMR so that the alternator always sees the largest effective voltage v_x that can be used for that level of output power. For a boost-type SMR, this is done by ensuring that the lowest duty ratio possible (for the required level of output power) is always used. One simple controller structure which achieves this is illustrated in Fig. 9.

In Fig. 9, the conventional control mechanism is formed by the compensator G (usually a lag controller) and the field current regulator. Given an output power demand, the average value of the field current is adjusted to maintain the average value of the output voltage v_o equal to the reference voltage $V_{o,\mathrm{ref}}$. If the required power level is low enough, field current regulation is sufficient in delivering power to the load. In this mode of operation the compensator output x and the limiter output S_f are both less than one. As a result, the input to the controlled limiter $x' < 0$ and therefore the duty ratio of the MOSFETs is 0. With field current regulation at a zero duty ratio, the controller operates in the same manner as today's automotive regulator. If the power demand is further increased at a given alternator speed, field current alone will no longer be sufficient to support the output power. At this point, the compensator output x will increase beyond 1 which will force the field current regulator to supply maximum current. With the field current at its maximum and the compensator output x increasing beyond 1, the input to the controlled limiter x' will increase from 0. The increase of signal x' from zero will result in an appropriate control signal V_d to generate a duty ratio for the MOSFETs to provide the demanded output power. The duty ratio will be increased by an

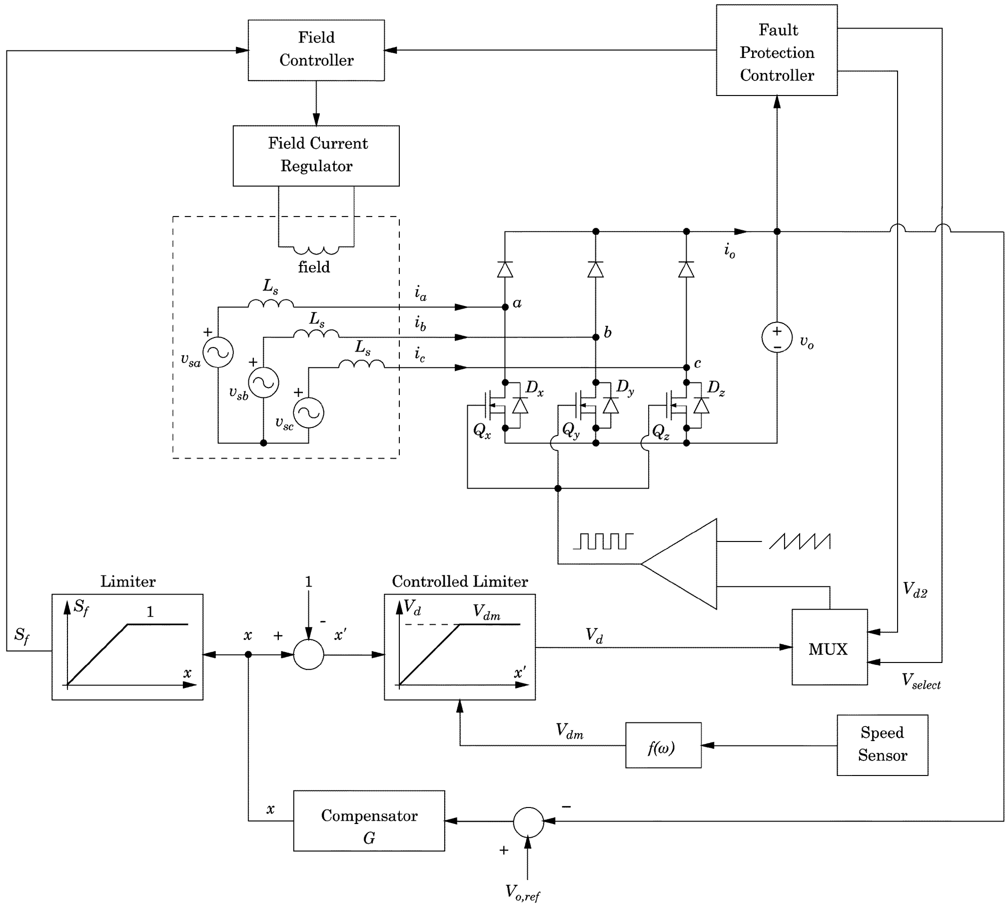

Fig. 9. Alternator with switched-mode rectifier and efficiency optimizing controller.

amount necessary to support the output power or to reach the load-matched condition, whichever is lower. The duty ratio corresponding to the load-matched condition is set by $V_{\rm dm}$ on the controlled limiter and is derived from a speed sensor using the function $f(\omega)$ (6). The fault protection controller can be implemented in a variety of ways to provide immunity from system transients. In its simplest form, it can be a crowbar and reset trigger on the devices. For example, in the event of a load-dump transient, the MOSFETs can be turned on and field field current turned off to force the phase currents to decay to zero.

A variety of other control laws also exist. In general, the field current (or field regulator duty ratio) and SMR duty ratio are jointly selected as a function of output voltage and speed to regulate the output voltage, achieve high-power operation (when needed), and achieve other goals at partial load (such as maximizing efficiency). What all such controllers share is the regulation of the SMR for the load-matched condition when maximum output power is needed.

IV. Experimental Demonstration of Load Matching

In this section, we provide experimental results of the load matching technique that support the analytical results presented in the earlier sections.

A. Description of Experimental Setup

The experimental setup consists of a standard Lundell automotive alternator (Ford 130 A) driven by a computer-controlled variable speed drive. Also included in the test stand is a dynamometer which is utilized to measure the mechanical power into the alternator. For the purposes of our experiments, the internal alternator field current regulator is disabled and a constant field current is supplied to the alternator by using an external power supply ($i_{f,\max} = 3.6$ A). The full-bridge three-phase rectifier that is a part of the original alternator assembly is disabled in order to connect the phases directly to the SMR. The alternator is loaded by the parallel combination of an electronic load (HP6050A) and a resistor bank. The electronic load is also utilized to set the output voltage level.

The switched-mode rectifier used in the prototype system is of the topology illustrated in Fig. 8(e). The diodes are each implemented with an IXYS DSS2X41-01A Schottky diode module (comprising 2 paralleled diodes each nominally rated at 40 A and 100 V). The active switches are IXYS IXFN230N10 power MOSFETs (6 mΩ nominal, 100 V). Tightly coupled across the output of the switched-mode rectifier (output to ground) are six paralleled ITW Paktron 106K100CS4 multilayer polymer film capacitors (10 μF, 100 V). These capacitors serve to suppress the high-frequency switching currents developed at the output of the boost rectifier. The

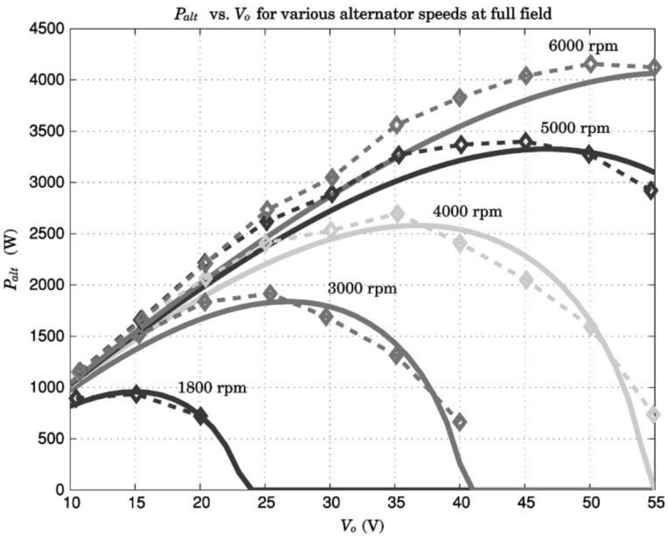

Fig. 10. Alternator output power versus alternator output voltage for several speeds. Solid and dashed plots correspond to analytical and experimental results, respectively.

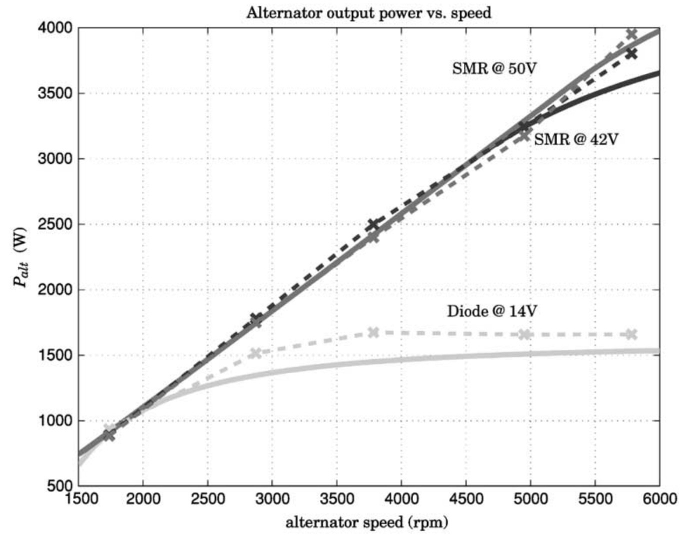

Fig. 11. Alternator output power versus speed for different operating conditions: comparison of analytical and experimental results.

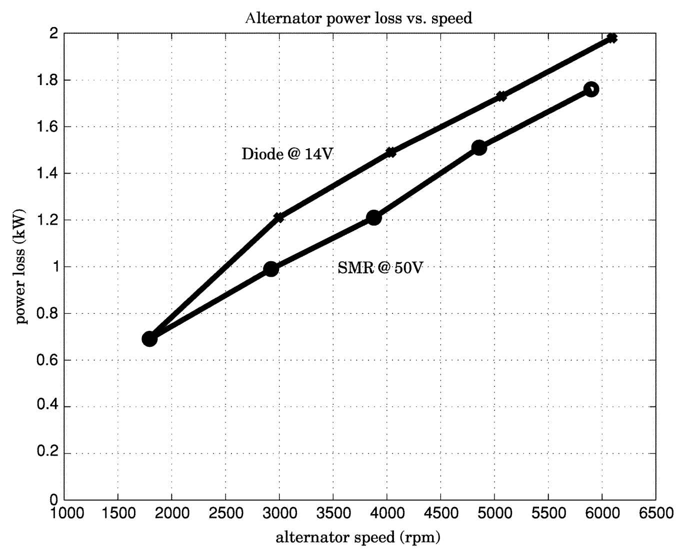

Fig. 12. Experimentally-determined alternator losses at full field across speed for different operating modes. The SMR load-matching technique (at its optimal output voltage) yields the same or lower losses than diode rectification at its optimal output voltage.

power MOSFETs are each driven through a resistor/diode network by a UC2710 gate driver. The devices are modulated together with a specified duty ratio at a switching frequency of 100 kHz using a UC3823A pulse-width modulation IC. Power and control interconnects are implemented on a printed circuit board, with the power devices also attached to a heat sink (IMI Marston 96CN02500A200, 0.29 °C/W with free convection). This design was found to be robust and suitable for bench-top validation of the proposed approach.

B. Experimental Results Versus Speed

To verify the analytical results presented Section II, a number of tests were performed at several alternator speeds. At a given constant speed, the alternator system output voltage, V_o, was varied and the resulting output power recorded in order to validate the analytical results shown in Fig. 3. The results of these tests are summarized in Fig. 10 where the dashed curves represent the experimental results and the solid lines are the analytical results from Fig. 3. As can be seen from this figure, there is good agreement between the measurements and the analytical results. The agreement between the experimental and analytical results show the validity of our simplified analytical models despite the approximations that were utilized in their derivation.

To validate the analytical results of Fig. 6, the alternator and switched-mode rectifier were utilized across a range of speeds and output voltages with both diode rectification $(d = 0)$ and under the load-matched condition of (5). The dashed curves in Fig. 11 shows the measured maximum power output of the alternator system for three cases: diode rectification at 14 V and switched-mode rectification at 42 V and 50 V. The solid lines in the figure are identical to the curves of Fig. 6 and are repeated for the sake of comparison. Once again, the experimental results validate the analytical results derived earlier in the report. Clearly, tremendous increases in output power are achievable across speed using the new SMR load-matching technique.

C. Power Losses

As described in earlier in this section, the experimental test stand includes a dynamometer which allowed the measurement of mechanical input power to the alternator system. Using the measurements of electrical output power and mechanical input power, one can plot the power loss in the alternator system. Shown in Fig. 12 are the measured power losses versus speed at full field for the alternator system utilizing a diode rectifier at 14 V and a switched-mode rectifier at 50 V. (Again, these voltages represent the optimal output voltages of the two operating modes for the alternator used in the experiments. Similar results are obtainable in each mode at other output voltages merely by rewinding the machine stator appropriately.) This figure shows that the power losses associated with the alternator system using switched-mode rectifier load-matching are less than or equal to the ones with diode rectification over the

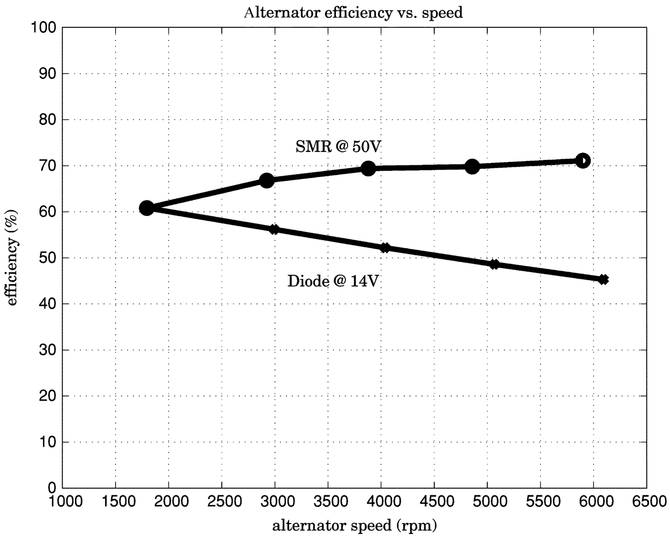

Fig. 13. Experimentally-determined alternator efficiency at full field across speed for different operating modes.

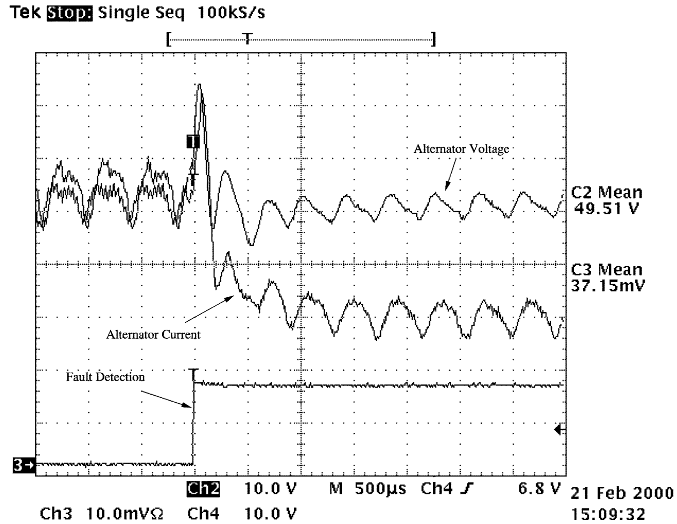

Fig. 14. Experimental demonstration of load dump transient suppression using the switched-mode rectifier (horizontal: 500 μs/div; vertical: 10 A/div, 10 V/div).

range of operating speeds. This results primarily from the fact that the new operating technique utilizes the same (or lower) stator and device currents than the conventional diode rectifier approach at all operating speeds. Thus, we can conclude that the proposed load-matched operating technique is actually advantageous from a thermal design point of view.

D. *Efficiency Improvement*

Since the proposed system achieves both lower losses and increased power output, the efficiency of the overall system is improved tremendously. The experimentally-measured mechanical input to electrical output efficiency at full-field is plotted in Fig. 13 for the alternator system using conventional diode rectification at 14 V and SMR load-matching at 50 V. With the conventional diode rectified system, the efficiency starts at around 61% at idle speed of around 1800 rpm and declines to about 45% near the cruising speed of 6000 rpm. With the switched-mode rectified system, the efficiency also starts near 61% at idle speed but *increases* to about 71% at cruising speed. This represents a dramatic improvement in the efficiency of the alternator. The improved efficiency provided by the new SMR load-matching is valuable from a fuel economy and environmental point of view and will become even more so as the average electrical loads in vehicles continue to increase.

V. Load Dump Protection

As discussed in earlier sections, the Lundell alternator has large stator synchronous reactances which in turn have large reactive voltage drops during normal operation. As a result, very large machine back-emf voltage magnitudes are needed to source the rated machine current. If a large current consuming load is suddenly removed from the alternator output terminals, the reactive drops become smaller and a larger fraction of the back-emf voltage appears at the alternator output while the field current is reduced by the regulator. The resulting transient is commonly referred to as a *load dump* transient. In today's 14 V alternators, the load dump transient can have peak voltages of 80 V and last hundreds of milliseconds. In 42-V machines, the transient peak may reach hundreds of volts. This is unlikely to be acceptable in practice, motivating the search for effective, inexpensive transient suppression techniques. In this section, it is shown that load dump transient suppression can be achieved through proper utilization of the switched-mode rectifier.

A. *Use of SMR for Load Dump Protection*

Load dump transient fault protection can easily be implemented within the framework of the new system. A fault protection controller is utilized to detect and manage load dump transients in the system through appropriate control of the field current and SMR duty ratio. When a significant overvoltage is detected at the output terminals of the alternator system, the fault protection controller acts to decrease the field current and adjust the SMR duty ratio to limit the load dump transient at the alternator output.

In the simplest version of the approach, the boost switch(es) of the SMR can be turned on continuously (crowbar operation) and the field current regulator can be adjusted for deexcitation of the field 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.

B. *Experimental Results*

Fig. 14 shows the experimental results of a load dump transient test on an SMR-based system with 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 μs 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 in the new system can be further clamped using a transient voltage suppressor (TVS). This is much less practical with the long, high-voltage transients in conventional systems. It may be concluded that rapid transient suppression can be achieved within the framework of the new system. This is valuable in present-day 14-V alternators, and of central importance for future high-voltage alternator systems.

VI. Jump Start Technique

There is a desire to introduce 42 V and dual $42/14$-V automotive electrical systems in the near future. Providing jump start capability for 42-V systems from 14 V or 28 V is a major deployment issue. To solve the jump-start problem, expensive dc/dc converter solutions are usually considered. In this section, we show that jump start can be implemented using the alternator and the switched mode rectifier. It is shown that the low voltage charging source connected between the machine neutral and system ground can be used to charge the 42-V bus by utilizing the alternator synchronous inductances and SMR as a dc/dc converter.

A. Motivation

A dual- or high-voltage system having a starter motor coupled to a high-voltage bus requires a charged high-voltage battery to start. In cases where the high-voltage battery is not fully charged or is depleted, it is desirable to be able to charge the depleted high- voltage battery from a low-voltage source (such as a 14-V or 28-V system) in order to provide jump-start capability for dual/high voltage systems. In an automobile which includes only a single high-voltage system, one may desire to transfer energy from a low-voltage power source, battery or alternator of a different vehicle to the high-voltage system. In a dual-voltage system, one may desire to transfer energy from the low-voltage battery of the dual-voltage system to the high voltage battery of the dual-voltage system or from the low-voltage battery or alternator of a different vehicle to the high voltage battery of the dual-voltage system.

B. Jump-Charging Implementation

Here we show that the alternator and switched-mode rectifier can be used to implement jump charging in dual/high voltage systems (e.g., 42-V or $42/14$-V systems.) One possible way to implement jump-charging within the framework of 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 voltage sources are 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 battery at the output of the switched-mode rectifier from the charging source. This represents an important improvement in the alternator system functionality over what is achieved in conventional systems.

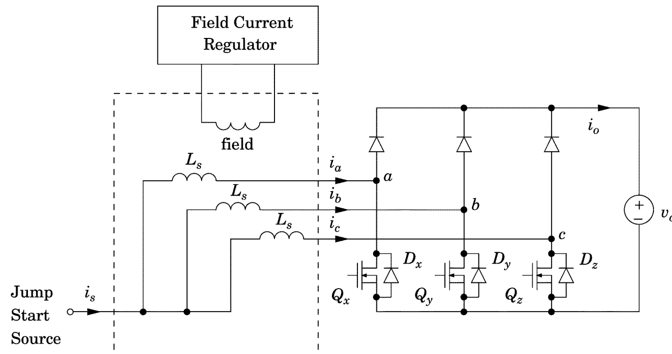

Fig. 15. 42-V jump start charging technique using the SMR.

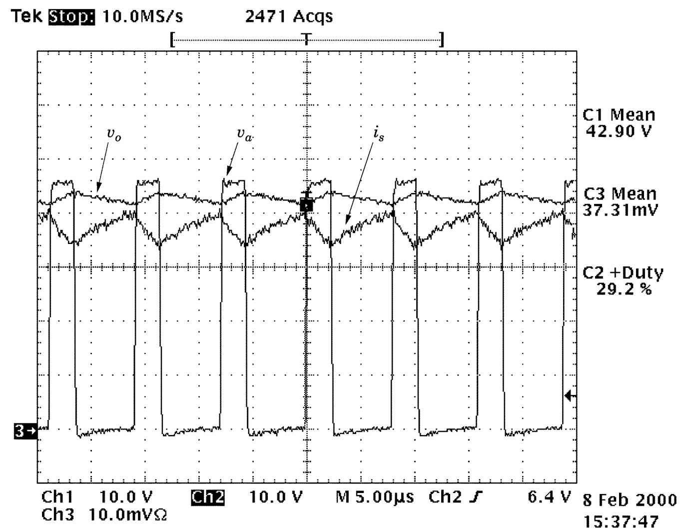

Fig. 16. Experimental results demonstrating the alternator/SMR-based jump charging technique. A 14-V jump charging source is utilized. The illustrated results represent a delivered output power of about 920 W at 87% efficiency (horizontal: 5 μs/div; vertical: 20 A/div, 10 V/div).

C. Experimental Results

Fig. 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 a 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 at little incremental system cost.

VII. 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], [8]–[12]. 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

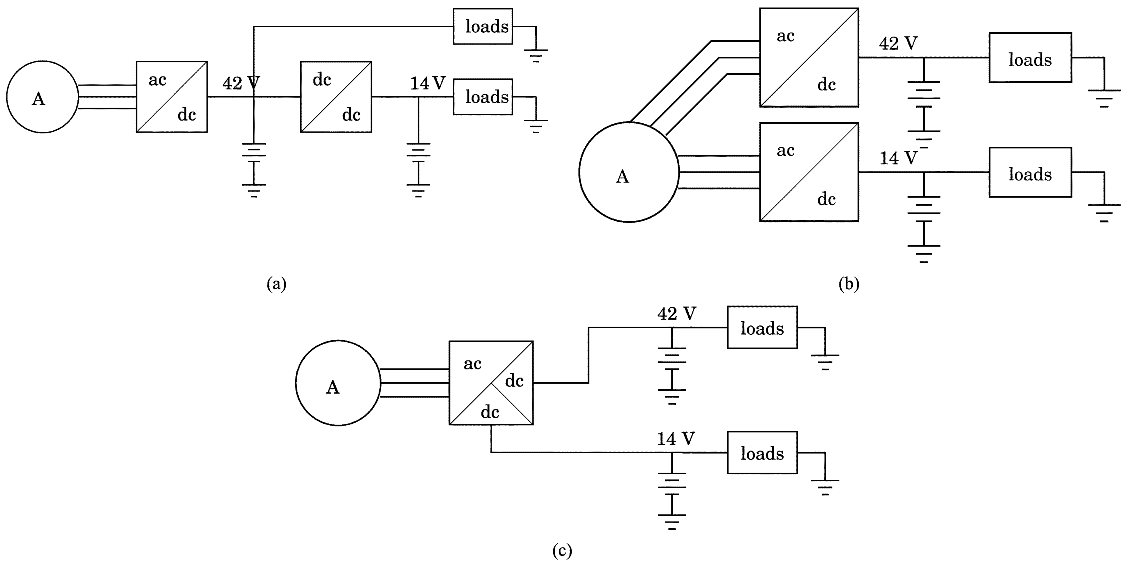

Fig. 17. Candidate dual-voltage architectures: (a) dc/dc converter architecture, (b) dual-stator alternator architecture and (c) dual-rectified alternator architecture.

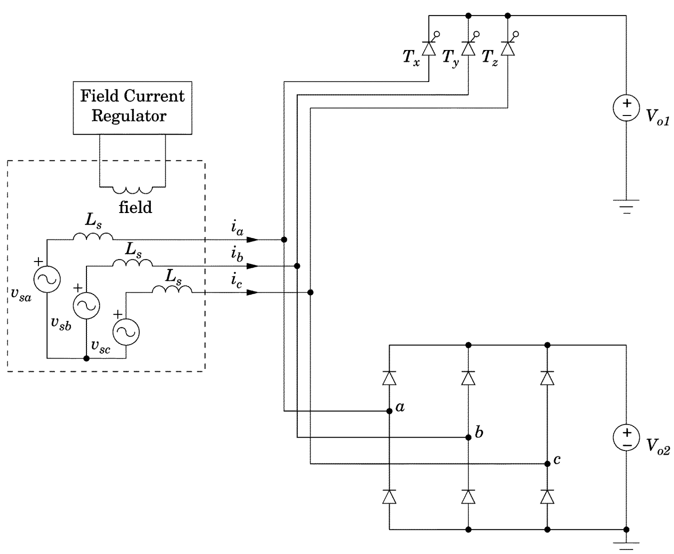

Fig. 18. Particular implementation of the dual-rectifier alternator architecture.

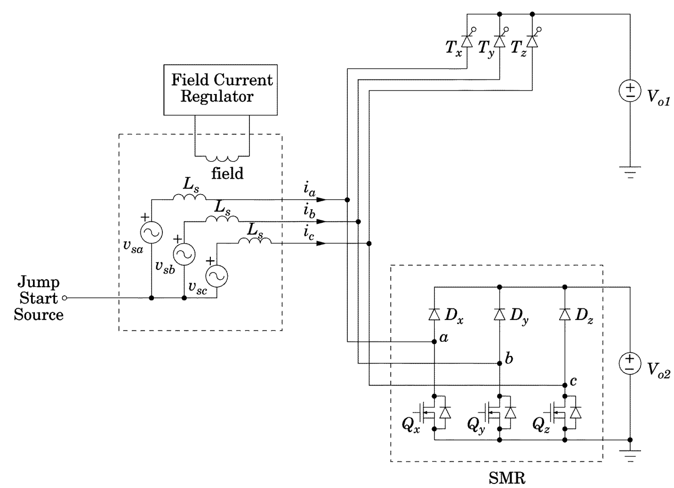

Fig. 19. Dual-rectified alternator architecture implementation using the switched-mode rectifier structure.

of the low-voltage bus and jump charging (if a bidirectional converter is used), but tend to suffer from the high cost of dc/dc converters. Other candidate dual-voltage architectures, illustrated in Fig. 17(b) and (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.

A. Conventional Dual-Rectified Alternator

One often-considered dual-output alternator is the dual-rectified alternator illustrated in Fig. 18 [11]–[15]. 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 [15]. 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.

B. Dual-Output SMR Load-Matched Alternator

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

VIII. Additional Considerations

There are a number of considerations that must be addressed in order to introduce any new technology into automobiles. Among these are cost, reliability, and fault tolerance. Here we provide a preliminary treatment of these considerations, with a focus on qualitative comparison of the proposed approach to existing methods.

Cost is a major factor driving the almost universal use of diode-rectified Lundell alternators in automobiles. The low manufactured cost of such alternators is a function of the machine structure itself, along with the large manufacturing volume and associated investment in specialized manufacturing equipment. The diode rectifiers used in present-day systems have low manufactured cost for similar reasons. While the cost of controlled switches (e.g., power MOSFETs) are rapidly decreasing, the incremental costs of a switched-mode rectifier may not yet be justifiable in cases where it is possible to use a low-cost Lundell machine with a diode rectifier. However, as power requirements rise, Lundell machine costs can rise rapidly[2]. For high power levels, the use of a switched-mode rectifier and load-matching control (which enable a smaller machine size to be employed) may already be justified on an economic basis.

[2]The inexpensive rotor structure utilized in the conventional Lundell machine does not scale well, due in part to mechanical limits on the stamped pole pieces. This can lead to substantially increased cost for larger machine sizes.

The use of switched-mode rectification is also likely to be justified in alternators for 42-V and dual 42-V/14-V electrical systems. Meeting the strict transient limits proposed for such systems [2] with diode-rectified Lundell alternators will necessitate the use of precision clamping circuits, due to the load-dump transient discussed previously. As the cost of such clamping circuits is high at present, the transient control feature of switched-mode rectifiers (Section V) may in itself justify their use in 42 V applications. Similarly, the ability to provide jump-start charging using the switched-mode rectifier (Section VI) offsets the high cost of providing this capability through other means (such as a dedicated charger). Thus, it may be expected that the proposed technology will be economically advantageous for future 42-V systems.

Reliability and fault tolerance are also important considerations in automotive applications. One question that may be raised is whether replacement of three diodes with power MOSFETs and their controls significantly compromises system reliability and fault tolerance. While extensive analysis and field testing will be required to fully address this question, some basic observations can be made on this matter. The most important failure mechanism associated with the switched-mode rectifier is likely to be power device failure. Typical failure rates for field-effect transistors are higher than those for diodes, but not dramatically so (e.g., a factor of two [16]). Given that other failure mechanisms in alternators (e.g., brush failure) are at least as important as device failure, it is reasonable to predict that introduction of a switched-mode rectifier will not greatly impact alternator reliability. Furthermore, the consequences of a device failure in a switched-mode rectifier are identical to those in a conventional diode-rectifier. In either case, the severity of the fault is much lower than other possible failure modes (e.g., regulator failure). We thus conclude that—to first order—designs incorporating a switched-mode rectifier can be acceptable from a reliability and fault tolerance standpoint [17]–[19].

IX. Conclusion

Rapid growth in automobile electrical power requirements is pushing the limits of conventional automotive alternators and is motivating the development of high-power and high-voltage automotive electrical systems and components. This paper introduces a set of new design and control techniques for automotive alternators that yield dramatic improvements in performance and functionality as compared to conventional systems.

A new load-matching technique is introduced that allows substantial increases in alternator output power and efficiency to be achieved through the use of a simple switched-mode rectifier. Only minimal, inexpensive modifications to existing alternators are required to implement the new technique, and simple control laws based on readily-available signals can be utilized. Analysis and implementation of the proposed technique are addressed, and simple analytical control laws for the approach are established. Experimental results demonstrating output power increases of factors of 2.5 (peak) and 1.9 (average) along with substantial increases in efficiency are provided. This new technique overcomes the power limitations of present-day Lundell alternators, and allows significant improvement in vehicle fuel economy (and commensurate reduction in environmental impact) 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 major present challenges in automotive power generation and control. It is expected that the 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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