EXTRACTING MORE POWER FROM THE LUNDELL CAR ALTERNATOR

EXTRACTING MORE POWER FROM THE LUNDELL CAR ALTERNATOR

D.M. Whaley, W.L. Soong and N. Ertugrul
University of Adelaide
Adelaide, Australia

Abstract
Due to the increasing power demands in automotive applications, the conventional power generator (Lundell alternator) is rapidly reaching its limits. This paper examines an approach that allows substantial increases in the output power and efficiency of automotive alternators by allowing the alternator to operate at its optimum output point. Theoretical predictions are compared with experimental results using a commercial car alternator; increases of up to 200% in output power and significant improvements in efficiency are demonstrated at high speeds.

1 INTRODUCTION

1.1 The Future of Automotive Power Generation

The introduction of new high-powered accessories is rapidly increasing the average electrical load in automobiles and this is expected to continue to rise [1] (see Figure 1). Such devices, which include electrically heated catalytic converters and active suspension systems, are pushing the standard automotive alternator to its limits. In addition to this power generation limitation, the proposed 42V electrical system is another reason for developing a higher voltage and higher powered alternator. An example of the power requirements for a high power alternator is 4kW at idle speed and 6kW at maximum engine speed [2] (see Figure 2).

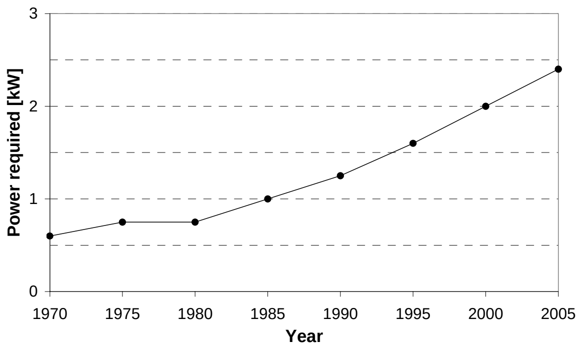

Figure 1: Average automotive electrical power requirements versus year [1].

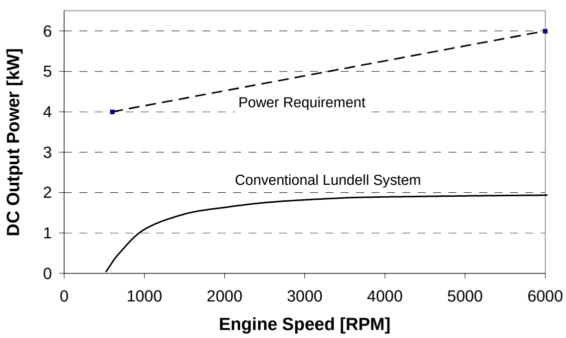

Figure 2: Typical Lundell alternator performance versus example high power requirements [2].

1.2 The Lundell Alternator

The Lundell alternator is the most common power generation device used in cars. It is a wound-field three-phase synchronous generator containing an internal three-phase diode rectifier and voltage regulator. The rotor consists of a pair of stamped pole pieces (claw poles), secured around a cylindrical field winding. The field winding is driven from the voltage regulator via slip rings and carbon brushes. Figure 3 shows a conventional alternator rotor and stator.

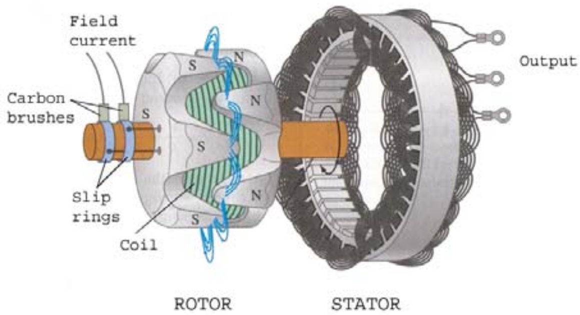

Figure 3: Exploded view of a Lundell alternator [3].

The output voltage of the alternator is maintained at about 14V DC, as this is the nominal charging voltage of a 12V lead-acid battery. The voltage is regulated at 14V by an internal controller that continuously samples the battery voltage and adjusts the field current accordingly. The field current is controlled by varying the duty-cycle of the pulse-width modulated (PWM) voltage applied to the field winding. The inductive nature of the field winding acts as a low-pass filter and thus the field current is essentially DC (see Figure 4).

As the electrical load increases (more current is drawn from the alternator) the output voltage falls. This drop in output voltage is detected by the regulator which increases the duty-cycle to increase the field current and hence raise the output voltage. Similarly if there is a decrease in electrical load (the output voltage climbs), the duty cycle decreases to reduce the output voltage.

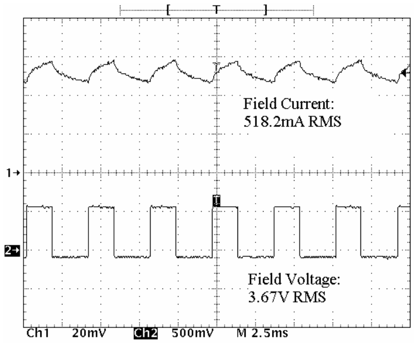

Figure 4: Field current and voltage waveforms of the Lundell alternator. Ch1: 200mA/div, Ch2: 10V/div.

The maximum alternator output is limited by heating of the rotor and stator windings and by magnetic saturation of the machine. As shown in Figure 2, conventional Lundell alternators are limited to about 2kW. The efficiency of these alternators is about 40 to 55%.

1.3 Future Alternators

Recently there has been a considerable amount of work into developing higher power automotive alternators with improved efficiency. Most of this work has focused on using inverter driven machines based on induction, switched reluctance, surface permanent magnet (PM), and interior PM machines [2]. The main issue with inverter driven machines is that the system cost is several times the cost of the conventional alternator, mainly due to the cost of the power electronics and control circuitry.

Perreault and Caliskan [1] have proposed an innovative method of improving the output power of the Lundell alternator without using an expensive inverter. This is based on a switched-mode rectifier (SMR) which allows the alternator to operate at its maximum output power point over a wide range of speeds.

This paper uses the studies in [1] as a primary source, and investigates the potential for Lundell alternator output power improvements using both analytical predictions and experimental results.

2 THEORY

2.1 Alternator Electrical Model

Figure 5 shows a simple alternator model with a SMR. The stator is modelled as a Y-connected three-phase sinusoidal voltage source with each phase including a leakage inductance. The SMR is essentially a boost converter following a rectifier. The SMR acts a DC/DC converter which allows the effective DC link voltage seen by the machine to be reduced from the actual DC link voltage, V_{DC}, to $(1\text{-}d)V_{DC}$, at a duty-cycle d. This extra control flexibility over an uncontrolled rectifier allows more power to be extracted from the alternator over a wide speed range. This allows the SMR to be modelled as a standard rectifier with variable output voltage. With a SMR, the field current can be kept constant at its maximum value as the output voltage regulation is done by duty-cycle control.

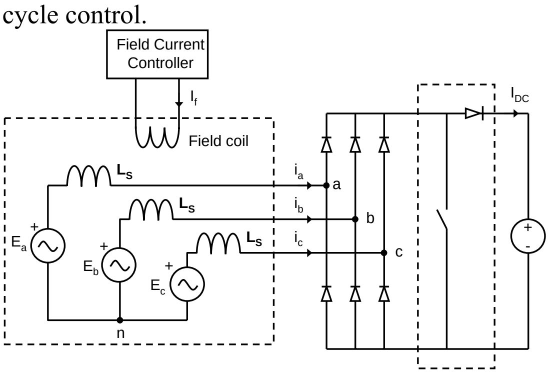

Figure 5: Simple electrical model of alternator with SMR [1]. The stator / rotor and boost converter are enclosed in the dashed boxes.

The SMR can be modelled by the machine phase equivalent circuit, as seen in Figure 6. This model is based on the following given assumptions [5], which allow the modelling of the rectifier and voltage source as a variable three-phase resistor:

- The rectifier forces the alternator phase currents to be strictly in phase with the phase voltages of the alternator,
- The phase currents continue to be sinusoidal, despite the non-sinusoidal voltage waveforms.

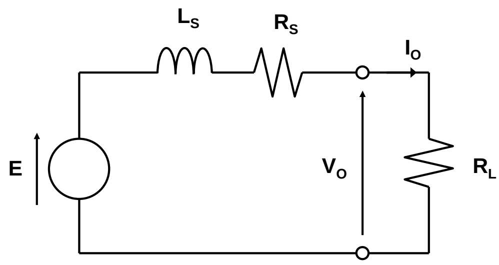

Figure 6: Alternator phase equivalent circuit.

where E is the back-EMF, L_s is the phase inductance, R_s is the phase stator resistance; and R_L is the effective load resistance. In addition V_o and I_o are the alternator output voltage and current, respectively. This model ignores saliency effects, iron losses and magnetic saturation.

2.2 Predicted Output Characteristics

The calculated maximum output power of the alternator is predicted and given in Figure 7 and Figure 8 as a function of output voltage and speed, respectively. The output power was calculated as $P_{DC}=3V_oI_o$, and V_{DC} was calculated as $1.283*\sqrt{3}*V_o$. In these predictions, the field current is set to its maximum value as this gives the maximum back-EMF and hence output power. The speed is kept constant whilst the load resistance, R_L, is varied; the output voltage, V_{DC}, and power, P_{DC}, are then plotted. This process is repeated for five different alternator speeds. A similar process is used to plot Figure 8, except the output voltage, V_{DC}, is fixed and the required load resistance and resultant output current are calculated for a range of alternator speeds. This is repeated at four different output voltages.

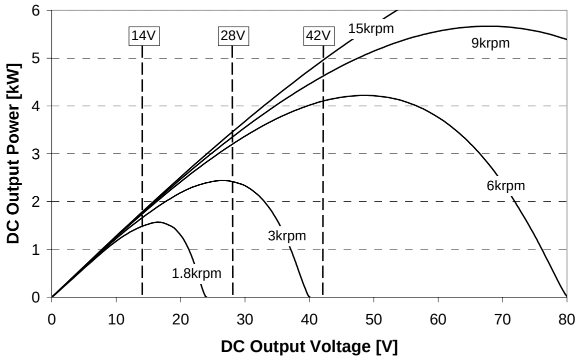

Figure 7: Predicted alternator output power versus output voltage, for various alternator speeds.

Figure 7 illustrates that for each speed curve, the alternator acts like a constant current source, for output voltages lower than about 25% of its open circuit voltage. It also shows there is a linear relationship between the maximum power point (peak) and the output voltage. Let us consider the vertical 42V dashed line, this line suggests that at this output voltage power can not be generated for speeds below 3,000rpm, as there is insufficient back-EMF voltage. This is also seen in Figure 8.

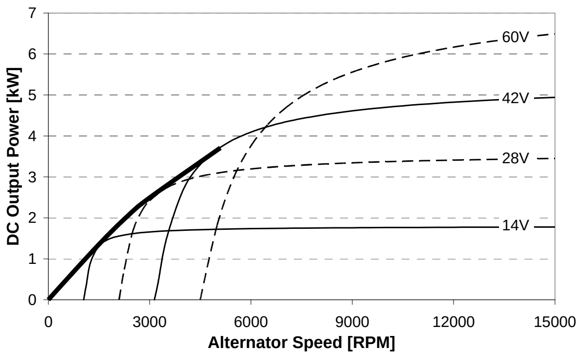

Figure 8: Predicted alternator output power as a function of speed, at 14V, 28V, 42V and 60V. The bold line shows the expected output characteristic of a 42V system with a SMR.

The increase in power is not solely due to a higher output voltage, as rewinding the stator would raise the output voltage, but would lower the output current, thus not improving the output power. For example if a 14V stator was rewound to obtain 42V output, the output current rating would be only one third of the 14V stator's output current rating; thus rewinding cannot improve the output power of an alternator. Instead, higher output power is obtained with a SMR as it allows the effective DC output voltage seen by the alternator to be varied to maximise output power at any speed, while maintaining a constant DC output voltage to the load. This enables a continuous transition between different characteristic voltage curves (any point along or below the bold and 42V curves) in Figure 8 to be obtained, allowing maximum power to be generated at low speeds.

Figure 8 indicates that at low speeds, such as engine idle, the output power cannot be increased; as the optimum output voltage is already close to the standard 14V output.

3 EXPERIMENTAL ARRANGEMENT

The system block diagram of the test setup is given in Figure 9. The alternator was tested at speeds up to 15,000rpm, corresponding to an engine speed of 7,000rpm, as this is the absolute limit in most modern vehicles. These speeds were achieved using two different test rigs.

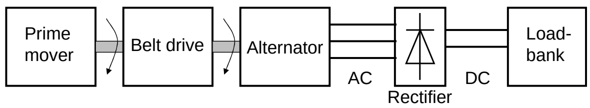

Figure 9: System block diagram.

3.1 DC Machine Dynamometer

The first test rig used a 1,500rpm, 5kW DC machine with a belt ratio of 3.7:1, as seen in Figure 10. This enabled the alternator to be operated at speeds up to 5,600rpm.

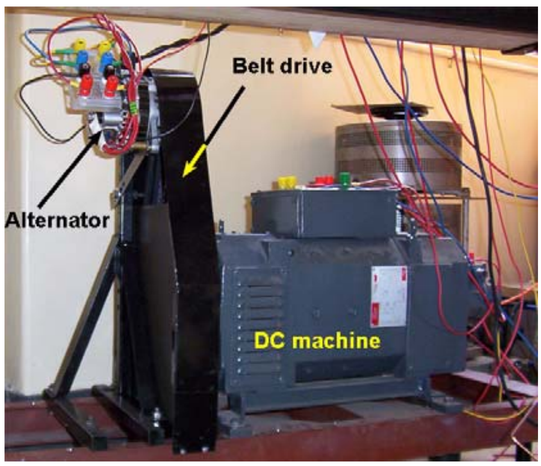

Figure 10: DC machine dynamometer.

3.2 Car Engine Dynamometer

A second test rig was constructed to overcome the speed limitations of the first test rig. The V6 engine was directly bolted to a tubular steel frame on rubber wheels (see Figure 11). The engine test rig is a fully operational setup with a push-pull lever that acts as an accelerator, which is used to control the engine speed. The speed can be read either from the tachometer or from the frequency of the alternator line voltage. The engine was operated up to 7,000rpm, which corresponds to an alternator speed of 15,000rpm.

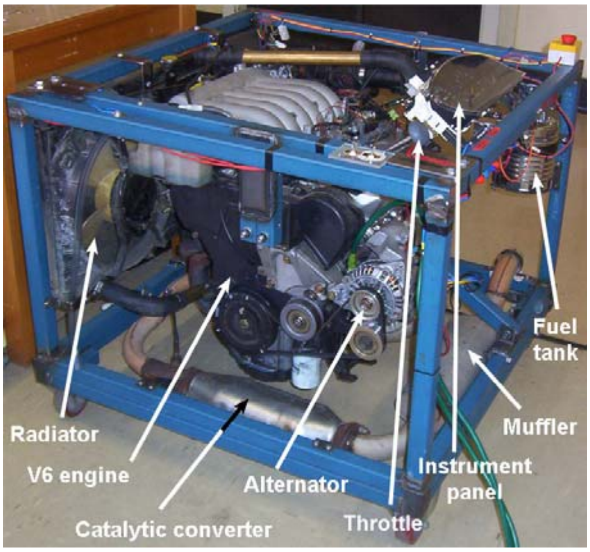

Figure 11: Car engine dynamometer.

3.3 Modifications to the Lundell Alternator

The alternator was modified to allow the field current to be either controlled by the internal regulator or to be set at a fixed value by an external power supply. The stator windings were also modified to allow connection to a separate rectifier or other power electronic device. Figure 12 shows the modifications which allowed the alternator parameters to be obtained through the open and short circuit tests.

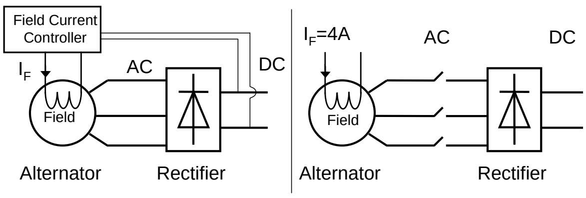

Figure 12: Conventional (left) and modified (right) alternator circuit diagrams.

3.4 Load-Bank

A 6.3kW variable resistive load was constructed to allow accurate loading of the alternator (see Figure 13). This load is capable of operating up to its rated values of 150A and 42V. The configuration of the switches, available on the load-bank, allows power to be drawn at either: 14V, 28V or 42V at currents up to 150A, at 1A increments.

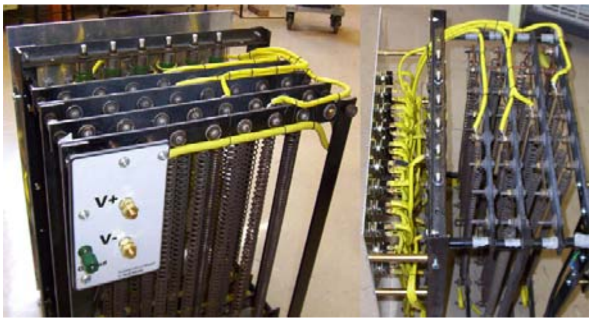

Figure 13: Variable load-bank structure showing the 27 load resistors and switches.

4 LUNDELL ALTERNATOR TEST RESULTS

4.1 Internal Regulator Operation

The alternator was tested using its internal regulator to characterise its performance. This mode of voltage regulation was only performed on the DC machine setup and thus data was recorded up to alternator speeds of about 5,600rpm. Figure 14 shows how the regulator varies the field current as a function of alternator speed for different load currents.

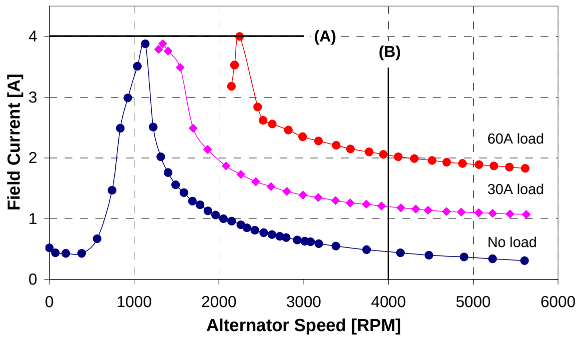

Figure 14: Field current variation with speed for different load currents, using the internal regulator.

Let us consider the no load curve in Figure 14. When the alternator is stationary, the regulator supplies it with a small field current. As the alternator speed increases, the regulator detects the increasing back-EMF voltage and increases the field current until it reaches its maximum value. This corresponds to the output voltage reaching its rated value. As the speed increases further, the controller reduces the field current to maintain a constant output voltage.

Consider the horizontal (A) and vertical (B) lines, given in Figure 14. Line A shows that the output current capability of the alternator increases with speed. Similarly for a fixed speed, line B, the field current must increase to supply increased loads.

The field current was also recorded against output current at constant speeds (see Figure 15).

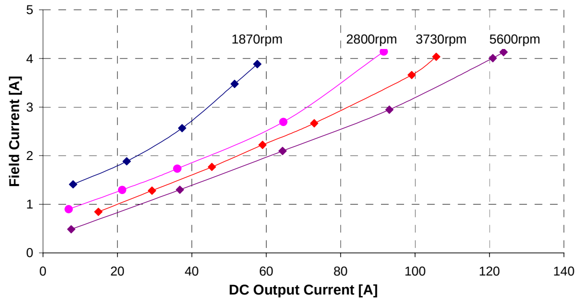

Figure 15: Field current variation as a function of load conditions, at various alternator speeds.

Figure 15 demonstrates that there is an approximately linear relationship between the field and the output currents. The change in slope at higher output currents is caused by saturation. Both Figure 14 and Figure 15 reveal that the maximum allowable field current is 4A.

4.2 Operation under Constant Field Excitation

A DC power supply was used to energise the field windings with 4A. The internal rectifier was used but the internal regulator was bypassed, see Figure 12. The output voltage was dependent on speed only, and was regulated by varying the load-bank resistance. The alternator was tested with output voltages of 14V, 28V and 42V on the car engine test rig (Figure 16).

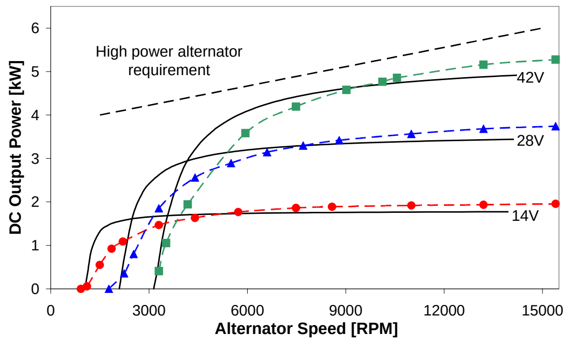

Figure 16: Output power versus speed at constant output voltages. Solid lines represent predicted values and discrete points represent measured values.

As seen in Figure 16, the minimum speed at which the alternator begins to generate power, increases with output voltage. This occurs because high back-EMF and hence a high speed is required to produce a high output voltage. The SMR would be used to maximise the power at low speeds by varying the output voltage, and also at high speeds to limit the output to 42V.

Figure 17 shows the measured DC output power as a function of DC output voltage at different speeds, using the DC machine test rig. The results reveal that it is possible to increase the output power of a standard Lundell alternator by operating at maximum field current and allowing the output voltage to increase above 14V.

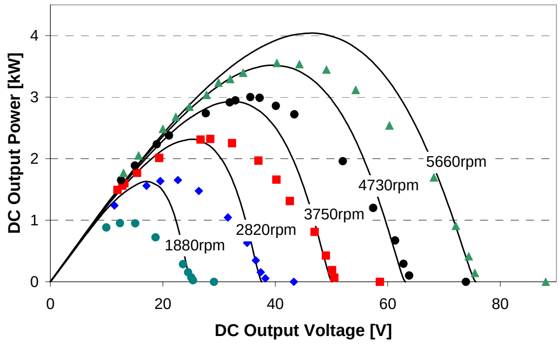

Figure 17: Output power versus output voltage at constant speeds. Solid lines represent predicted values and discrete points represent measured values.

4.3 Regulator versus Constant Field Current Mode

The maximum output power of the inbuilt regulator was compared to operating at maximum field current with 14V output voltage. Significant power increases were noticed across the entire speed range (Figure 18).

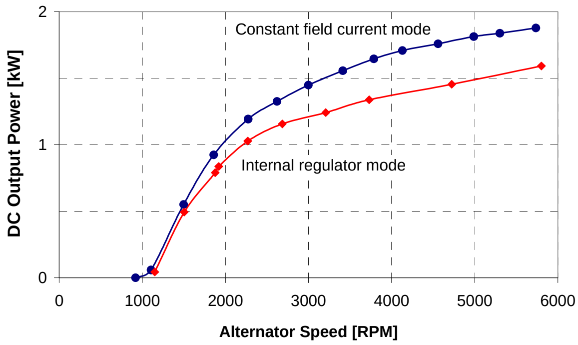

Figure 18: Comparison of modes at 14V output.

The largest difference in output power was found to be about 290W at 5735rpm. Part of the difference is because in the internal regulator mode, the alternator supplies the power for the field winding (up to 50W). It is likely that the remainder of the difference is due to the maximum field current of the internal regulator being somewhat less than 4A.

4.4 Efficiency of Alternator

The efficiency of the Lundell alternator was calculated for both the internal regulator and constant field current modes as seen in Figure 19, Figure 20 and Table 1. Efficiency data could only be calculated using the DC machine test rig as the input power, to the alternator, could not be measured using the car engine test rig. The efficiency values include the drive belt, alternator and rectifier losses, but not the field losses for the constant field current operation. In addition to the constant field current mode being more efficient at 14V than the inbuilt regulator mode, it was found that at higher speeds, the efficiency increased with increasing output voltages. The use of the SMR between 1,500 and 5,000rpm would not only allow the maximum power to be obtained, it would also maintain the full-load efficiency at about 62%.

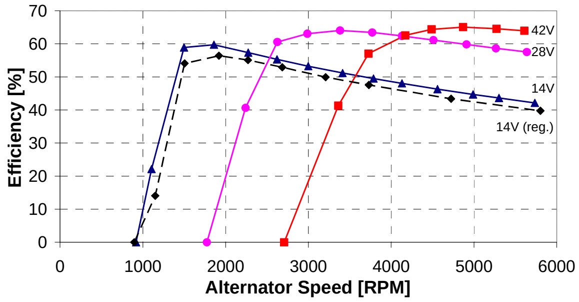

Figure 19: Alternator efficiencies versus speed. The dashed line represents inbuilt regulator mode, and the solid lines represent fixed field current mode.

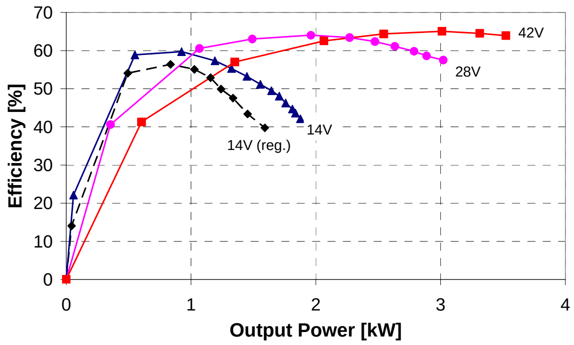

Figure 20: Alternator efficiency versus output power. The dashed line represents inbuilt regulator mode, and the solid lines represent fixed field current mode.

Table 1: Summary of alternator efficiencies

Output voltage [V]	Field current mode	Peak efficiency [%]
14	inbuilt regulator	56
14	constant current	60
28	constant current	64
42	constant current	65

The difference in efficiencies between the two field current modes is due to: unchanged stator copper losses, despite larger output powers, and the external supply of field current. Figure 20 shows that for a constant output voltage the efficiency decreases as output power increases. This occurs as high speeds are required to generate large powers and iron losses increase with speed. The 14V-constant field current mode offers an increase in peak efficiency compared with the internal regulator mode.

5 CONCLUSIONS

This paper examined the use of a switched-mode rectifier to increase the output power and efficiency of a standard Lundell automotive alternator. The SMR allows the alternator to operate at an output voltage corresponding to the maximum power output whilst maintaining a constant DC output voltage. Theoretical performance predictions were compared with experimental results obtained using a standard rectifier with variable output voltage to simulate the switched-mode rectifier.

The key results are as follows:

- At low speeds, such as engine idle, the output power remained unchanged, about 600W.
- The output power increased significantly at higher speeds. It was observed that an alternator speed of 15,000rpm the output power increased from 1.6kW with the internal regulator, to 5.2kW, a 225% improvement.
- The maximum efficiency increased from 56%, with the internal regulator, to 65% giving a significant improvement in alternator efficiency.

The results presented in this paper indicate that a standard Lundell alternator with a switched-mode rectifier is close to meeting the high power alternator requirements, at high speeds, but does not offer any significant improvements in output power at low speeds.

6 FUTURE WORK

The practical integration of the switched-mode rectifier and Lundell alternator needs to be addressed. This includes implementation of the power electronics and closed-loop control.

ACKNOWLEDGEMENTS

This work was made possible by the donation of a complete car engine by Mitsubishi Motors Australia and was supported by a 2003 Australian Research Council Discovery Grant. Technical support from the Electrical and Electronic Engineering Workshop staff in the construction of the test rigs and machine set-up is gratefully acknowledged, as is the support provided by B.L. Chapman and Y.L. Lim.

REFERENCES

[1] D.J. Perreault and V. Caliskan. “A new design for automotive alternators”. In IEEE/SAE International Congress on Transportation Electronics (Convergence), SAE paper 2000-01-C084, 2000.

[2] E.C. Lovelace, T.M. Jahns, J.L. Kirtley Jr. and J.H. Lang, "An Interior PM Starter/Alternator for Automotive Applications, ICEM, Sept. 1998, Istanbul.

[3] D.C. Giancoli, “Physics: Principles with applications” 5^{th} ed., Upper Saddle River, NJ: Prentice Hall, 1998, pp 630-631.

[4] G. Hassan, D.J. Perreault and T.A. Keim, “Design of Dual-Output Alternators with Switched-Mode Rectification”, PESC '03. IEEE 34th Annual Conference on , vol.4, June 2003, pp. 1992 – 2000.

[5] T.M. Jahns and V. Caliskan, “Uncontrolled Generator Operation of Interior PM Synchronous Machines Following High-Speed Inverter Shutdown”, IEEE Trans. Industry Applications, vol. 35, no. 6, December 1999, pp. 1347-1357.