

# Maximum Power Transfer Boost Supply

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## ABSTRACT

A simple boost topology power supply is designed to extract maximum power transfer from a single cell alkaline battery. Matching the effective load to the source internal impedance, the converter theoretically obtains the maximum power transfer condition from a Thevenin equivalent modeled source. Hysteresis control and self oscillation are provided by a single low power comparator and reference. In this paper a functional design is given and some of the issues encountered in dealing with low voltage, high current energy transfer are discussed.

## I. INTRODUCTION

Oregon State University mechanical engineering students compete in a national design contest sponsored by the American Society of Mechanical Engineers (ASME.) The design problem for this year consisted of moving a given load over a distance in the shortest possible time [1].

The energy source for the project is specified by contest rules to be a single 1.5V AA alkaline cell of a certain brand. The conversion from electrical to mechanical energy is to occur only in a specified small brush commutated DC motor [1].

Some contest participants realized that because the motor reaches its back emf limited speed very quickly at only 1.5V, it is clear that a boost in voltage would give a tremendous advantage. The author was approached with questions as to the possibility of constructing circuitry to accomplish this.

A battery, especially a small alkaline cell, cannot be regarded as having zero internal impedance. The existence of internal impedance restricts the maximum power transfer to any load. If the system is modeled by a Thevenin equivalent circuit (linear impedance assumption,) maximum power transfer occurs when the load resistance is equal to the Thevenin model source internal resistance [2]. The resulting voltage divider between two equal impedances causes the voltage at the battery terminals to drop to 1/2 its open circuit value, and the power transfer to the load is given by:

$$P = \frac{V_{no\_load}^2}{4 * R} \quad (1)$$

where  $R$  is the value of the load and internal impedance, and  $V_{no\_load}$  is the open circuit output voltage.

An active load can extract the maximum power from a battery by drawing sufficient current to force the terminal voltage down to one half the open circuit value. Using a boost topology supply, this power may be delivered to a passive load at a higher output voltage. In the case of the ASME sponsored contest, an accelerating motor imposes the need for the supply to deliver power at a variable (increasing) voltage to compensate for increasing back emf.

To satisfy these requirements, a boost supply is designed using simple hysteresis control. By monitoring the battery terminal voltage, the converter draws increasing current until a certain target minimum terminal voltage is reached, ideally slightly under the ideal  $1/2 V_{no\_load}$  point. It then allows this current to ramp back down until a target maximum voltage is attained at the battery terminals. These current "ramp up" and "ramp down" times correspond to the inductor charge and discharge times of the boost converter circuit.

The difficulty to be overcome in building a supply of this nature is that of the extremely low input voltage. Even the open circuit voltage of the battery will not provide adequate power for MOSFET gate drive or control functions, and when the supply is operating, the available input voltage can drop to around  $1/2$  this value. Some form of auxiliary supply is needed to deliver a reliable, constant source of higher voltage for control and driving functions. Also, on account of the low input voltage and limited source power, converter quiescent and operating losses must be minimized to realize a net gain in power transfer.

## II. IMPLEMENTATION

The converter is designed with a separate low power "auxiliary supply" and main power conversion unit. The auxiliary supply generates a stable source of 6 volts, used for all the control and driving operations of the main supply. Requirements include reliable start up from a single 1.5V cell potential, and full voltage generation from the minimum anticipated input voltage of around 0.7V.

This auxiliary supply is facilitated by the use of the MAX857, a specialized low voltage boost converter chip. This chip will self-start from a fully charged 1.5V cell, and is guaranteed to operate with input voltages down to 0.8V [3]. Its adjustable output may be set up to 6V, which is adequate to provide drive to a "logic level" power MOSFETs used in the main power conversion circuit. A small 105mH inductor wound on a ferrite bobbin core provides conversion energy storage, and output energy storage and smoothing is accomplished by a 150mF high frequency rated electrolytic capacitor.

The main power conversion section functions as a boost topology converter. The difference between this implementation and the more usual boost regulator is simply the fact that the input quantity is being regulated instead of the output. The controlling comparator monitors the input voltage at the battery terminals. When the input voltage is higher than a set "target voltage," the comparator drives the MOSFET Q1 on, thus ramping up the current in L1. When the voltage is lower than the target voltage, Q1 is turned off, allowing the current in L1 to ramp down as it delivers power at a boosted voltage to the output. The target voltage setting is derived from a low power reference with a potentiometer, allowing the best operating point to be experimentally determined. The MAX934, an ultra low-power, low voltage quad comparator and reference is used. Special features of this comparator include the ability to source positive output current [4]. This sourcing ability allows a single comparator to drive a logic level power MOSFET reasonably efficiently with no additional driving circuits or current multiplication transistors, provided the operating frequency is maintained within reasonable bounds.

The combination of hysteresis, set by R1, R2, and R3, and the inductance of L1 in conjunction with the input and output voltages set the operating frequency of this supply. When the comparator output is low, the battery terminal voltage is divided by R1 and the parallel combination of R2 and R3 to ground, giving Q1 turn on at:

$$V_{in} = \frac{V_{REFDIV}(R_1 + R_3 || R_2)}{R_3 || R_2} \quad (2)$$

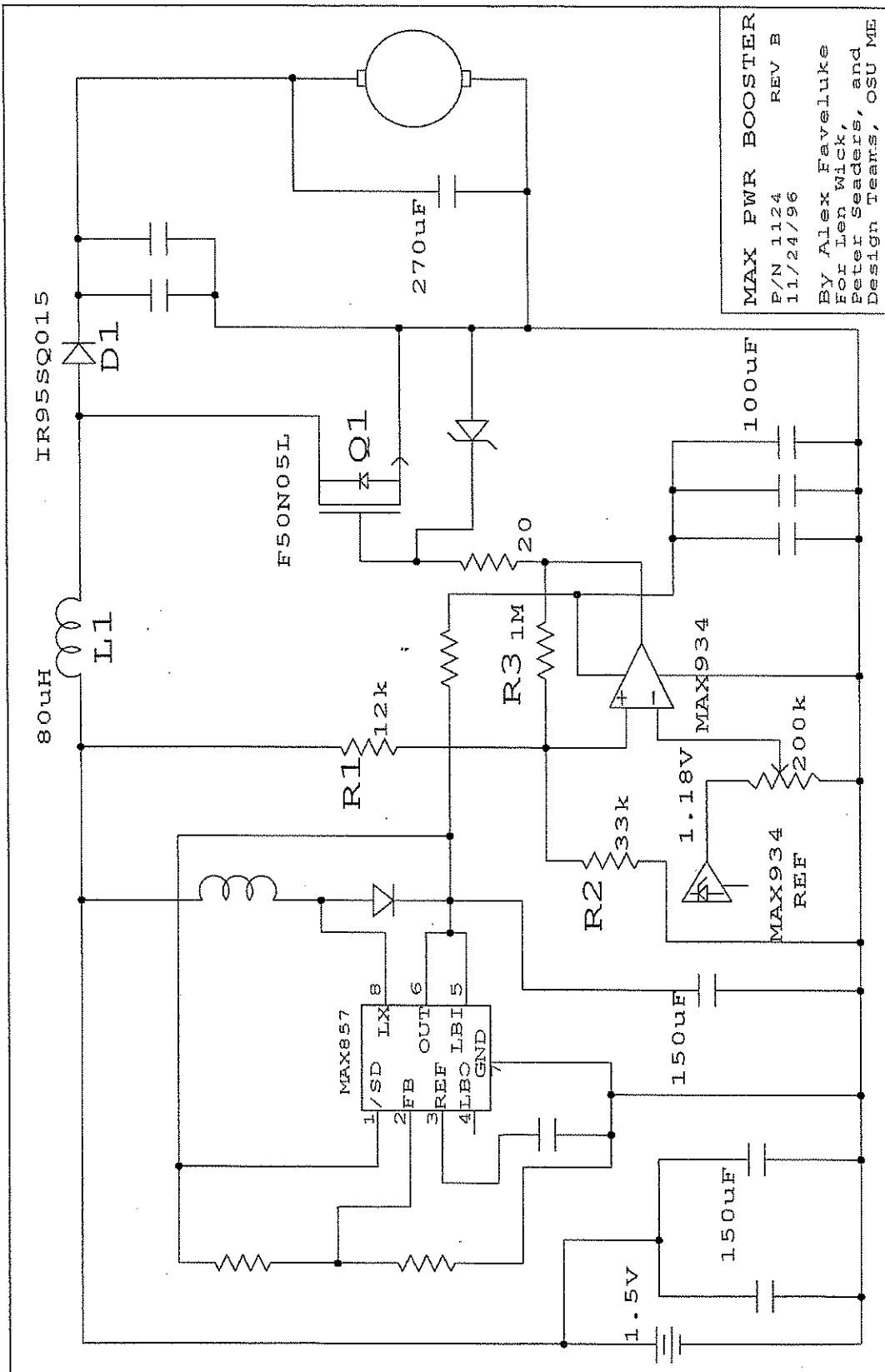


Figure 1 - Max. Power Booster

When the comparator output is high, the battery terminal voltage is again divided by the combination of R1, R2, and R3, however, in this case, R3 is connected to the logic supply voltage, at 6 volts. One way to determine the turn off threshold is to use a Thevinin equivalent circuit to model the combination of R3 and R2, where:

$$V_{th} = 6 \frac{R_2}{R_2 + R_3} \quad \text{and} \quad R_{th} = R_3 || R_2 \quad (3,4)$$

then Q1 turn off will occur at:

$$V_{in} = \frac{(V_{REFDIV} - V_{th})(R_1 + R_{th})}{R_{th}} + V_{th} \quad (5)$$

With the design values of:

$$\begin{aligned} R_1 &= 12k \\ R_2 &= 33k \\ R_3 &= 1M \end{aligned}$$

and  $V_{REFDIV} = 0.58V$ ,

the calculated Q1 turn on and turn off points, respectively are 0.798V, and 0.724V, giving a hysteresis band of about 0.072V.

When Q1 is on, the positive charging voltage on inductor L1 is the battery terminal voltage, minus winding resistance and Q1's  $I \cdot R_{DSON}$  voltage drop. When Q1 is off, the negative discharging voltage on inductor L1 is  $V_{out} + V_d - V_{in}$ .

If the battery is modeled as a theoretically perfect resistive thevinin source, an expression for the frequency can be found as,

Q1 turn on when  $V_{th} - IR_{th} = V_{in(on)}$  with  $V_{in(on)}$  calculated from eq. (2)

Q1 turn off when  $V_{th} - IR_{th} = V_{in(off)}$  with  $V_{in(off)}$  calculated from eq. (5)

With the given values for R1, R2, and R3, and with battery thevinin voltage and resistances estimated to be 1.58V and 0.18 ohms, Q1 turn on occurs when input current drops to 4.34A, and Q1 turn off occurs when current has reached 4.76A. The current swing in inductor L1 is thus 0.42 amps.

With voltage approximated as constant, time for a change DI in an inductor:

$$t = \frac{(L)(\Delta I)}{V} \quad (6)$$

Switching frequency is:  $f = \frac{1}{T_{on} + T_{off}} \quad (7)$

**Table 1. Theoretical Operation**

Output Voltage	Q1 On Time	Q1 Off Time	Frequency
0.5V	57 $\mu$ s	246 $\mu$ s	3.3kHz
0.75V	57 $\mu$ s	88 $\mu$ s	6.9kHz
1V	57 $\mu$ s	54 $\mu$ s	9.0kHz
3V	57 $\mu$ s	13 $\mu$ s	14kHz
6V	57 $\mu$ s	6 $\mu$ s	16kHz

**III. TESTING AND RESULTS**

The converter was attached to a load and tuned for maximum power output using the on-board potentiometer to adjust the target battery terminal voltage for maximum power delivery at the output. The specified battery has an open circuit voltage of around 1.59V, giving the theoretical maximum power transfer point as 0.80V, but slightly higher output power was attained at an input voltage around 0.95V.

A rheostat was then attached, and input and output quantities were measured at various output load impedances to make up Table 2, illustrating operating characteristics at a range of current and voltage load levels.

**Table 2. Operating Results**

Output Voltage	Output Current	Input Voltage	Input Current (approx.)	Input Power (approx.)	Output Power	Conversion Efficiency
3.57	0.48	0.96	3.3	3.17	1.71	0.54
3.02	0.61	0.95	3.3	3.14	1.84	0.58
2.65	0.67	0.96	3.3	3.17	1.77	0.56
2.35	0.74	0.96	3.3	3.17	1.73	0.55
2.00	0.84	0.96	3.3	3.17	1.68	0.53
1.54	1.01	0.96	3.3	3.17	1.56	0.49
1.08	1.30	0.96	3.3	3.17	1.40	0.44
0.65	1.79	0.95	3.3	3.14	1.16	0.37
0.42	2.40	0.95	3.3	3.14	1.01	0.32
0.34	3.16	0.94	3.3	3.10	1.07	0.35

Notice that there is a dramatic loss in efficiency as the output voltage is lowered. This is due to voltage drop across the output Schottky diode junction. At voltages under about 0.4V, the converter's losses in the output diode alone are actually higher than the output power. Also note that the input quantities are maintained reasonably constant, due to the regulating action of the controller on the input power source.

The ASME contest specified motor was connected to the output. A small magnet was mounted to the shaft and a hall effect sensor was used to measure rotor speed. Motor operation with the

converter is compared to the same motor operating directly from the same specified battery. Maximum shaft speed at no load was measured at 6954 rpm with battery only, and 24360 rpm with battery and boosting converter. Torque was not quantifiably measured, but unfortunately the converter does act to reduce locked rotor torque, due to the low efficiencies at low output voltage.

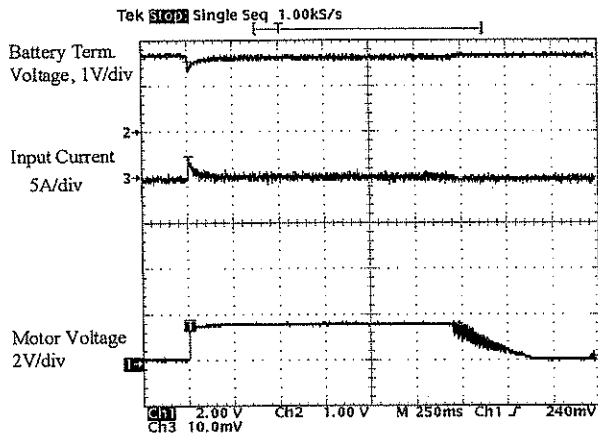


fig. 2  
Battery Only  
Driving Motor

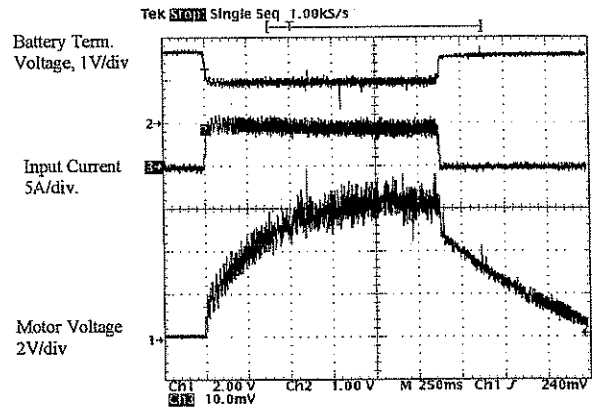


fig. 3  
Boost Converter  
Driving Motor

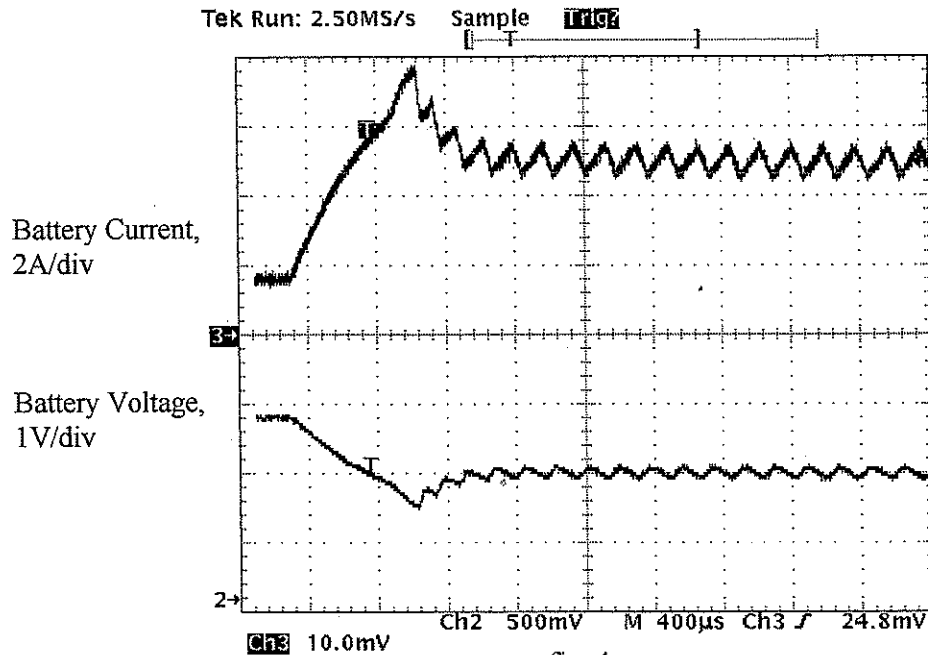


fig. 4  
Converter Start-Up  
and Operation

#### IV. CONCLUSIONS

One of the ASME design teams making use of the converter here at Oregon State won the local contest out of a field of close to 30 entrants, coming in with a times about 20% under the nearest competition. (The other team using the converter had a mechanical system problem in one of the run-off matches.) In spite of this, on examining the conversion efficiencies, it is obvious there is much improvement and optimization that has yet to be accomplished.

The most obvious power loss is coming from the output diode. Even though a low-drop Schottky rectifier was used, at low output voltages an unacceptable amount of power is lost. Worst of all, the locked rotor torque is limited, due to the effective voltage available to apply to the locked rotor motor is actually lower than the battery terminal voltage. An additional MOSFET used as a synchronous rectifier would theoretically alleviate this problem, although it would involve adding considerable complexity to the system as issues of voltage shifting, high side drive and dead time need to be dealt with. A synchronous rectifier system, due to the higher complexity and increased drive requirements, may draw substantially more constant current from the auxiliary supply. Any current draw from the auxiliary supply is paid for at a large penalty because it adds to the total low voltage input current at a level multiplied by the auxiliary supply boost ratio.

A lower voltage, lower  $R_{\text{DS(on)}}$  MOSFET should be used for Q1. The part used has a 50V rating, which is unnecessary in this supply, and there are available extremely low resistance low voltage rated FETs that would make a major improvement. Also, there is room for improvement in the main power conversion inductor L1. DC winding resistance should be minimized, because current is flowing continuously. AC performance is not as important, because the effective amplitude of AC current is very low. A gapped ferrite pot core was used in the prototype, wound with multiple strands magnet wire, where a high permeability powder toroid or gapped ferrite toroid would probably serve the purpose better, due to the potential of very low winding resistance for the same inductance.

The low voltage, ultra low power comparator used has one disadvantage. Response time is extremely slow in comparison to most conventional comparator chips. Typical response time is 12ms at 10mV overdrive and 4ms at 100mV overdrive. This excludes the possibility of high frequency operation, and even at low frequencies will limit the high voltage output end of operation. Referring to table 1, the theoretical "off time" at 6V output is only 6ms, approaching the high overdrive response time of the comparator. A higher performance comparator may improve overall power output, even if it draws more quiescent current from the auxiliary supply.

One of the most critical elements of this converter system is the connections to the battery. Ordinary battery holders are supplied with thin wire and weak spring contacts. Voltage drops over connections in a 1.5V, relatively high current system are bad enough. This converter system draws currents up to 4.5 to 5 amps, at input voltages well under one volt, and any resistance in input leads or connections can quickly negate any benefits of its use. A special battery holder was constructed to apply high pressures to brass contacts soldered to large gage wire. To make matters even more difficult, a switch is necessary on the input, because the output must not be open circuited with an input power source connected. In the test system, a large knife switch was used for its low contact resistance.

Measurement of operating quantities was challenging. Because the connected battery runs down very quickly, all measurements at a given data point must be taken practically simultaneously. Also, test lead and meter shunt resistances dramatically affect performance. Leads of minimal length were used in current measurements, but the instrumentation definitely hurt power delivery capability. Voltages were measured at the converter input, eliminating meter shunt loss from efficiency calculations, but measured efficiency will be adversely affected due to auxiliary and quiescent power being a higher percentage of total power delivery. A more testable version of this device would be constructed with low ohmic shunts soldered directly on the board, and may even include provisions to measure separately power used in the auxiliary supply.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] ASME 1997 design contest rules, on World Wide Web at:  
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