Automatic Permanent Magnet Generator Controller
for Small Applications

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Engineering

By

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ABSTRACT

Adkins, William “Scott” M.S.Egr., Department of Electrical Engineering, Wright State University, 2015. Automatic PMG Controller for Small Applications. This thesis is used to describe the proof of concept and design for a much needed answer to a major flight time limitation in smaller application drones. All small electric drones and small electric vehicles have the same major problem, short run-times. The average time a multi-rotor helicopter runs is for approximately 20 minutes. The concept idea of the combination of a permanent magnet generator (PMG) and a controller can extend this flight time. The basic idea is to add the similar function an automobile has, which is the alternator. This thesis will include, but not limited to the following for an Automatic PMG controller for a PMG primary source that would be theoretically added to the vehicles power systems:

- Design needs for longer application usage
- Design steps taken with conceptual reasoning
- H-Bridge Buck-Boost description & operation
- Simulation and testing of the proof of concept
- Integration methods, and
- Implementation.

It also serves as design template of a voltage and current source controller for multiple small application platforms and will be compared to the state-of-the-art design concepts in trying to reach a similar goal.
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DEDICATION

I would like to dedicate the inspiration of this thesis to my wife (Lauren) and two daughters (Haley & Avery). They have inspired me to push my boundaries further than I could have ever anticipated.
CHAPTER 1: INTRODUCTION

This document has information on the design process, simulation & testing, build, and proof of concept of an automatic voltage control unit for power management on small applications using a generator as its primary source of energy, such as UAV drones that are widely used for both military and civil markets. This document will provide a design concept of adding a small Permanent Magnet Generator (PMG) to source power to the application. By adding a PMG, there is a need for controlling the power being supplied from the PMG, depending on the applications load demand. This thesis is meant to be a proof of concept and basic start-up design of such a controller. This document will also present the current limitations of the smaller applications to better depict the need for this design or others like it.

The objective is to utilize two small IC’s, LTC3789 and LTC4020, in part to design the main power management circuits that will allow for a steady voltage output and in parallel, maintain or charge the vehicles battery source, much like an alternator in an automobile. This thesis will help prove the concept that by supplying another power source on small applications that it can be controlled by a small package controller. Currently the state of the art design of such a package including a PMG as its source has yet to be perceived, however alternative energy sources have been sought out, such as hydrogen fuel celled vehicles from the company EnergyOr. With their hydrogen fuel cell technology they have accomplished the world setting flight time record of a multi-rotor helicopter to be an astonishing 3 hours, 42 minutes, and 48 seconds. The objective of this thesis is to design a control unit to be provided in the further development of adding a PMG as another source of energy for a multi-rotor helicopter in order to beat the world setting record and provide something practical and marketable at a cheaper cost and smaller package design.

By adding a PMG as another source of energy driven by an internal combustion engine set to a certain RPM, it is theoretically assumed to accomplish a flight time of 4 to 6 hours at an affordable price to be practical and marketable.
CHAPTER 2: TYPES OF SMALL APPLICATIONS AND THEIR NEEDS

2.1 Aerial Applications

Currently there are many types of small applications being used in the world today by both military and civil parties. Smaller applications vary from UAV drones to hobby usage. Types of aerial applications include, but not limited to:

- High Efficient Remote Control Aero Planes
- Remote Control Helicopters
- Single Air Duct Fan Drones
- Multi-Rotor Helicopters

2.1.1 Flight Limitations

There are many types of limitations for aerial applications. Also depending on the design type can determine most of the limitations. Environmental conditions can also determine the end points to these limitations. Weight is one primary limitation to any aerial platform design. The limit to this is usually constricted by the power of the thrust output from the motors which turn the prop (‘s). Range is also a limitation, which can be defined as the distance the vehicle can travel and for how long. Since weight can only be described on a case-by-case basis, this document will focus on the increase of the flight time while neglecting any vehicle design constraints. The average flight time of any aero vehicle using only non-combustion motors, aka DC motors to drive the propellers, is approximately 15 to 20 minutes. Higher efficiency or robust builds can fly up to 40 minutes, however companies like EnergyOr have begun research and development with hydrogen fuel cell technology to extend these flight time to 3 hours, 43 minutes, and 48 seconds, but at the cost of considerable weight additions. [5] Any type of air vehicles can vary in flight times depending on the constraints of the specifications. Such constraints consist of the following, but not limited to,

- On-Board weight
- Flight Dynamics
- DC Electric Motor Efficiency
- Battery Ratings and Performance Characteristics, and
- Electro-Magnetic Interference (EMI).
All of which determine the drain on the vehicles electrical system, which ultimately determines the flight time.

2.2 Land Applications

Small electric land vehicles can also benefit from the voltage controller and PMG addition in the same way aerial vehicles would. The land based vehicles are built more rugged and is used in several fields from hobbyist, military, to space programs. A typical land based design is a four-wheeled DC electric motor driven vehicle. Similar to the aerial platform this design type uses a similar micro controller to control each electric motor and is usually remotely operated via a RF radio.

2.2.1 Run Time Limitations

Given that land based vehicles are most generally built more rugged, weight is usually a major contributor to the overall run time. However, the weight and the vehicles terrain/environment combined act as the major contributor to the length of the run time. All of the same battery limitations and controls that apply to aerial vehicles are also shared with the land base applications.

2.3 Improvements Needed for Small Land & Air Applications

Generally available improvements on the market include efficiency of components, better performing batteries, superior controls for electric motors, and additional batteries. However, all of these tactics ultimately end up trading off with some other aspect of the design. For example, by adding more batteries can most certainly exceed the designed on-board weight and begin to reduce the overall efficiency of the electric motors. There are two main constraints that typically don’t have much wiggle room and they are the weight and vehicle run/flight time. From the beginning a weight constraint needs to be decided upon to ultimately come up with potentials for the most efficient design. After the weight is picked, the battery is the most important decision to make for either land or aerial applications. The battery characteristics will have to meet all of the combined components needs as well as being large enough to provide a slightly larger than average life span. This thesis will eliminate one aspect of the decision making process by relieving the impact of battery life constraint. Through a buck-boost controller and battery management system a PMG can be controlled to fulfill the vehicles needs and extend the run/flight time by large amounts.
2.4 State-of-the-Art/Comparisons

Currently in the world of high pursuits in small UAV electrical drones very few have tried and succeeded in accomplishing the expectations of the demands for long flight times. Companies like 3D Robotics, DJI, and EnergyOr are the only companies that have come close to meeting long flight time records as well as producing high quality product that meets several of the demands of today’s market. DJI and 3D Robotics have very similar platforms that which will provide a slightly above average flight time with multiple accessories that are customizable to meet the consumers demand, such as cameras, GPS, high lift capacity, and reliability in unknown environments. Both of the company’s multi-rotor helicopters operate using only a LiPo battery as its primary source and have improved the efficiency of the common multi-rotor helicopter builds by selecting high efficient DC electrical motors, high efficient electronic controllers, light weight frame designs and accessories. Picking higher efficient components and removing weight has long been the popular choice to increasing flight time amongst the majority of the UAV community for some time now. Some examples of flight times for these companies are as follows:

1. DJI has improved on its phantom class of quad copters and manufactured the Spreading Wings S900 which can fly up to 18 minutes with high quality cameras and HD digital video while transmitting live stream data and footage, which is most commonly used for videography and photographs [6].

2. 3D Robotics has long been the leader in UAV multi-rotor design concepts by aid of open source coding and consumer brought ideas to increase efficiency. Their latest model, Solo, offers up to a 25 minute flight time with no accessories added on to it. With a camera and servos attached for videography the Solo can achieve up to a maximum of a 20 minutes flight time [7].

3. The leader, and world setting record holder of multi-rotor helicopter flight time, is by the company EnergyOr. They have decided to get away from using the traditional LiPo Battery source and have designed a UAV that uses hydrogen fuel technology as its primary source of energy to be used for the vehicle. They have also exhausted all traditional efficiency concerns with the components on the UAV. The combination of efficiency improvements and replacing the LiPo
battery with hydrogen fuel cell technology they have accomplished the world setting record of longest flight time by a multi-rotor helicopter. “EnergyOr Technologies Inc., a leading developer of advanced PEM fuel cell systems, recently demonstrated the world’s longest multirotor UAV flight, flying for a record 3 hours, 43 minutes and 48 seconds, improving upon its previous world record of 2 hours, 12 minutes and 46 seconds from March 16th, 2015.” [5]

By adding a PMG as an additional source of energy driven by a small high efficient combustion engine to one of the examples from DJI or 3D Robotics it can be theoretically assumed to achieve a much longer flight time. The following is an example of the amount of time the engine can run for in this scenario:

Specs:
- Manufacture Saito, Model FA-30 burns 10cc/min @ full throttle [8]
- Fuel tank size = 100 oz

Calculations:
\[
\frac{10cc}{1min} \times \frac{60min}{1hr} \times \frac{0.033814oz}{1cc} = \frac{20.29oz}{hr} \quad (eq. 1)
\]
\[
\frac{1hr}{20.29oz} \times \frac{100oz}{1} = 4.93hr \quad (eq. 2)
\]

By this simple unit conversion calculation, in comparison to the state-of-the-art concepts, it can be theoretically assumed that by adding a combustion engine to rotate a PMG, where the PMG’s primary function is to supply power to the Automatic PMG Controller and the Automatic PMG Controller’s primary function is to manage the PMG’s power to the vehicles load systems and maintain a surface charge on the vehicles on-board battery, that the flight time can be extended to approximately 5 hours in a lossless environment. The only constraint to the flight time is the size of the fuel tank in this scenario and the vehicles dynamic load characteristics will have to be considered when selecting the size of the PMG and controller components, which may have an impact on the combustion engine horsepower ratings.
Chapter 3: PERMANENT MAGNET GENERATOR (PMG)

3.1 Overview of PMG

A PMG is a synchronous machine/generator that produces a variable speed variable frequency variable voltage driven by a mechanical rotation. Depending on the amount of poles in the PMG will ultimately determine the frequency of the machine using the following formula.

\[ f(\text{Hz}) = \frac{\text{RPM} \times \text{Poles}}{120} \]  

(3)[9]

The PMG can be designed as a single or multi-phase unit. For the purpose of this thesis a three phase machine will be used for increased efficiency. A PMG is a generator that is comprised of a rotor and a stator, where the rotor is generally made up of permanent magnets and the stator is what is connected to the load. A magnetic field is generated as the rotor is spun in either direction and is induced into the stator, therefore creating electrical potential to be used. It is important to keep in mind the PMG output when designing the Automatic PMG Controller due to the range of the input voltage coming into the controller unit.

3.1.1 3-Phase vs. Single Phase Machine

For this thesis a single phase and 3-phase PMG was considered for the design. In a single phase machine there is one signal that is produced for all 360° of rotation of the machine (see Fig. 1). Single phase is the most common type of utility voltage found homes and buildings across the U.S. and is operated at 60 Hz. Although single phase is the common choice of home electronics, this was determined to be less than desired for this thesis. The problem with single phase is that the current is supplied by one single source and would have to be operated at a much higher frequency for the desired regulation in the voltage controller.
3-phase machines are designed to have three separate voltage sources shifted by 120°, ultimately providing a longer period of positive voltage during one cycle of rotation (360°) (see Fig. 2). This lends itself to be more efficient at the rectification point and allowing for more desired filter component selection and allows the current to be shared among three different sources and allowing for a more compact PMG design.

3.2 Purpose of PMG in Application Design

The purpose of the PMG in any of the applications is to provide a source of power with minimal effort on a vehicle that has tight design constraints and limited accessibility to a primary source of energy. The PMG is to generate power for the entire electrical
system on the vehicle for as long as designed. The designed amount of time that it will be
used will be determined by the amount of time the gasoline engine is available for
mechanical rotation via the fuel available to burn.
The PMG is to be selected or designed to be light in weight, high efficiency, 3-phase, and
rugged frame for environmental exposures. It will be driven by a high efficient nitro-
gasoline internal combustion engine at a set RPM to maintain frequency, while supplying
3-phase voltage into a full-wave rectifier. The PMG will output 25 to 37 VAC L-N @ 1
kHz. The current density of the PMG will be determined based on the vehicle load
demands, which will require further research and study developments to better
understand the dynamics of the load characteristics. This voltage will then be regulated to
the vehicles load to maintain a certain voltage by the Automatic PMG Controller based
on the vehicle design parameters and will also serve as a means to charge the existing on-
board battery.

3.3 Primary Source of Mechanical Rotation
The PMG requires torque in order to produce electrical potential on its output.
Nitro-gasoline internal combustion engines have been used on small aero planes for a
long time and have become highly efficient in operation through years of improvement in
design. This type of motor is suggested to provide the primary source of mechanical
rotation required by the PMG. The RPM of this motor is controlled by the on-board flight
controller and will be set to a specific RPM to provide the desired frequency and voltage
output from the PMG. Any heavy loads that are experienced during vehicle operation
affecting the engines RPM will be compensated by the flight controller in order to
maintain a certain RPM. The engine should also be located at the center of the aircraft to
reduce the dynamic flight characteristics for reduction of frame vibration, which could
drastically affect the vehicles performance.
Chapter 4: AUTOMATIC CONTROLLER

4.1 Overview of Automatic Controller

The automatic controller is designed to be a small set of power electronics to control the voltage being supplied from the PMG and regulate the vehicles primary source of energy, via LTC3789 IC, while maintaining or charging the vehicles backup source of energy, being the battery, via LTC4020 IC. This particular controller has multiple features to its design, such as voltage control for electrical system, current controlled battery charging, over voltage protection, over current detection, soft start-up functions, signal conditioning/filtering, high efficient buck-boost modes of operation, and small package design. The primary goal for the controller design and PMG combination was to mimic an alternator in a car. The following sections will describe in detail every aspect of the prototype controller as well as the simulation and testing results from the preliminary design.

4.2 Design Process

4.2.1 Design Specifications

\[ V_{in} = 36 \text{ V}_{DC} \]
\[ V_{out} = 12 \text{ V}_{DC} \]
\[ V_{bat(\text{float})} = 11.5 \text{ V}_{DC} \]
\[ I_{out(\text{MAX})} = I_{L(\text{Max})} = 15 \text{ Amps} \]
\[ R_L = 10 \Omega \]
\[ f_s(\text{Buck−Boost}) = 600 \text{ kHz} \]
\[ f_s(\text{Battery Charger}) = 500 \text{ kHz} \]

4.2.2 Block Diagram & Schematic

Fig. 3 Automatic PMG Controller Block Diagram
4.2.3 Input Power Source

For optimum performance a mock-up 3-phase delta wound PMG was used for simulation and design purposes. The minimum output voltage will be 6 VAC at 400Hz and with a maximum of 38 VAC at 400 Hz. Neglecting all design parameters of the PMG besides the voltage and frequency was determined to be sufficient for the design and simulation of the PMG controller, therefore three AC voltage sources, separated by 120°, were used to simulate the input power source. The PMG voltage output for simulation process was set to 37 VAC.
4.2.3.1 Bridge Rectifier Design
A full-wave rectifier is most desired for AC-to-DC conversion. The part number RFN30TS6D was chosen to be the best diode available for this task. Its specification is as follows:

\[ V_{RM} = 600 \text{ V @ Duty} \leq .5 \]  
\[ I_o = 30 \text{ A} \]

(eq.4)[3]  
(eq.5)[3]

This means for every positive and negative portion of the sine wave cycle, there will be a positive representation on the output of the bridge rectifier for each phase, while maintaining a 120° phase shift for each phase.

4.2.4 Buck-Boost Micro-Controller
In order to maintain output voltage for the vehicles load system a Buck-Boost micro-controller is required. A buck-boost setup was most desired due to the changing PMG output voltage depending on the internal combustion engine RPM. This way no matter where the engine speed is, the output from the micro-controller will always be a steady voltage. The part used in this experiment is manufactured by Liner Technologies and has a part number as LTC3789. “The LTC3789 is a current mode controller that provides an output voltage above, equal to or below the input voltage.”[1] “The LTC3789 provides a constant-current regulation loop for either input or output current. A sensing resistor close to the input or output capacitor will sense the input or output current.” [1] The specifications and design equations can be found in the datasheet in the APPENDIX A.
The image below (see Fig. 5) depicts the sensing resistor location (right side) and the output voltage programming resistor divider network location (bottom).

The buck-boost micro-controller modes of operation are buck ($V_{IN} >> V_{OUT}$), buck-boost ($V_{IN} \approx V_{OUT}$), and boost ($V_{IN} << V_{OUT}$). The LTC3789 utilizes an H-Bridge for its buck-boost topology. This setup allows for a wide range of input voltage while preventing the need for separate buck and boost topologies to accomplish the same thing. The H-Bridge setup also allows for seamlessly transition in between different modes of operation. The figures below (see Fig. 6, Fig. 7, and Fig. 8) will describe the difference between all modes of operation of the LTC3789.
“When $V_{IN}$ is greater than $V_{OUT}$, switch C is open and switch D is closed and switches A and B operate as in a standard buck regulator (Figure Fig. 7), switching the output voltage according to the pulse-width modulation (PWM) frequency to create a lower output level. When $V_{IN}$ is less than $V_{OUT}$, switch B is open and switch A is closed, leaving switches C and D to operate as in a boost regulator (Figure Fig. 8), charging and discharging the inductor to boost the output above $V_{IN}$. When $V_{IN}$ is near $V_{OUT}$, the device operates in buck-boost mode where buck and boost operations occur as needed during a switching cycle.”[1]
From the manufacturers datasheet (see APPENDIX A) the maximum duty cycle for buck mode is as follows:

\[ D_{\text{MAX, BUCK}} = \left(1 - \frac{1}{12}\right) \cdot 100\% = 91.67\% \]  

(eq. 6)[1]
From the manufactures datasheet (see APPENDIX A) the minimum duty cycle for boost mode is as follows:

\[
D_{\text{MIN,BOOST}} = \left( \frac{1}{12} \right) \cdot 100\% = 8.33\%
\]  

(eq. 7) [1]

Fig. 11 Boost Region (VIN << VOUT)

Fig. 12 Duty Cycle for Modes of operation
For component selection on the LTC3789 demo board prototype the following design equations were used from the manufacturer’s datasheet, refer to APPENDIX A.
\[ \Delta I_{L(Buck)} = \frac{V_{out}}{f_s(Buck-Boost)L} \left( 1 - \frac{V_{out}}{V_{in}} \right), \quad \text{where } L = 3 \, \mu\text{H} \quad (\text{eq. 7})[1] \]

\[ \Delta I_{L(Buck)} = \frac{12}{600 \cdot 10^3 \cdot 3 \cdot 10^{-6}} \left( 1 - \frac{12}{36} \right) = 4.44 \text{ Amps} \quad (\text{eq. 8})[1] \]

\[ I_{\text{Ripple}(Buck)} = \frac{\Delta I_{L(Buck)} \cdot 100}{I_{out}} \% = \frac{4.44 \cdot 100}{15} = 29.63\% \quad (\text{eq. 9})[1] \]

\[ \Delta I_{L(Boost)} = \frac{V_{in}}{f_s(Buck-Boost)L} \left( 1 - \frac{V_{in}}{V_{out}} \right) \quad (\text{eq. 10})[1] \]

\[ \Delta I_{L(Boost)} = \frac{6}{600 \cdot 10^3 \cdot 3 \cdot 10^{-6}} \left( 1 - \frac{6}{12} \right) = 1.67 \text{ Amps} \quad (\text{eq. 11})[1] \]

\[ I_{\text{Ripple}(Boost)} = \frac{\Delta I_{L(Boost)} \cdot 100}{I_{out}} \% = \frac{4.44 \cdot 100}{15} = 11.11\% \quad (\text{eq. 12})[1] \]

\[ R_{\text{sense}} = \frac{2 \cdot 140 \text{mV} \cdot V_{\text{in(minimum)}}}{2 \cdot I_{\text{out(Max Boost)}} \cdot V_{out} + \Delta I_{L(Boost)} \cdot V_{\text{in(minimum)}}} \quad (\text{eq. 13})[1] \]

\[ R_{\text{sense}} = \frac{2 \cdot 140 \cdot 6}{2 \cdot 15 \cdot 12 + 1.67 \cdot 6} = 4.5 \, \text{m}\Omega \quad (\text{eq. 14})[1] \]

Since,

\[ V_{out} = \frac{(R2 + R1) \cdot 0.8}{R1} \quad (\text{eq. 15})[1] \]

\[ R2 = \frac{V_{out} \cdot R1}{0.8} - R1, \quad \text{where } R1 = 20 \, \text{k}\Omega \quad (\text{eq. 16})[1] \]

\[ R2 = \frac{12 \cdot 20 \cdot 10^3}{0.8} - 20 \cdot 10^3 = 280 \, \text{k}\Omega \quad (\text{eq. 17})[1] \]

These components were determined to be the minimum requirements to attain the output voltage setting and maximum current limit setting on the LTC3789 demo board selected for prototyping and proof of concept. Further component calculations would be required when designing the actual buck-boost micro-controller for the Automatic PMG Controller by using the manufacturers datasheet. When redesigning the output voltages and current limits for the prototyping demo board, these calculations will need to be used to determine the correct component selections.

4.2.5 Battery Charging IC

Just like an alternator in automotive applications, the battery charging circuit will continue to supply voltage and current to the vehicles battery in order to maintain a sufficient surface charge. In this experiment the part number LTC4020 was used to
accomplish a charging circuit of 11.1 volts at a 1.5 amp-hour charge rate. “The LTC4020 is an advanced high voltage power management and multi-chemistry battery charger designed to efficiently transfer power from a variety of sources to a system power supply rail and a battery.”[2] The LTC4020 has a wide input voltage range from 4V to 55V and is only limited to by the inductor and MOSFET’s current limit, therefore depending on your amp-hour charging rate will ultimately determine the size of the controller’s components. For the purpose of this project a maximum charge rate of 1.5 amp-hours was picked to prevent any battery damage, but is not limited to 1.5 amp-hours. The buck-boost inductor has a peak current rating of 15.5 amps, however the results from simulation are as follows (see Fig. 15):

\[ I_{LMAX} = 13.5 \text{ A} \] (eq.18)

Fig. 15 Simulation of Peak Inductor Current

The LTC4020 battery charging IC will sense the voltage of the battery and determine to either charge or not. By configuring the topology to ensure battery voltage is at 11.1V the IC will control the buck-boost topology to try to achieve the desired voltage if battery voltage is less than the configured battery voltage. The images below (see Fig. 16 & Fig. 17) shows battery voltage and charging current at an accelerated charging cycle from 9.3 volts to 11.1 volts.

Fig. 16 Battery Voltage and Charge Current
The LTC4020 for this project was configured to constant current and constant voltage control (CC/CV) due to the lithium polymer (LiPo) battery being used in the experiment. The IC has two other modes of operation that will accommodate lead-acid and NiCd/NiMH types of batteries. By operating in CC/CV mode the IC will accommodate three types of charging cycles. LiPo batteries require a preconditioning charge to prevent premature battery failure and allow for safe charging if the battery has been depleted considerably. After or if precondition takes place there are two types of charging cycles; float charge and recharge. Recharge occurs if the battery has been preconditioned or is found to be a safe voltage for recharging at maximum charge rate. Float charge is the point the IC transitions from CC to CV and reduces the amount of charge current. Below in the table (see Table 1) you will find the charging cycle descriptions from the manufactures datasheet.

<table>
<thead>
<tr>
<th>Typical CC/CV Charge Cycle Voltages (Per Cell)</th>
<th>Li-Ion</th>
<th>LiFePO4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precondition</td>
<td>2.94V</td>
<td>2.52V</td>
</tr>
<tr>
<td>Float</td>
<td>4.2V</td>
<td>3.6V</td>
</tr>
<tr>
<td>Recharge</td>
<td>4.095V</td>
<td>3.51V</td>
</tr>
</tbody>
</table>

Table 1 CC/CV Charge Cycle Voltages

The programmed battery voltage is determined from a simple voltage divider network (see Fig. 18 (Bottom)) and is compared to an internal 2.75 volt reference. The equation to program the battery voltage can be found below:
\[ V_{(\text{bat,Float})} = 2.5V \cdot \left(1 + \frac{R_{FB1}}{R_{FB2}}\right), \quad \text{where} \quad R_{FB1} = 33 \, \text{k}\Omega \quad (\text{eq. 19})[2] \]

\[ \therefore R_{FB1} = \left(\frac{V_{(\text{bat,Float})}}{2.5} - 1\right)R_{FB2} = \left(\frac{11.5}{2.5} - 1\right)33 \cdot 10^3 = 118.8 \, \text{k}\Omega \quad (\text{eq. 20})[2] \]

The battery charging current setting resistor (see Fig. 18 (Right)) equation can be found below:

\[ R_{CS} = \frac{0.05V}{I_{CSMAX}}, \quad \text{where} \quad I_{CSMAX} = 1.5 \, \text{A} \quad (\text{eq. 21})[2] \]

\[ \therefore R_{CS} = \frac{0.05}{1.5} = 333 \, \text{m}\Omega \quad (\text{eq. 22})[2] \]

The following equations can be helpful when finding the switching MOSFET’s in the battery charging IC buck-boost topology. Switching Power loss at 250 kHz is estimated by the following equations provided from the manufactures datasheet, refer to

**APPENDIX B:**

If \( \text{Vin} > \text{Vout} \) (Buck Mode):

\[ P_{ON(A)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(A))} \cdot \left(\frac{V_{OUT}}{V_{IN}}\right)^2, \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 23})[2] \]

\[ P_{ON(B)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(B))} \cdot \left(1 - \frac{V_{OUT}}{V_{IN}}\right)^2, \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 24})[2] \]

\[ P_{ON(C+D)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(C,D))}, \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 25})[2] \]

If \( \text{Vin} < \text{Vout} \) (Boost Mode):

\[ P_{ON(A+B)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(A,B))}, \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 26})[2] \]

\[ P_{ON(C)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(C))} \cdot \left(1 - \frac{V_{OUT}}{V_{IN}}\right), \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 27})[2] \]

\[ P_{ON(D)} = I_{LMAX}^2 \cdot \rho T \cdot R_{DS(ON(D))} \cdot \left(\frac{V_{OUT}}{V_{IN}}\right), \quad \text{where} \quad \rho T = 1.5 \quad (\text{eq. 28})[2] \]

These components were determined to be the minimum requirements to attain the battery voltage setting and maximum current limit setting on the LTC4020 demo board selected for prototyping and proof of concept. Further component calculations would be required
when designing the actual battery charging IC for the Automatic PMG Controller by using the manufactures datasheet, refer to **APPENDIX B**. If redesigning the output voltages and current limits for the prototyping demo board, these calculations will need to be used to determine the correct component selections.

The figure below (see Fig. 18) shows the simulation circuit used of the battery charging IC:

![Battery Charging IC Schematic](image)

**Fig. 18 Battery Charging IC Schematic**
4.2.6 Protection/Detection Features

Each chip within the PMG controller has associated protection features already such as, over-voltage, over-current, soft-start, short-circuit, current limit fold-back and feedback networks. However other protection features, such as over-voltage and over current (fuses), have been placed in the circuit for similar functions for redundancy. Over-Voltage and Current limits have been set to satisfy the testing scenario for prototyping, but will need further investigation to have a broader scheme for multiple platform configurations

4.2.6.1 Over-Voltage

There are multiple areas where over-voltage protection has been put into place, such as the input voltage and each IC has its own associated over-voltage protection set by a simple voltage divider network and a sensing resistor and comparing that voltage to an internal voltage reference to ensure the load output voltage is less than 12.5 volts and that the charging circuit will also not allow the battery voltage to become higher than 11.1 volts. These setting are crucial in the design process due the violent nature of overcharging a lithium polymer battery. The charge rate can also be set in the configuration of the battery charging IC circuit to prevent faster that desired charging rates. Below in the figure (see Fig. 19) is the simple circuit used for over voltage protection on the output of the bridge rectifier prior to the input of the IC’s. This particular circuit works by steering the over voltage back into a voltage source instead of allowing it to reach the IC’s and cause damage. The voltage was set to 36 volts for this demonstration, but in reality will be driven into a separate voltage network coming from the PMG, such as a flyback converter setup through an output transformer that will also supply nominal voltages to accessories on the vehicle.

Fig. 19 Input Over-Voltage Protection
4.2.6.2 Over-Current

In both IC chips current limit fold-back protection is available and accomplishes limiting the load current by using the buck mode with very low duty cycles and even skipping cycles. During the initial testing phases several fuses were used to prevent any over current damage. Fuses were placed at the output of the bridge rectifier and for each phase output from the simulated PMG source. In the final design there will only be one fuse for each of the IC’s input. To prevent any damage

4.2.6.3 Soft-Start

Each IC has a soft-start function that allows for the PMG to achieve maximum RPM to ensure optimum efficiency from the automatic controller. During the soft-start process the battery charging IC provides the status of the charging circuit via LED’s. The table below (see Table 2) explains the functions of the LED’s start up sequence, which provides useful troubleshooting information if there was an error to occur prior to actual charging.

<table>
<thead>
<tr>
<th>Status Pins State</th>
<th>CC/CV (Mode = 0V)</th>
<th>Lead-Acid (Mode = INTV\textsubscript{CC})</th>
<th>CC (Mode = -NC-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat1 Stat2 OFF</td>
<td>OFF</td>
<td>Not Charging – Standby or Shutdown Mode, (I\textsubscript{CS} &lt; C/10)</td>
<td>Not Charging – NTC/Bad Battery Fault Or Shutdown</td>
</tr>
<tr>
<td>OFF ON</td>
<td>ON</td>
<td>Bad Battery Fault</td>
<td>Float Charge</td>
</tr>
<tr>
<td>ON OFF</td>
<td>OFF</td>
<td>Charging Cycle OK: Trickle Charge or (I\textsubscript{CS} &gt; C/10)</td>
<td>Absorption Charge</td>
</tr>
<tr>
<td>ON ON</td>
<td>ON</td>
<td>NTC Fault</td>
<td>Bulk Charge</td>
</tr>
</tbody>
</table>

Table 2 Battery Charging IC LED Status

The soft-start feature is particularly important when using any type of AC motor or generator to allow proper build up during the start-up because of increasing torque being applied to the motor/generator. This initial torque will drastically reduce once the motor /generator is up to speed due to reduced kinetic energy. By allowing the IC’s to start up
milliseconds after the PMG is up to speed allows for a consistent and efficient use of their components and reduces stress on the IC’s and loads.

4.2.7 Filter Design

The filter design for this project was mostly to ensure the least amount of ripple for the DC output of the bridge rectifier and the output voltages of IC’s. However, each IC has associated filter design to ensure proper configuration for the specific voltage outputs and currents and came pre-packaged on the LTC3789 and LTC4020 demo boards. Calculations for a re-design of the filtering for inputs and outputs on the IC’s will require the equations from the manufactures datasheets, refer to APPENDIX A & APPENDIX B.

4.2.7.1 Input & Output Filtering

For the input, filter capacitance is essential when trying to accomplish as close as possible to DC volts. The goal is to minimize the ripple voltage. For the IC’s chosen, a ripple voltage of less than 500 mVpp was desired. Considering that the input current is continuous during the boost region and is discontinuous during the buck region of the LTC3789, finding Cin is limited by the input RMS current.

\[
I_{\text{RMS}} \approx I_{\text{OUT(MAX)}} \cdot \frac{V_{\text{OUT}}}{V_{\text{IN}}} \cdot \sqrt{\frac{V_{\text{IN}}}{V_{\text{OUT}}} - 1} \quad \text{(eq. 29)[1]}
\]

\[
I_{\text{RMS}} \approx 1.2 \cdot \frac{12}{36} \cdot \sqrt{\frac{36}{12}} - 1 = 566 \text{ mA} \quad \text{(eq. 30)[1]}
\]

For Cout it will try to reduce the output voltage ripple and can be found by using the following equation:

\[
V_{\text{OUT(Ripple)}} = \frac{I_{\text{OUT(MAX)}} \cdot (V_{\text{OUT}} - V_{\text{IN(MIN)}})}{C_{\text{OUT}} \cdot V_{\text{OUT}} \cdot f} \quad \text{(eq. 31)[1]}
\]

\[
\therefore C_{\text{OUT}} = \frac{I_{\text{OUT(MAX)}} \cdot (V_{\text{OUT}} - V_{\text{IN(MIN)}})}{V_{\text{OUT(Ripple)}} \cdot V_{\text{OUT}} \cdot f} \quad \text{(eq. 32)[1]}
\]

\[
C_{\text{OUT}} = \frac{1.2 \cdot (12 - 6)}{500 \cdot 12 \cdot 600 \cdot 10^3} = 2 \mu\text{F} \quad \text{(eq. 33)[1]}
\]
4.2.7.2 EMI Design

EMI must be taken into consideration for multiple reasons. The LTC3789 & LTC4020 both have MOSFET’s that have high switching load-on and load-off transients and are designed to drive large capacitances where the bypass capacitor locations must be considered to prevent corrupting the signal ground references. As with most electrically operated drones and RC vehicles, the DC outboard running motors produces high magnetic frequencies. This magnetic frequency interference could drastically affect the IC’s DC-DC converter inductors. Most of these vehicles have a neutral zone that will help minimize the EMI effects which is typically located at the furthest point from the motors. Also to consider, the PMG itself will also produce a magnetic field that could impact the electronics on both the vehicle and the automatic controller. Location or design of a housing unit for the PMG must be taken into consideration to reduce the EMI effects.

4.2.8 PCB Layout Design

The PCB layout for the demo boards used in the proof of concept project can be found in APPENDIX C & APPENDIX D. The prototype PCB layout will closely represent the PCB layout design from the demo boards, as this was the manufactures recommended layout to reduce EMI effects and maximize performance and use of real estate. When designing the PCB layout for the Automatic PMG Controller all EMI concerns will need to be considered as well as the design aspect of maintaining the smallest package to ensure proper weight constraints are not exceeded.

4.3 Simulation & Testing

The following sections hold images gathered during simulation or actual testing. The simulation was built to the design specifications of using an 11.1 V 3S (3-cell) battery for charging depleted to 9.3 volts at an accelerated charge rate of 6.0 amp-hours for the LTC4020 and a voltage output of 12.0 volts at 2 amps (maximum) from the LTC3789. Some challenges the arose during simulation was finding the right combination of components to allow for an accelerated charging rate to expedite results as well as allowing for immediate start-up sequences. By changing the soft start capacitor values to a much lower value, almost non-existent, this allowed for immediate start-up sequences.
and speed up the simulation results. Also it was important to see the initial start-up of the PMG output characteristics with the AC power supplies initially starting at zero to better characterize realistic start-up impacts to the input voltages to the IC’s.

4.3.1 Simulation

4.3.1.1 Input Power Source

The figures below (see fig. 20 & Fig. 21) both show the start-up of the 3 phase PMG source with an overlaid waveform of the DC output of the full-wave rectifier (input voltage to IC’s). As the voltage rises in one single phase the input voltage to the IC’s begin to rise with it. As the one single phase begins to fall the filtering capacitor begins to hold a charge, thereby allowing the input voltage to slowly fall in comparison to the AC voltage source. At the intersection of the first phase and second phase, separated at 120 degrees, the first phase continues to fall while the second is rising, where the input voltage begins to rise more. Once the second phase begins to fall from its peak value the charge that is stored in the filter capacitor will continue to hold the input voltage allowing it to slowly fall in comparison to the second phase. This process is repeated from phase to phase and the DC output will rise and fall until maximum charge on the filter capacitor is obtained, where the filter capacitor will minimize any ripple in the input voltage to the IC’s by removing any large amounts of peak-to-peak values, thereby optimizes the DC representation of the AC voltage source into the IC’s to be regulated.

![Fig. 20 PMG Source with Bridge Rectifier Output Voltage (Vin)](image-url)
4.3.1.2 Buck-Boost Micro-Controller

The buck-boost micro-controller, LTC3789, has the task of maintaining the PMG’s output for the vehicle to use. In the images below, its operations are described. The figure below (see Fig. 22) shows the micro-controller in buck mode of operation (Vin > Vout). Where Vin is equal to approximately 35 VDC and Vout is equal to approximately 12.0 VDC.

In figure below (see Fig. 23) the load was set to a single non-changing load of 10 ohms, Vout is equal to approximately 12.0 VDC and Iout is approximately 1.2 Amps. A better understanding and further research of a typical vehicle’s dynamic load characteristics will need to be determined in order to better simulate the load changes of a normal system.
However, for proof of concept for the Automatic PMG Controller, a single non-changing load was found to be sufficient.

From the concept of design, it was desired to minimize the output voltage ripple in order to supply an optimized DC output due to the vehicles typical pulse width modulated loads. The intent was to ensure minimum amount of disturbance to the pulse width modulator source and ensure optimum cycles when activated. The figure below (see Fig. 24) depicts that the output voltage ripple was equal to approximately 45 mV.
One major aspect of the design concept is the amount of current through the buck-boost inductor as well as the battery charging buck-boost inductor. The figure below (see Fig. 25) shows the maximum peak-to-peak value of the buck-boost inductor current for the micro-controller. The maximum inductor current peak-to-peak value during normal buck mode of operation is approximately 4 Amps (pk-pk).

![Fig. 25 Buck-Boost Micro-Controller Inductor Current](image)

4.3.1.3 Battery Charging Circuit

The battery charging IC, LTC4020, has the task of using the PMG’s energy to control the sourcing of electrons to be stored into the battery. It will not only charge a depleted battery but will maintain a nominal surface charge to ensure optimum operation as long as the PMG is spinning. In the images below, its operations are described. The figure below (see Fig. 26) shows the battery voltage and battery current, which depicts the scenario of having a battery depleted from 9.3 VDC and being charged to 11.1 VDC.
The battery charging IC contains its own inductor for its buck-boost converter but is still yet another major aspect of the design concept when determining the amount of current through the battery charging buck-boost inductor. The figure below (see Fig. 27) shows the maximum peak value of the buck-boost inductor current for the battery charging IC. The maximum inductor current peak value during bulk charge is approximately 14 Amps (pk).
4.3.1.4 Full System Integration

The figures below depict the full system integration, i.e. PMG input source, Buck-Boost Micro-Controller, Battery Charging IC, and Load. The same load was chosen for full system integration to ensure similar results from individual IC simulation. The figure below (see Fig. 28) depicts the buck-boost micro-controller output voltage at approximately 12 VDC and the battery voltage depleted to 9.3 VDC and being charged to approximately 11.5 VDC.

![Fig. 28 Vout (black) & Vbat (red)](image)

The figure below (see Fig. 29) depicts the buck-boost micro-controller output Current at approximately 12 VDC and the battery voltage depleted to 9.3 VDC and being charged to approximately 11.5 VDC.

![Fig. 29 Iout (black) & Icharge (red)](image)

Overall the simulation was a success at proving the concept of adding a PMG and regulating its outputs to a determinant load setting. To improve on simulation further development and research of the vehicles dynamic loads during a normal and non-typical operation would improve on the simulation results. Since there is very little to no data or
research in this area, actual testing would be more suitable to begin building a model of
the dynamic loads in these situations. Furthermore, a model for the Automatic PMG
Controller would also be useful during the initial simulation of the dynamic loads
simulation.

4.3.2 Prototype Testing

For the actual hardware testing of the Automatic PMG Controller, demo boards of
both the LTC3789 and LTC4020 with modifications to suit the design in simulations
were found to be sufficient for verifying the simulations results and design concept. It
was also determined that a DC power supply was a sufficient primary source in place of
the PMG and full-wave rectifier assembly. To verify simulation the following test
equipment was utilized:

- 30 VDC, 5 Amp DC Power Supply
- 4-Channel 100 MHz Oscilloscope
- High Resolution DMM
- RF Radio Transmitter

The images in the following sections depicts actual hardware testing of the Automatic
PMG Controller

4.3.2.1 Test Setup

The figure below (see Fig. 30) shows the entire test setup for the evaluation of test
results. Both the LTC3789 and LTC4020 have been modified to represent the simulation
design for comparison to simulation results.
Fig. 30 Test Setup

The figure below (see Fig. 31) is the mock-up design of the Automatic PMG Controller with the addition of the vehicle's LiPo battery and a single Pulse Width Modulated (PWM) load that is controlled by a receiver which receives transmitted radio frequencies from the RF radio transmitter, which represents a typical load scenario of drone type of vehicle.
Fig. 31 Automatic PMG Controller

LTC3789 was modified to set the maximum current output to be 6 amps via a resistor divider network and fashioned such that it meet the IC’s topology calculations in the manufacturers datasheet, refer to APPENDIX A. The figure below (see Fig. 32) shows the modified LTC3789 and its modified section to achieve a set current limit.
LTC4020 was modified to set the battery float voltage to be 11.1 VDC via a resistor divider network and fashioned such that it meet the IC’s topology calculations in the manufacturers datasheet, refer to APPENDIX B. The maximum battery charge current was found to be sufficient at 2 Amps. Through hole resistors were used due to insufficient surface mount parts available and were also found to be sufficient for proof of concept. The figure below (see Fig. 33) shows the modified LTC4020 and its modified section to achieve a set the battery float voltage.
4.3.2.2 Buck-Boost Micro-Controller

In this section will be depicting actual hardware electrical performance results from the buck-boost micro-controller, LTC3789, portion of the Automatic PMG Controller. The figure below (see Fig. 34) demonstrates the turn-on transient of the micro-controller and displays the input voltage into the buck-boost micro-controller at 26.4 volts and operating in buck mode with an output voltage of 13 volts. It is important to note, that the particular oscilloscope being used during testing was slightly out of calibration and was found to be approximately 1.5 volts higher than actual when compared to a calibrated DMM.
Fig. 34 Vin (yellow) & Vout (blue) Transient-On

The figure below (see Fig. 35) demonstrates the turn-off transient of the micro-controller and displays the input voltage into the buck-boost micro-controller at 26.4 volts and operating in buck mode with an output voltage of 13 volts.

Fig. 35 Vin (yellow) & Vout (green) Transient-Off
Both the turn-on and turn-off transients were found to be satisfactory and with no abnormalities. The input voltage and output voltage were also determined to be similar to the simulation results and design calculations. The figure below (see Fig. 36) shows driving MOSFET (Q3) duty cycle during normal operation (Buck Mode) for this prototype design at approximately 53% with a switching frequency of approximately 200 kHz, which also represents the duty cycle and frequency of the current through the inductor.

![Fig. 36 Driving MOSFET Duty Cycle (Q3-Source)]

4.3.2.3 Battery Charging Circuit

In this section will be depicting actual hardware electrical performance results from the battery charging IC, LTC4020, portion of the Automatic PMG Controller. The figure below (see Fig. 37) depicts the duty cycle and frequency of the driving MOSFET (M4) during normal operation (Bulk Charge) at 73.09% at approximately 175 kHz. This figure also show the input voltage from the rectified PMG voltage source at 25 volts.
Once the battery was fully charged to 11.7 volts a reading was taken of the battery at the output of the charging IC and was found to be approximately 13 volts on the un-calibrated oscilloscope (see Fig. 38). A reading was taken with a calibrated DMM at the same point and was found to be approximately 11.7 volts (see Fig. 40), which can be found in the full system integration section.

Fig. 38 Vin (yellow) & Vbat (blue)
4.3.2.4 Full System Integration

In this section will be depicting actual hardware electrical performance results from the full system integration of the buck-boost micro-controller and battery charging IC, which creates the one of the main functions of the Automatic PMG Controller. The figure below (see Fig. 39) depicts the input voltage to the buck-boost micro-controller and is also a zoomed in picture of the oscilloscope from Fig. 40. The input voltage was measured at 26.4 volts and the output voltage was measured at 13.6 volts.

![Fig. 39 Vin(yellow) & Vbat (blue)](image)

The figure below (see Fig. 40) shows the rectified PMG voltage source (DC power supply) to be at 25.3 volts and a battery voltage at approximately 11.7 volts and an input current of 200 milliamps. The oscilloscope reading is described in figure above (see Fig. 39).
Overall the prototyping and hardware electrical performance testing was a success at proving the concept of adding a PMG and regulating its outputs to a determinant load setting. There is one particular measurement that was challenging when gathering the results, which was the battery actually being charged in real time. The overall safety of testing with a LiPo battery is inherently hazardous due to it unstable and violent nature in the event of extreme depletion, exceeding amounts of current during bulk charge, and over charging. In order to properly measure the battery voltage and current during bulk charge, a safe environment must be put in place, such as a fire proof box to hold the battery during testing and a safe storage bag when not in any testing phases. The test environment during the proof of concept was not sufficient during hardware testing, therefore once the proper safety equipment has been put into place, further analysis of a complete battery charge cycle from maximum depletion will be in order. For the purpose of proof of concept the battery was depleted to 10.9 volts to ensure a shorter charge time to reach maximum charge. The hardware testing has proven the concept of mimicking an alternator in an automobile within a degree of scientific certainty by demonstrating that the Automatic PMG Controller is capable of accepting the power being supplied by a PMG energy source and managing the PMG’s power to supply the vehicles load demands while maintaining the surface charge on the vehicles on-board battery.
Summary/Contributions

The contributions of the Automatic PMG Controller is summarized to be the starting point of extending the flight time of small aerial drones by way of adding an additional energy source, aka the PMG, and controlling the output of such source. The Automatic PMG Controller was originally thought of to be compared to a voltage regulator for an alternator in an automobile. The PMG’s output would be controlled and regulated down to a usable level of which the vehicle could then use to supply its loads. This device will now allow the addition of the PMG to small aerial drones by providing the gateway between source and load, and by way of controlling that source of energy. With further development in studies and research into a multi-rotor vehicles dynamic load characteristics and demands, this technology can be improved and integrated into practical usage. Furthermore, with this knowledge a small suitable PMG can either be picked from the market or there will be a need to design a small PMG that will meet the dynamics of the loads on a small drone, based on load studies performed. A better understanding of the vehicles current and power demands will better depict the exact needs for both the controller and PMG design. This controller is only the beginning to extending the flight time of these drones but has, at the very least, shown a major problem with the current flight performances of today’s small electrical drones and has provided a possible solution to such concerns. By adding the PMG and internal combustion engine to rotate the PMG and the Automatic PMG Controller regulating the PMG’s output, the flight time can be increased by a determinant amount only constrained by the vehicles weight carrying capacity and fuel tank size that is selected. In conclusion this topology could be utilized on multiple types of small platforms to increase the vehicles run-time and in simplistic terminology this could be considered as the gateway into hybrid technology for UAV drones. There is still much work to be accomplish with this design, however this should serve to prove the concept of operations for the Automatic PMG Controller to move forward in the design and testing process of adding a PMG as a primary source of energy in addition to the vehicles battery systems.
References


Figure References


Fig. 11. http://cds.linear.com/docs/en/datasheet/3789fc.pdf.


Table References


About the Author

W. Scott Adkins is an Electrical Test Equipment Design Engineer at General Electric Aviation Systems, Dayton, Ohio, USA. He holds an A.A.S. Degree majoring in Automotive Technology from Sinclair Community College, Dayton, Ohio, USA, B.S. in Electrical Engineering from Wright State University, Dayton, Ohio, USA. He is also an Advanced Master Certified Technician accredited from Automotive Service Excellence (ASE). He has over 16 years of automotive experience and over 6 years of engineering experience. His interest are in power electronics, aviation power electronics, automotive innovation, Op-amp configurations, renewable energy, and drone technology.
APPENDIX A

HIGH EFFICIENCY, SYNCHRONOUS, 4-SWITCH BUCK-BOOST CONTROLLER

FEATURES
- Single Inductor Architecture Allows VIN Above, Below or Equal to the Regulated VOUT
- Programmable Input or Output Current
- Wide VIN Range: 4V to 38V
- 1% Output Voltage Accuracy; 0.8V ≤ VOUT ≤ 38V
- Synchronous Rectification: Up to 95% Efficiency
- Current Mode Control
- Phase-Locked Fixed Frequency: 200kHz to 600kHz
- No Reverse Current During Start-Up
- Power Good Output Voltage Monitor
- Internal 5.5V LDO
- Quad N-Channel MOSFET Synchronous Drive
- VOUT Disconnected from VIN During Shutdown
- Iron Soft Start and VOUT Short Protection, Even in Boost Mode
- Available in 26-Lead QFN (4mm x 5mm) and 26-Lead SSOP Packages

APPLICATIONS
- Automotive Systems
- Distributed DC Power Systems
- High Power Battery-Operated Devices
- Industrial Control

DESCRIPTION
The LTC3789 is a high performance buck-boost switching regulator controller that operates from input voltages above, below or equal to the output voltage. The constant-frequency, current mode architecture allows a phase-lockable frequency of up to 600kHz, while an output current feedback loop provides support for battery charging. With a wide 4V to 38V (40V maximum) input and output range and seamless, low-noise transitions between operating regions, the LTC3789 is ideal for automotive, telecom and battery-powered systems.

The operating mode of the controller is determined through the MODE/PLLIN pin. The MODE/PLLIN pin can select between pulse-skipping mode and forced continuous mode operation and allows the IC to be synchronized to an external clock. Pulse-skipping mode offers high efficiency and low ripple at light loads, while forced continuous mode operates at a constant frequency for noise-sensitive applications.

A PGOOD pin indicates when the output is within 10% of its designated set point. The LTC3789 is available in low profile 26-pin 4mm x 5mm QFN and narrow SSOP packages.

For more information, visit www.linear.com/LTC3789
APPENDIX B

FEATURES
- Wide Voltage Range: 4.5V to 55V Input, Up to 55V Output (58V Absolute Maximums)
- Synchronous Buck-Boost DC/DC Controller
- Li-Ion and Lead-Acid Charge Algorithms
- ±0.5% Float Voltage Accuracy
- ±5% Charge Current Accuracy
- Instant-On for Heavily Discharged Batteries
- Ideal Diode Controller Provides Least PowerPath When Input Power is Limited
- Input Voltage Regulation for High Impedance Input Supplies and Solar Panel Peak Power Operation
- Onboard Timer for Protection and Termination
- Bad Battery Detection with Auto-Reset
- NTC Input for Temperature Qualified Charging
- Binary Coded Open-Collector Status Pins
- Low Profile (0.75mm) 38-Pin 5mm x 7mm QFN Package

APPLICATIONS
- Portable Industrial and Medical Equipment
- Solar-Powered Systems
- Military Communications Equipment
- 12V to 24V Embedded Automotive Systems

DESCRIPTION
The LTC4020 is a high voltage power manager providing PowerPath™ instant-on operation and high efficiency battery charging over a wide voltage range. An onboard buck-boost DC/DC controller operates with battery end float system voltages above, below, or equal to the input voltage.

The LTC4020 seamlessly manages power distribution between battery and converter outputs in response to load variations, battery charge requirements and input power supply limitations.

The LTC4020 battery charger can provide a constant-current/constant-voltage charge algorithm (CC/CV), constant-current charging (CC), or charging with an optimized 4-step, 3-stage lead-acid battery charge profile. Maximum converter and battery charge currents are resistor-programmable.

The IC’s instant-on operation ensures system load power even with a fully discharged battery. Additional safety features include pre-conditioning for heavily discharged batteries and an integrated timer for termination and protection.

TYPICAL APPLICATION
Buck-Boost DC/DC Converter Controller with PowerPath Battery Charger Accepts Inputs from 4.5V to 55V and Produces Output Voltages Up to 55V

5V to 3.3V 5-Cell Lead-Acid Supply/Charger Maximum Power Efficiency vs Vin (Application Circuit on Page 3/7)
APPENDIX C

DEMO MANUAL DC1757A
LTC3789EGN
High Efficiency
12V/12A Buck-Boost Converter

DESCRIPTION

Demonstration circuit 1757A is a high efficiency synchronous buck-boost DC/DC converter with a 6V to 36V input voltage range. It can supply a 12A maximum load current with a 12V output. The demo board features the LTC3789EGN controller. The constant frequency current mode architecture allows a phase-lockable frequency of up to 600kHz, while an optional output current feedback loop provides support for applications such as battery charging.

With a wide input range, wide output range and seamless transfers between operation modes, the LTC3789 is ideal for automotive, telecom, distributed DC power systems and battery-powered applications.

The light load operation mode of the converter is determined with the MODE/PLLIN pin. Use JP2 jumper to select pulse-skipping mode or forced continuous mode (CCM) operation. The switching frequency is pre-set at about 200kHz. The converter can also be externally synchronized to an external clock through the MODE/PLLIN pin (PLLIN terminal on the board). To shut down the converter, force the RUN pin below 1.2V (JP1: OFF). The power good output (PGOOD terminal) is low when the output voltage is outside of the ±10% regulation window.

Design files for this circuit board are available at http://www.linear.com/demo

PERFORMANCE SUMMARY (TA = 25°C)

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<thead>
<tr>
<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>Input Voltage Range</td>
<td>6V to 36V</td>
<td>6V to 36V</td>
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<tr>
<td>Output Voltage, Vo</td>
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<td>12V ±2%</td>
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<tr>
<td>Maximum Output Current, Iout</td>
<td>12A</td>
<td>12A</td>
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<tr>
<td>Typical Output Ripple, Vripple</td>
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<td>100mVp-p</td>
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<td>Typical Efficiency, η</td>
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<tr>
<td>Typical Switching Frequency</td>
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<td>200kHz</td>
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</table>

QUICK START PROCEDURE

Demonstration circuit 1757A is easy to set up to evaluate the performance of the LTC3789. Refer to Figure 1 for the proper measurement equipment setup and follow the procedure below:

1. With power off, connect the input power supply to VIN (6V to 36V) and GND (input return).
2. Connect the 12V output load between VOUT and GND (initial load: no load).
3. Connect the DVMs to the input and outputs.
4. Turn on the input power supply and check for the proper output voltages. VOUT should be 12V ±2%.
5. Once the proper output voltages are established, adjust the loads within the operating range and observe the output voltage regulation, ripple voltage and other parameters.
APPENDIX D

DEMO MANUAL DC2134A
LTC4020EUHF
High Power Buck-Boost
Multi-Chemistry Battery Charger

DESCRIPTION

Demonstration circuit 2134A is a high power buck-boost multichemistry battery charger featuring the LTC®4020. The board will accept an input voltage between 15V and 55V. The float voltage of the battery output (BAT) is 25.2V, with 6.3A maximum charge current. The converter output (V_OUT) has a voltage range of 21V to 28V, with 8A maximum load current. The LTC4020 contains a high efficiency synchronous buck-boost DC/DC controller, and uses a proprietary average current mode architecture.

The LTC4020 battery charger can provide a constant-current/constant-voltage charge algorithm (JP1: CC/CV, with mode pin grounded), constant-current charging (JP1: CC, with mode pin floated), or charging with an optimized 4-step, 3-stage lead-acid battery charge profile (JP1: lead-acid, with mode pin connected to INTV_CT).

The LTC4020 data sheet gives a complete description of the IC operation and application information. The data sheet must be read in conjunction with this quick start guide.

Design files for this circuit board are available at http://www.linear.com/demo/DC2134A

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<tr>
<th>PARAMETER</th>
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<tr>
<td>Input Voltage Range</td>
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<td>Battery Float Voltage (BAT) (Nominal)</td>
<td>I_BAT = 0A</td>
<td>25.2V</td>
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<tr>
<td>Converter Output Voltage (V_OUT)</td>
<td>I_OUT = 0A to 8A</td>
<td>21V to 28V</td>
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<tr>
<td>Maximum Battery Charge Current, I_BAT</td>
<td>I_OUT = 0A</td>
<td>6.3A</td>
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<tr>
<td>Maximum Converter Output Current, I_OUT</td>
<td>I_BAT = 0A</td>
<td>8A</td>
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<tr>
<td>Typical Efficiency</td>
<td>Y_MIN = 24V, Y_OUT = 25.2V, I_OUT = 8A</td>
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<tr>
<td>Typical Converter Output Ripple</td>
<td>Y_MIN = 55V, Y_OUT = 25.2V, I_OUT = 8A (20MHz Bandwidth)</td>
<td>109mVp-p</td>
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