Bi-directional Power System for Laptop Computers

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Abstract- Today the typical laptop computer uses three to five Li-Ion battery cells in series for efficient energy storage. For a typical four-cell system, the Li-Ion stacked cell voltage ranges from 10.8V to 16.8V. This high voltage poses a problem when attempting to step down to the necessary low voltages internal to the laptop. A new “intelligent” power management system is proposed that will enable the ac-dc converter to provide a regulated lower output voltage while still using three or more series Li-Ion cells as the main backup power source.

I. INTRODUCTION

Laptop computers are powered from three to five series connected multiple cell Li-Ion batteries when ac derived power is removed. Multiple series connected cells are used to provide efficient energy storage. While using fewer batteries in series may reduce the voltage of the battery pack, it increases the current requirements of the Li-Ion batteries. This higher current decreases the efficiency of the energy conversion during charge and more importantly discharge (as a result of internal battery and contact resistance).

The voltage range for a single Li-Ion cell is 2.7V minimum to 4.2V maximum. With four series connected cells, the dc voltage provided by the battery string will range from 10.8V to 16.8V. The input ac-dc converter “lump in the line” used to provide power to the Li-Ion battery charger for a four-cell application is typically 19.5V. This provides enough headroom to charge the batteries at their maximum constant voltage of 4.2V per cell. This same 19.5V ac-dc converter is used to provide input power for the laptop dc-dc converters.

Laptop system processor voltages are low, typically less than 1.4V. This low processor core voltage requirement will continue to be reduced to sub 1V levels to increase the speed of the computer. While the laptop is operating from the 19.5V ac-dc input or 4 cell Li-Ion voltage range, the process of stepping this high voltage down to the 1.2V or below is not ideal in terms of efficiency and frequency of operation. A non-isolated buck regulator would be the most common method of stepping the high 19.5V down to 1.2V. The ideal duty cycle (% of switch on time) is 7% for a 19.5V to 1.4V conversion. High frequency operation and efficiency are compromised while operating at very low and very high duty cycles.

As shown below in Fig.1, power switches are used to select the source that powers the laptop. When ac input is available, the horizontal switches are on, providing a path from the ac-dc to the internal dc-dc converters. With ac input removed, the input power for the laptop is provided by the series Li-Ion cells through the vertical power switches. For this architecture, multiple power path switches are used to select the input source. All of these switches must be low on resistance to minimize the voltage drops.

II. A NEW APPROACH

The wide voltage range of the series connected Li-Ion battery pack compromises the power system architecture of the laptop computer. An ideal system architecture would provide a common low input ac-dc bus voltage for the laptop dc-dc converters and the battery charger. This would enable the use of efficient, high frequency, low voltage dc-dc converters, resulting in smaller more efficient computers.

This ideal approach would boost a low ac-dc bus voltage to charge the series connected Li-Ion batteries. With ac power removed, the Li-Ion battery pack voltage is stepped down to provide power to the common low dc bus voltage. While adding additional power stages is not ideal, this paper proposes utilizing the same power converter that charges the Li-Ion batteries to step the battery voltage down for regulated low voltage system dc-dc converters.

With ac input voltage present, the regulated ac-dc converter delivers a lower voltage that powers the laptop dc-dc converters and also provides the input power to the synchronous boost battery charger. When the input voltage is removed, the synchronous boost now operates like a synchronous buck converter and regulates the laptop dc-dc converter input voltage slightly lower than the ac-dc input. This architecture provides a
regulated low voltage input for systems powered from the ac input or the series cell Li-Ion battery pack.

The bi-directional buck or boost power converter should not be confused with a conventional buck-boost converter. The bi-directional converter can not buck-boost. It operates in either buck mode (while delivering energy from the Li-Ion cells to the laptop dc-dc converters), or boost mode (stepping up the low regulated dc-bus voltage for constant current / constant voltage charging).

III. BI-DIRECTIONAL POWER CONVERTER ADVANTAGES

Listed in priority, there are many power system advantages to the bi-directional architecture.

- Single power train for battery charger (boost) and battery dc-dc converter (buck). This reduces the number of power switches and switching regulators necessary.

- Provides a regulated low voltage input to laptop dc-dc converters. Power conversion cost, size and efficiency are all impacted by range of input voltage. For the existing laptop architecture, pulse width duty cycles as low as 7% are necessary to convert a 19.5V input to a 1.4V output. Simple buck regulator switching losses and steady state losses are higher as a result of the high input voltage. Dc-dc converters, used to develop the low processor core voltages for high speed computing, are smaller and more efficient when the input voltage range is limited to lower voltages.

- Eliminate the need for power transfer switches. The input source can be “hot” plugged into and out of the laptop. When plugged in, the system will run off of the ac input while the battery is charged. When ac is removed, the bi-directional converter will supply power to the low voltage dc-bus.

- Boosting the low voltage dc input to charge the battery minimizes the chopped input current typical of buck converters lowering electromagnetic interference.

IV. BI-DIRECTIONAL BATTERY CHARGER / POWER SUPPLY IMPLEMENTATION

A PIC16F88 Flash microcontroller combined with a high frequency analog pulse width modulator (MCP1630) were used to manage the function of the bi-directional converter as shown in figure 3. The PIC® microcontroller communicates with a battery manager, (Microchip PS501 located internal to the battery pack), that provides the state of charge information from the batteries.

The battery manager collects precise battery data (temperature, voltage, charge and discharge currents). This data is reported over the SMBus interface to the PIC microcontroller based bi-directional laptop charger / power supply.

The PIC microcontroller processes the battery manager data and computes the charge current and charge time while continuously updating the charge current setting. While charging, the bi-directional boost converter functions as a programmable current source. Once the Li-Ion battery pack reaches the constant voltage phase of the charge cycle, the PIC microcontroller continuously adjusts the charge current to maintain constant battery voltage until the charge cycle is complete.

Once complete, the PIC microcontroller sets the charge current to zero. While programmed to zero charge current the bi-directional converter operates at a duty cycle that will not charge the battery (boost) nor discharge the battery (buck). When the high side switch is on, energy is removed from the battery; when turned off, that same energy is returned to the battery. Average battery current is equal to zero while the converter is still operational. It is important for the bi-directional converter to be switching even when not charging the batteries. It must be ready to provide power to the dc-bus in the event of ac input interruption.

All Li-Ion battery packs must have integrated protection. This protection includes two back to back switches, a fuse (non-re-settable or re-settable) and a sense resistor. The sense resistor connection is necessary for the bi-directional converter as analog feedback for the high-speed analog loop closure (Fig.3).

With the ac-dc power removed the bi-directional converter will automatically switch to buck mode. A resistor divider and error amplifier are used to regulate the bi-directional converter while bucking the battery voltage down to the low dc-bus voltage.

Two loops are used to control the bi-directional converter. While operating from batteries, a voltage mode loop is used. While operating from the ac input source and stepping up the input, a voltage controlled current source is used.
As shown above in Fig.4, two control loops are summed together then fed into the MCP1630 to perform the high-speed analog control function.

When the ac input is not available, the resistor divider connected to the dc bus voltage is used to set the regulation point of the bi-directional converter while bucking down the battery pack voltage. The voltage regulation point is flexible and was set to 6V. The I_amp non-inverting input is sensing the voltage drop across the battery current sense resistor. With the bi-directional converter transferring energy from the battery pack to the dc bus, the voltage drop across the sense resistor is negative (below ground). This drives the I_amp output into the lower rail (virtual ground) providing the lower half of a divider for the V_amp to work into to regulate the dc bus voltage.

The ac-dc input voltage is set slightly higher than the regulated buck dc voltage. In this case it was set to 7V. When plugged into the laptop, the dc-dc converters will operate directly from the ac-dc input. The V_amp inverting input is driven above the set regulation point driving the voltage error amplifier output into the low rail (virtual ground). This now provides a divider for the I_amp amplifier to work into to regulate the dc bus voltage.

By communicating with the battery manager, the bi-directional converter uses the battery cell voltages (not terminal voltage), current and temperature to set the charge current. With this information the charge cycle can be accelerated. Resistance between the battery terminals and cell connections (contact resistance, protection switch resistance and current sense resistance) introduce voltage drops during charge and discharge cycles. The bi-directional converter can compensate for the voltage drops by charging the battery terminals at a higher voltage. At lower temperatures, the battery charge rate can be increased to reduce the charge time of the batteries.

The common error voltage signal developed by the two control loops is fed into the MCP1630 to generate the proper pulse width. This signal is compared with the ramp generated from the OSC input (provided by the microcontroller). The range of this error signal is bounded by the 15 kΩ and two 10 kΩ resistors that form the control loop dividers. Bounding the duty cycle so that it can never reach 100% is a boost converter requirement. The maximum buck duty cycle is set by the pulse width of the OSC IN provided by the microcontroller. The buck duty cycle should never reach 75% with the minimum four-cell battery voltage equal to 10.8V and the buck output voltage set to 6V.

Once the battery has reached full charge, the battery manager will provide an offset voltage reference to program the charge current to zero. An offset voltage is used to ensure that the PIC microcontroller can program zero current (programmed offset is larger than amplifier offset) to terminate a charge cycle. Li-ion batteries must terminate charge when the battery manager indicates that the batteries are full.

The bi-directional converter is able to respond to the drop in dc-bus voltage when the input ac-dc power is removed (dc-bus voltage drops from the ac input 7V supply).
V. EXPERIMENTAL RESULTS

The bi-directional power converter was prototyped for proof of concept. Lab data was collected and is reported in this section. Converter efficiency exceeded 93.5% while bucking from four series cell Li-Ion batteries. Power was abruptly connected and removed to evaluate the speed of recovery in both directions. Oscilloscope plots are shown in Fig. 8 and Fig. 9.

Experimental results were taken from a converter using the following parameters.

Table 1. Experimental Power System Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency</td>
<td>500 kHz</td>
</tr>
<tr>
<td>Typical Efficiency</td>
<td>93.5%</td>
</tr>
<tr>
<td>Inductor Value</td>
<td>15 µH</td>
</tr>
<tr>
<td>Ac Bus capacitance</td>
<td>200 µF</td>
</tr>
<tr>
<td>Battery capacitance</td>
<td>20 µF</td>
</tr>
<tr>
<td>Dc Bus Voltage (Buck Operation)</td>
<td>6V</td>
</tr>
<tr>
<td>Dc Bus Voltage (Boost Operation)</td>
<td>7V</td>
</tr>
</tbody>
</table>

Efficiency is a key figure of merit for a battery powered laptop computer application. While delivering energy from the battery to the laptop, efficiency is the most critical.

Data was taken for this 500 kHz synchronous converter over input voltage and load. The trade-off in efficiency is between the buck generated dc-bus voltage and the laptop dc-dc converters. The efficiency of the bucking bi-directional power converter will be higher for higher output voltages while the efficiency of the laptop low voltage output converters would decrease with a higher input voltage. As stated, the bi-directional buck output voltage can be set to a wide range of voltages.

Another important feature of the bi-directional power system is its ability to regulate the dc-bus voltage with the removal of input power. Fig. 8 displays the dc-bus voltage as input power is removed. For this most critical transition (losing input power), the ac-dc input voltage is higher (7V) than the regulated value of the bi-directional buck converter (6V). This 1V of “headroom” provides enough time for the charge current to reverse and provide energy to the low voltage dc-bus.

Live insertion of power without transfer switches is a key advantage of the bi-directional power converter. Fig. 9 below displays the dc-bus voltage perturbation while “hot” plugging the ac-dc input source. In this transition there is no emergency in starting the battery charge cycle. Using the microcontroller A/D, the pretence of the input voltage will be noted and battery charging will begin based on the information provided by the battery manager. This “live” insertion should not adversely effect the dc-bus voltage that is providing power to the laptop dc-dc converters.
VI. CONCLUSION

The bi-directional power converter can revolutionize the portable computer power system. By boosting the input voltage to charge the batteries and bucking the voltage down to a usable voltage, energy can be stored and delivered more efficiently. This topology reduces the number of components and simplifies the power management system for portable laptop computers. It enables the use of low input voltage, high frequency step down converters to regulate very low processor core voltage.

Because the ability to store energy at high voltages makes energy delivery more efficient, the bi-directional power converter can also be used for other energy storage portable applications.

Using a microcontroller and high-speed analog PWM enhances the laptop power management system. “smart” charger features can be implemented. High switching frequency and fast analog loop closure are key to maintaining regulation with the removal and insertion of the ac-dc input.

REFERENCES


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