A High Power Bi-Directional DC-DC Converter

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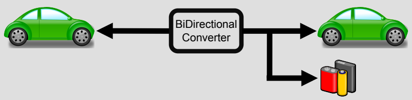
Abstract

This poster describes a high power, bi-directional DC-DC converter designed for NASA's newest robotic rover being developed at Johnson Space Center. Efficient bi-directional DC-DC conversion is essential for many electric vehicle operations:

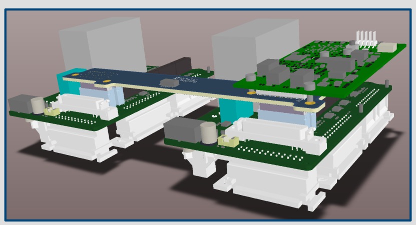
- Supplying regulated power from the batteries to the motors.
- Regulating transients during regenerative braking.
- Power transfer back and forth in flywheel designs.
- Vehicle-to-vehicle power transfer for on-the-go charging.

These functions require the ability to efficiently regulate output voltage and current in both directions through the converter. Furthermore, output voltages may need to be higher or lower than the input.

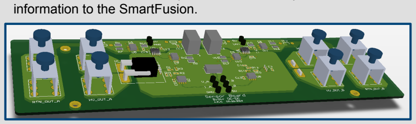


Hardware Design

The finished converter consists of several custom PCBs, all designed using Altium Designer. The main processing is done on an ARM Cortex M3 onboard an Actel SmartFusion (top right board in the picture below). Mitsubishi 3-phase IGBT half bridges are used for switching. Two custom boards containing a single Mitsubishi power module lay at the bottom of the assembly and are controlled by the SmartFusion.

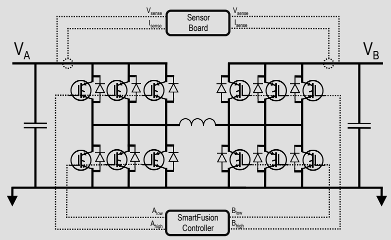


Isoalted current and voltage sensing is performed by an external sensor board. This board is pictured below and provides feedback information to the SmartFusion.



Converter Design

Topology
The converter takes advantage of a half bridge topology on both sides of the power inductor. The Mitsubishi 3-phase IGBT bridges are shorted together to create a single phase bridge with 3 times the current capacity, allowing up to 150 amps at 600 volts to flow in either direction. With a half bridge on each side of the converter, the same hardware can be used to buck, boost, and buck-boost. Since the converter is symmetric, anything that can be done one way, can also be done in the other direction.



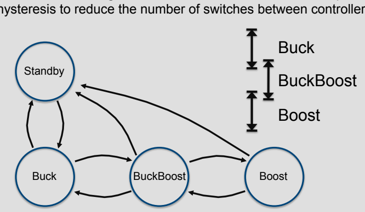
Buck
By switching the upper switches on the input side, the converter implements a buck stage from the input to a lower output voltage.

Boost
By switching the lower switch on the output side, the converter implements a boost stage from the input to a higher output voltage.

BuckBoost
By switching the upper switch on the input side and the lower switch on the output side, the converter implements a buckboost stage and creates an output voltage that either high or lower than the input voltage.

Operation

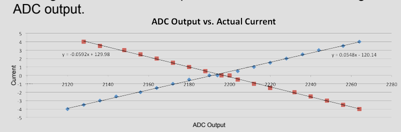
The converter must seamlessly transition between modes in order to provide the best vehicle performance. While a buckboost stage can provide lower and higher voltages, it requires two switching elements and thus results in twice the switching losses. For best performance, the buckboost stage should only be used when the output voltage target is fluctuating near to the input. The buckboost stage prevents transients that result from rapidly switching back and forth between bucking and boosting. A state machine was designed to switch between modes and provide hysteresis to reduce the number of switches between controllers.



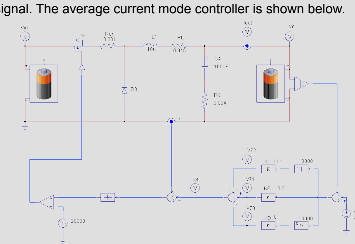
In 10A load tests, the buck and boost stages are 94% efficient. The buckboost stage is 91% efficient.

Software Controls

Implementation
All controllers were designed and simulated using the PSIM software package. Once validated, the controllers and state machine were implemented in C to run on the SmartFusion's ARM Cortex M3. Isolated current and voltage measurements were used as input. Accurate feedback control was obtained by utilizing the linear relationship between actual current/voltage and ADC output.

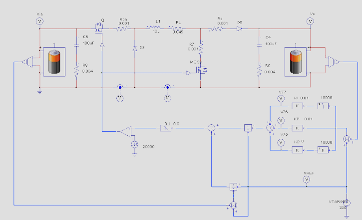


Average Current Mode Control
An average current mode (ACM) controller is used for the buck stage. The ACM controller works on the principle that the current over the inductor changes much faster than the output voltage of the system. There is a fast inner current loop and a slower outer voltage loop. A digital reference voltage is used to create the error signal which is fed into the PID controller to create the gate drive signal. The average current mode controller is shown below.

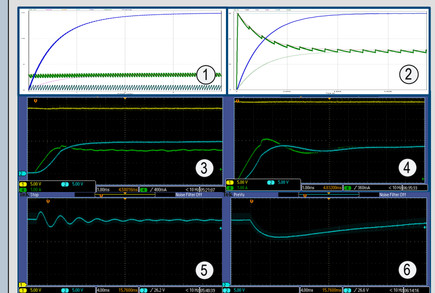


Constant Current Mode
For producing a constant current on the output at a voltage that is lower than the input, a modification of the ACM controller is used. The voltage loop in the above controller is removed, the new error signal becomes the digital reference current minus the system current, and the PID controller is moved downstream from the error current signal. This is a simple closed loop PID current controller.

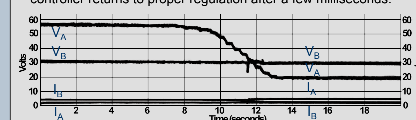
Voltage Mode Control
For both the boost and buckboost stages, a voltage mode controller is used. For this controller, an ideal feedforward reference duty cycle is created from the input voltage and the target output voltage. The difference between this ideal reference duty cycle and the PID compensated error signal is then used to drive the IGBT gates. The voltage mode controller as used for the buckboost stage is shown below.



Results

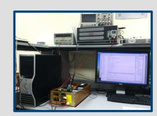


Plot 1 is a PSIM simulation showing a current step response for the constant current controller. Plot 3 is same test using the actual converter. Minimal overshoot is observed and the steady state current remains stable. Plot 2 is a PSIM simulation showing a voltage step response the ACM controller. Plot 4 is the same test using the actual converter. Plot 5 shows the voltage transient when the state machine transitions from the buckboost to the buck stage. Plot 6 shows the voltage transient when switching the boost to the buckboost stage. After a few volt transient, the controller returns to proper regulation after a few milliseconds.



Above is the CANalyzer output showing the converter successfully regulating V_B as V_A sweeps from high to low on a resistive load. V_B is kept constant as the converter switches from buck, to buckboost, to boost stages. Small transients are seen at controller transitions.

Future Work



This converter will sit between the wheel modules and the battery in the finished vehicle. Future work will involve working on the CAN interface to facilitate vehicle integration and bringing the converter from the lab to a vehicle. Another future area of work is to add a transformer for isolation between the A and B sides. An additional potential research area is investigation of 2 piece inductors to facilitate vehicle-to-vehicle links by having each vehicle contain half of the converter.

References

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