PHEV – Plug-In Hybrid Electric Vehicle Charger

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Why the electric car?

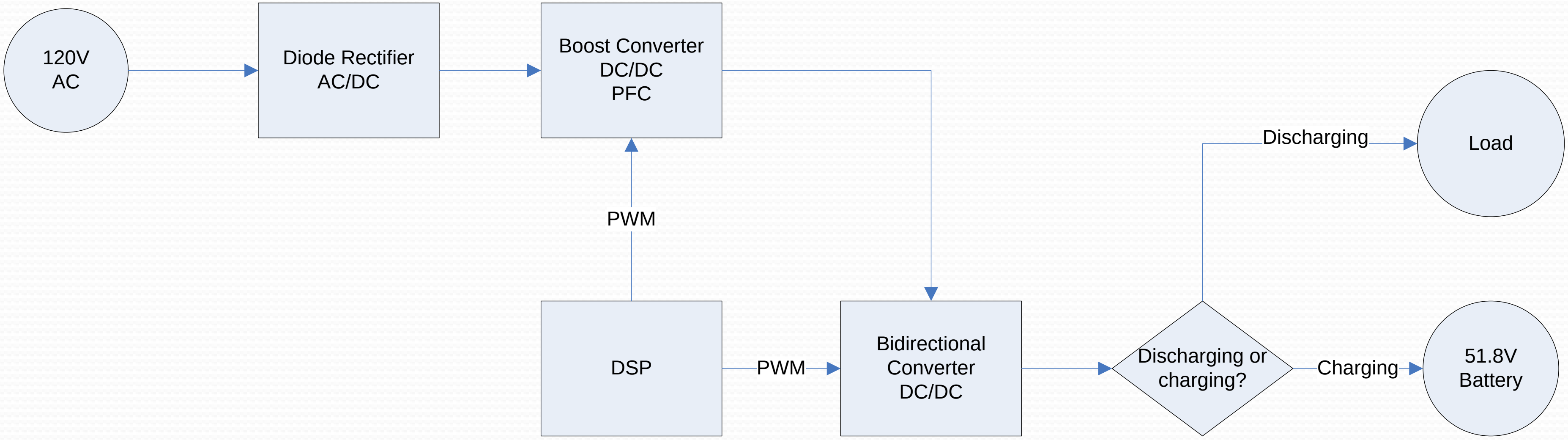
- Reduce our foreign oil dependence
- Reduce carbon emissions

Outline

- Functional Description
- Progression of Project
  - Implementation/Construction
  - Testing
- Results

Project Summary

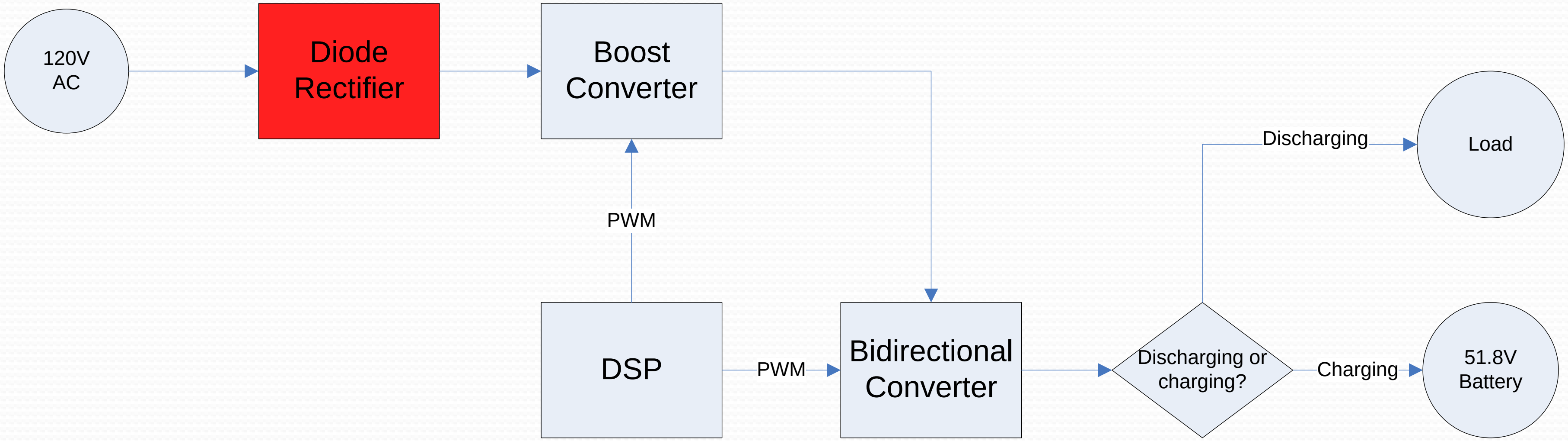
- Convert 120 volt AC grid power to the required 51.8[V] DC value to efficiently charge an electric vehicle battery
- Discharge battery via Bi-directional converter into a variable load



Project Goals

- Create a PHEV charging system capable of outputting up to 1k[W] of power for the operation of a variable load.
- Implement a control system using a DSP for the purpose of driving MOSFET gates
- Efficiently Charge a Li-Ion battery using our power electronics system

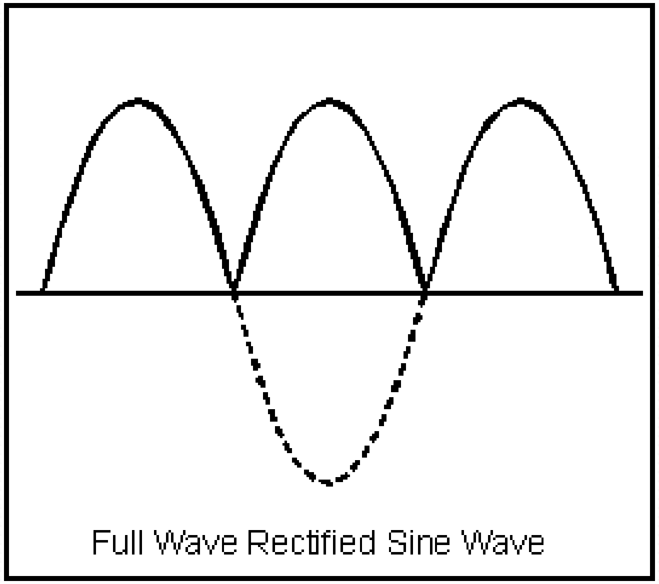
Diode Rectifier

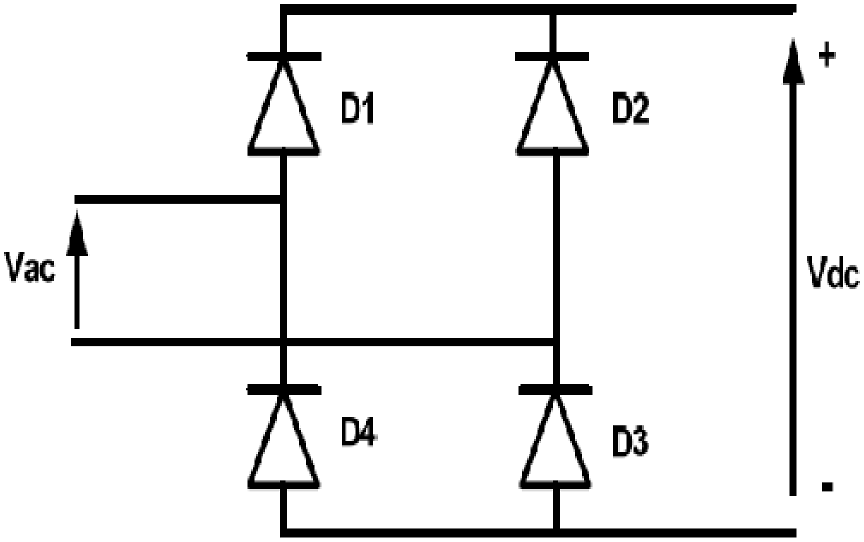


Functional Description

Diode Rectifier

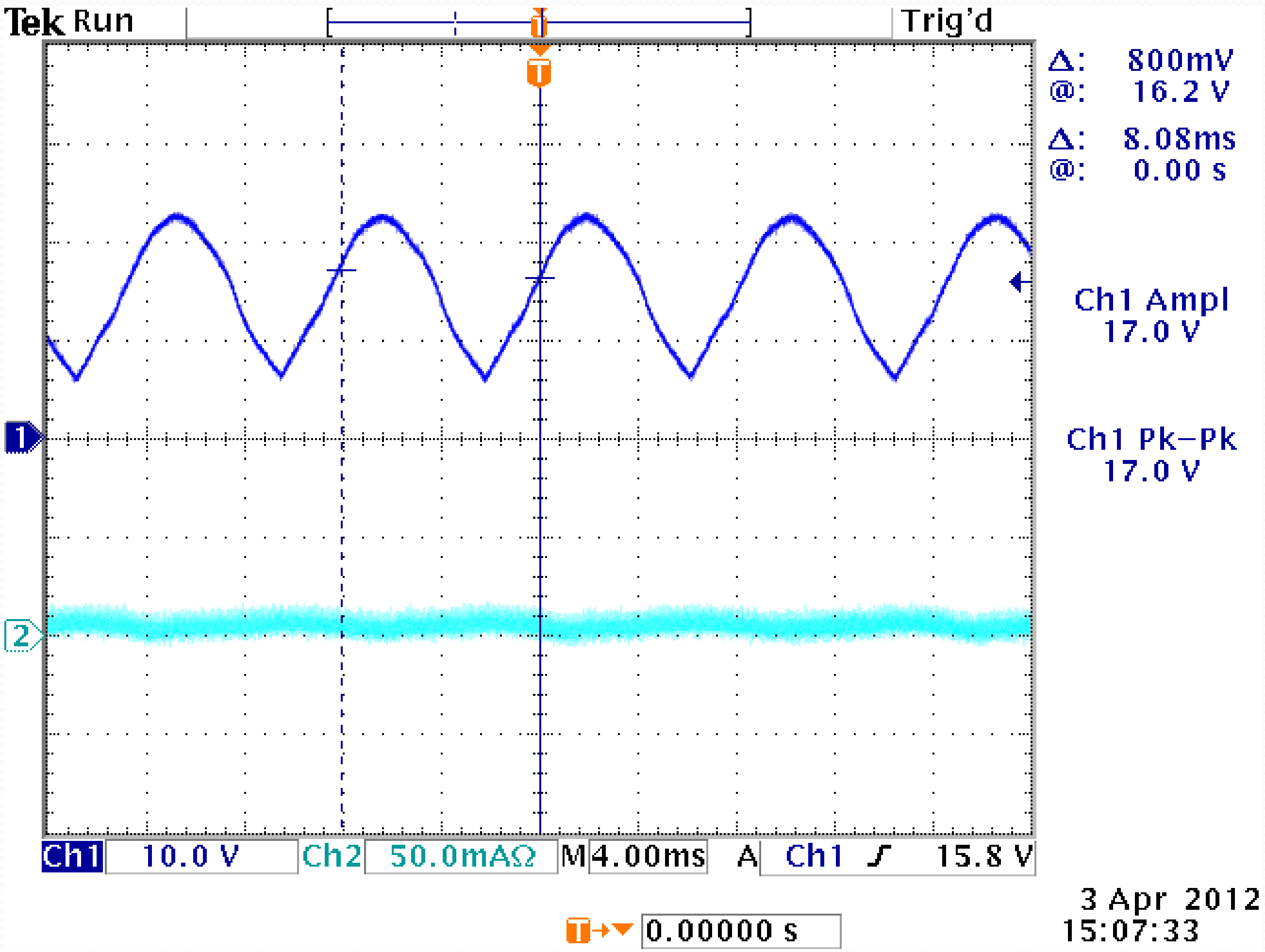
- Rectifies 120[V_{rms}] AC grid power
- Precedes Power Factor Correction



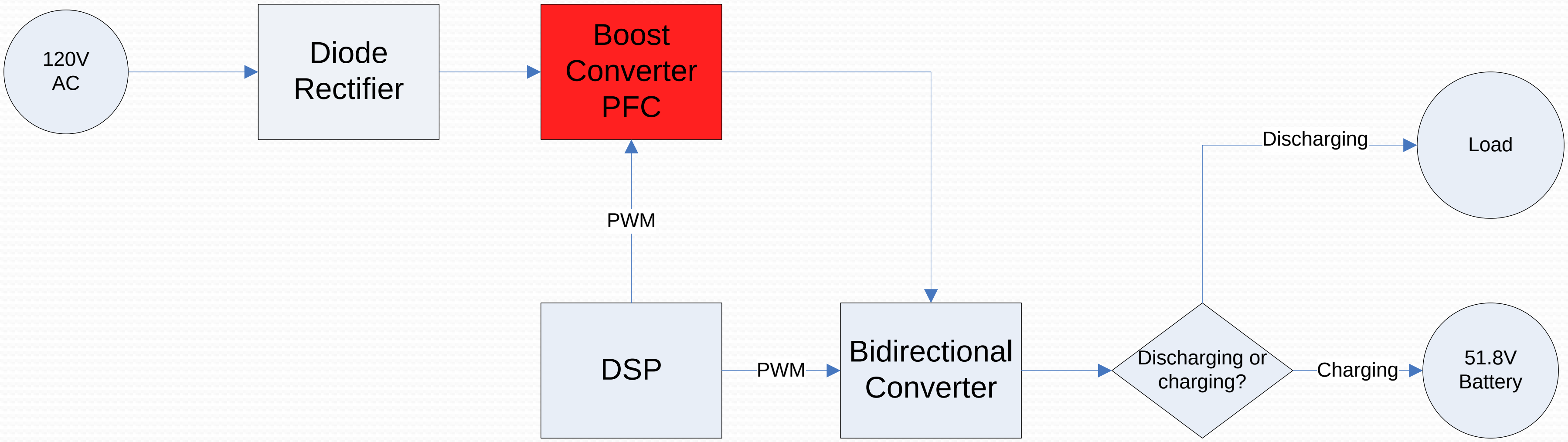


Functional Description

Diode Rectifier

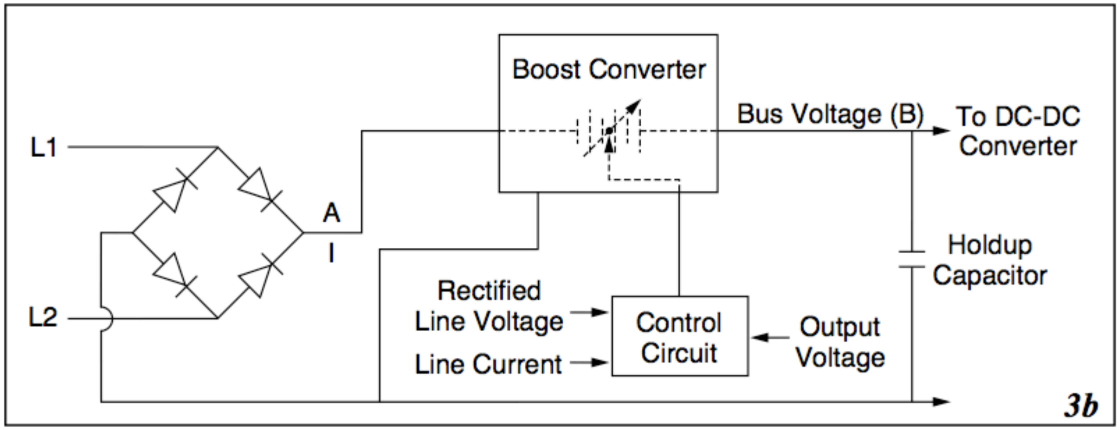


Power Factor Correction



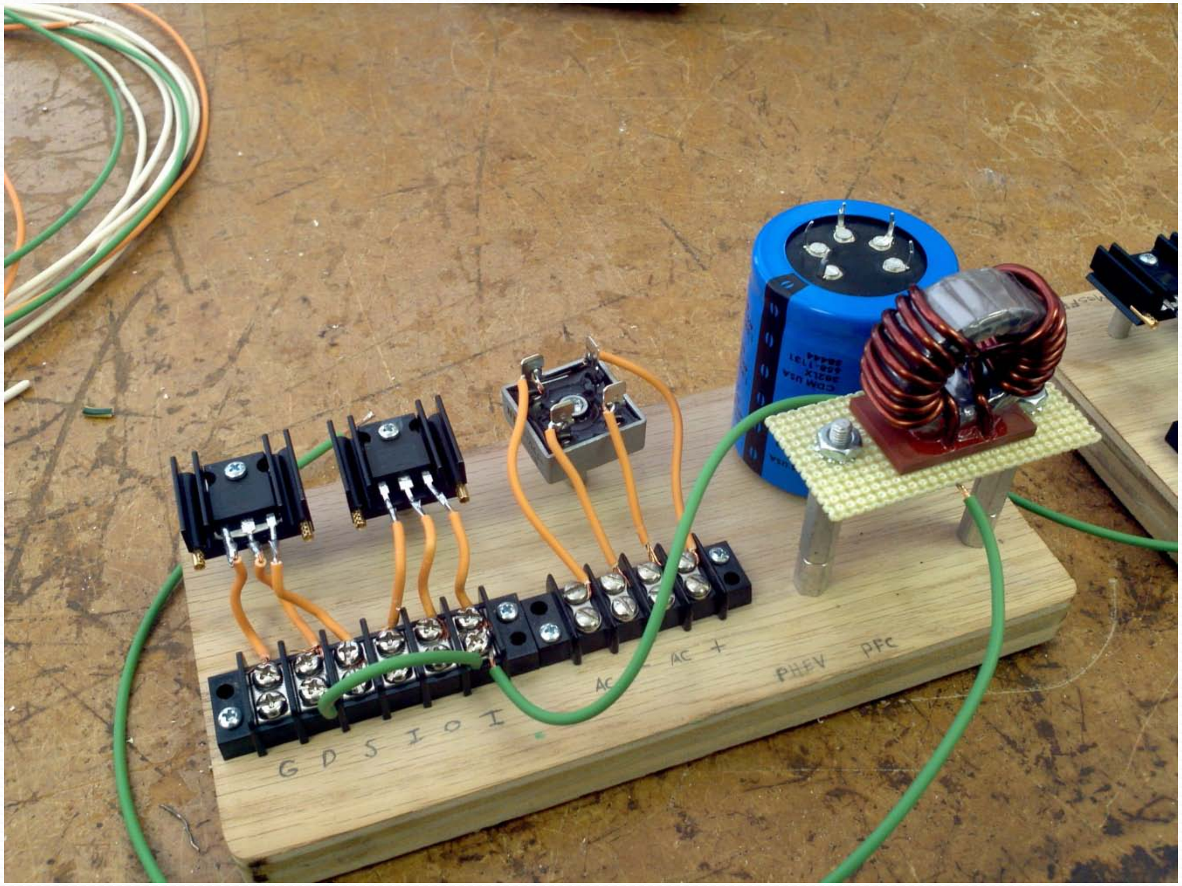
Power Factor Correction

- Power Factor
  - Dimensionless number from 0-1
  - Ratio of real to apparent power
  - 1 is in unity (ideal)
- Passive power factor correction- Capacitor, Inductor
- Active power factor correction- Boost Converter

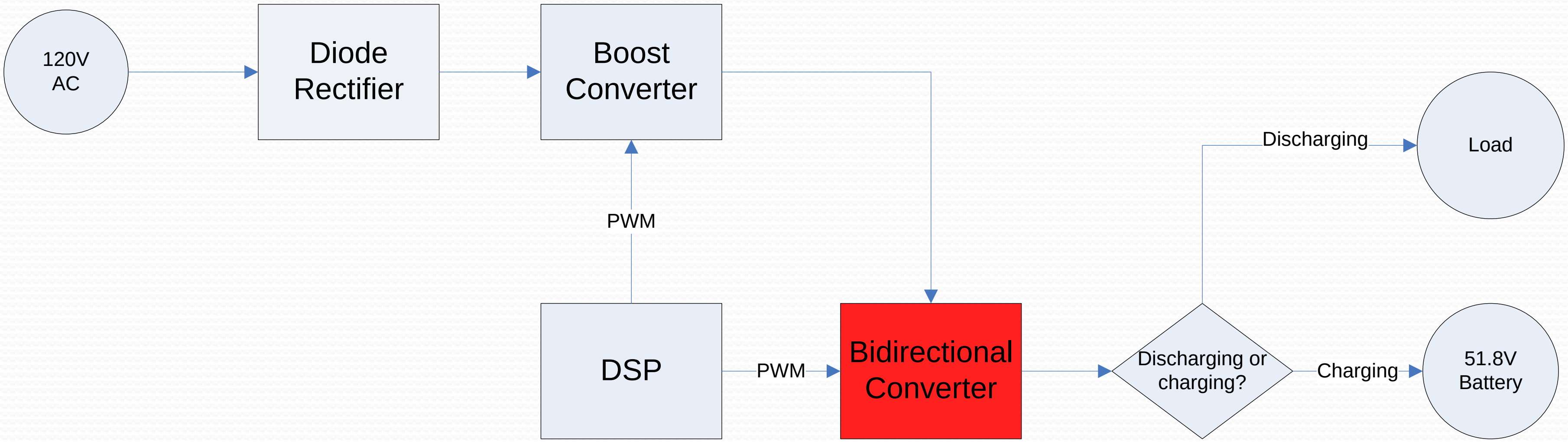


Implementation

Diode Rectifier / Power Factor Correction



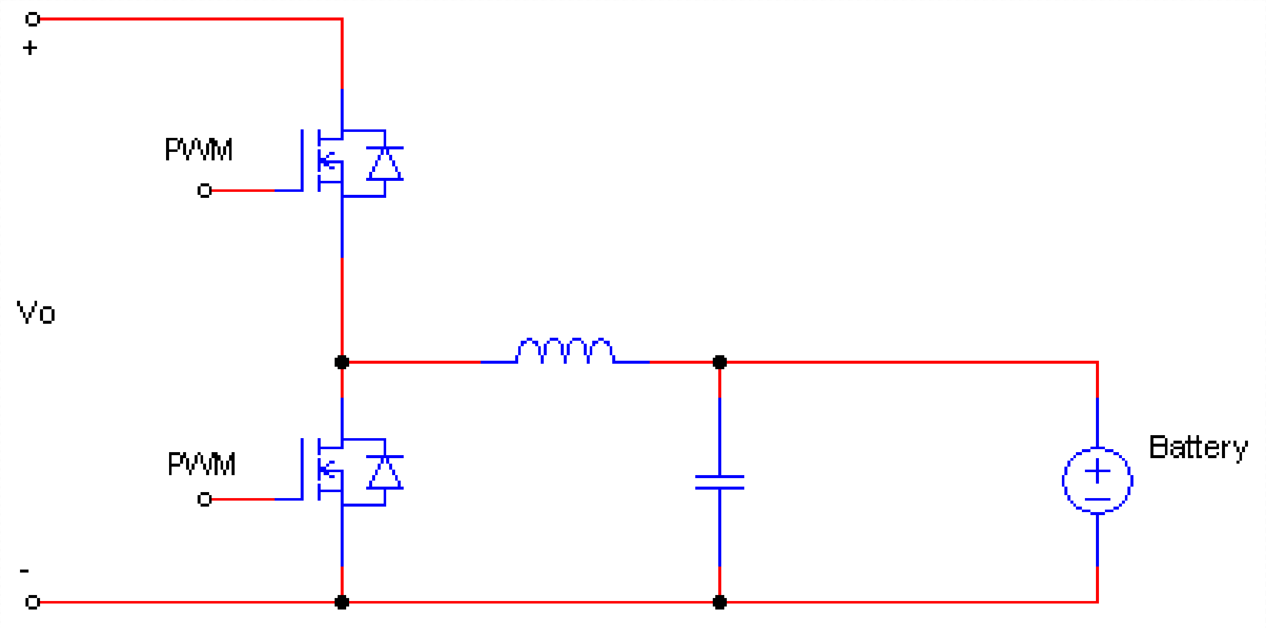
Bi-Directional Converter



Functional Description

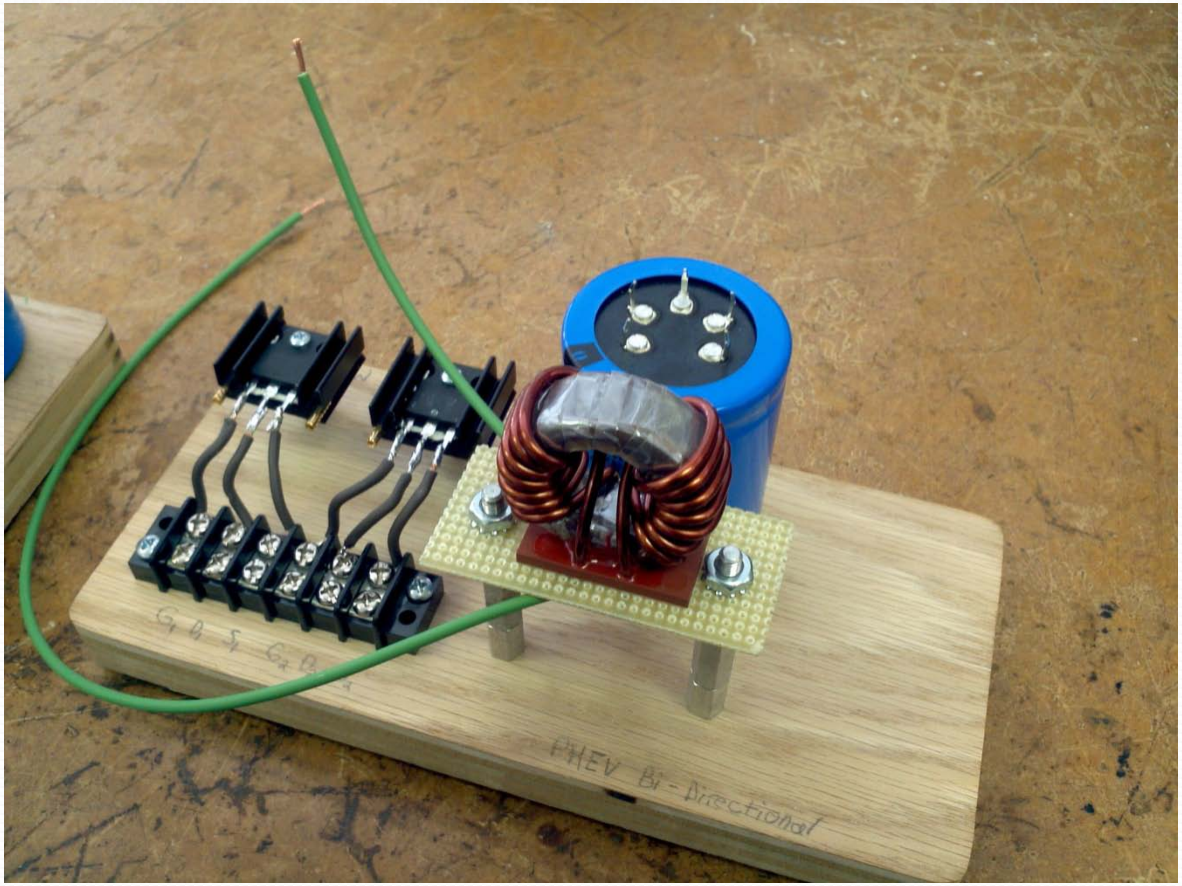
Bi-directional Converter

- To be used in place of the individual Buck and Boost converters' architecture
- Requires more detailed control system



Implementation

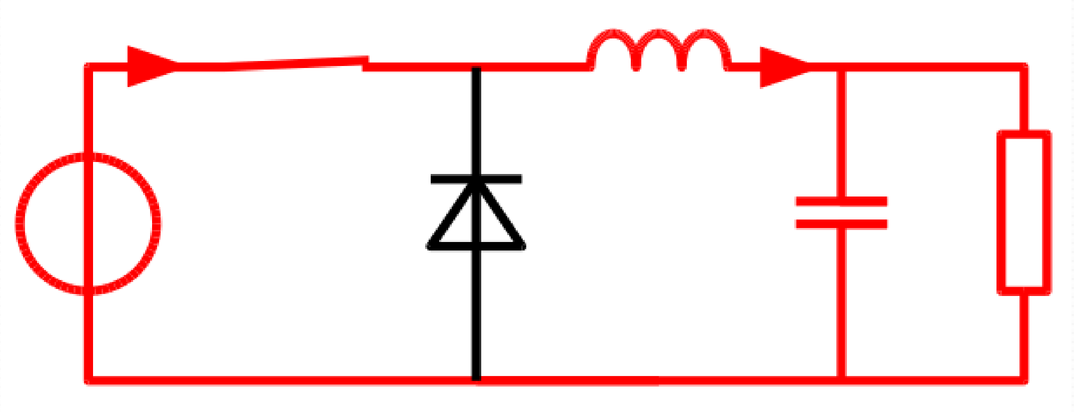
Bi-Directional Converter



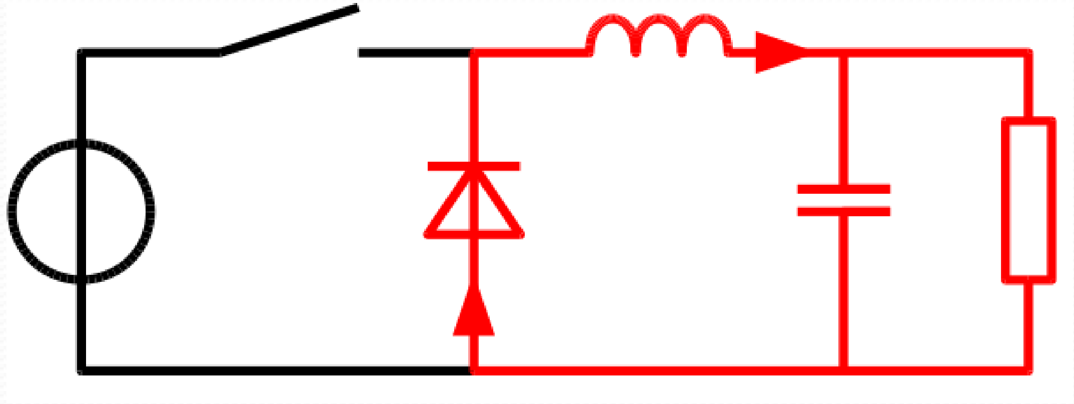
Functional Description

Buck Converter

- Drops input voltage based on MOSFET Duty cycle
- Half of the Bi-directional Converter



Stage 1

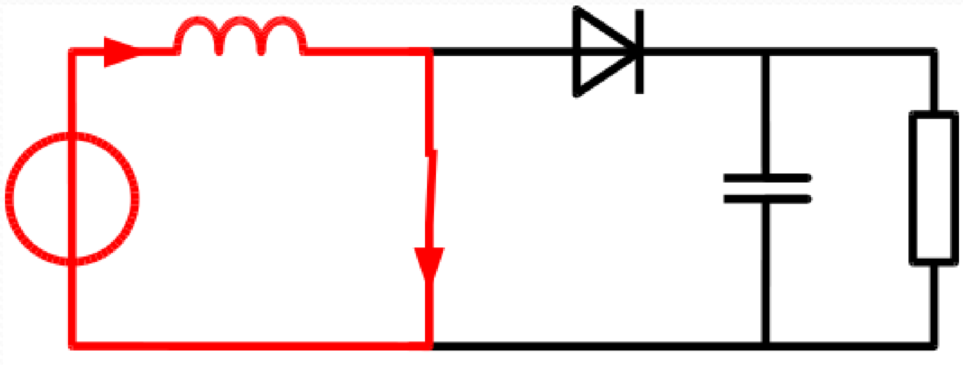


Stage 2

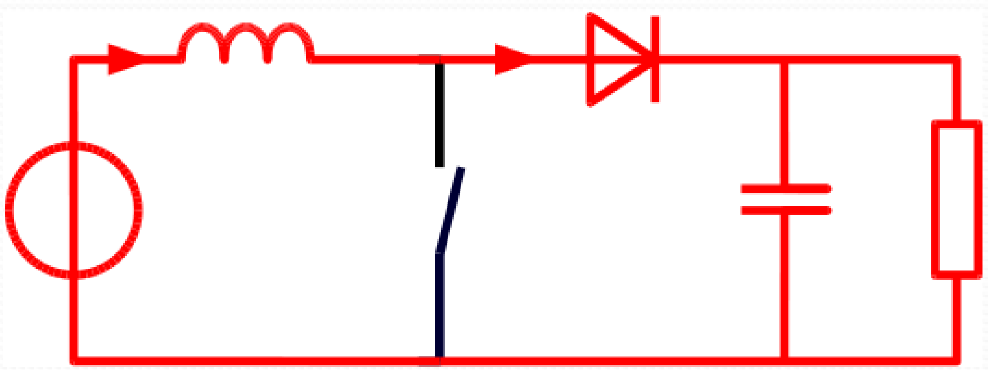
Functional Description

Boost Converter

- Boosts input voltage based on MOSFET duty cycle
- Part of Power Factor Correction
- Half of Bi-directional Converter

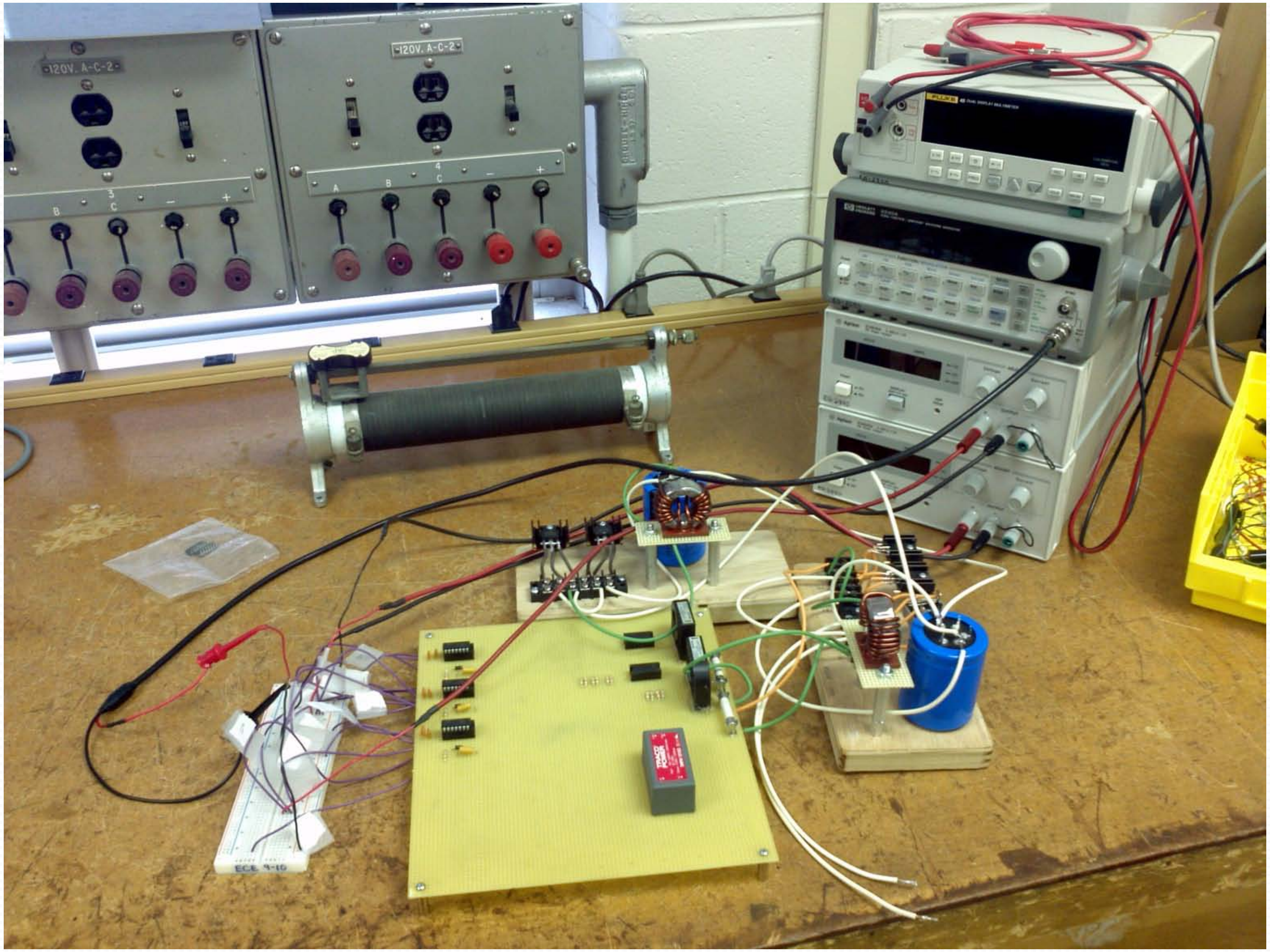


Stage 1



Stage 2

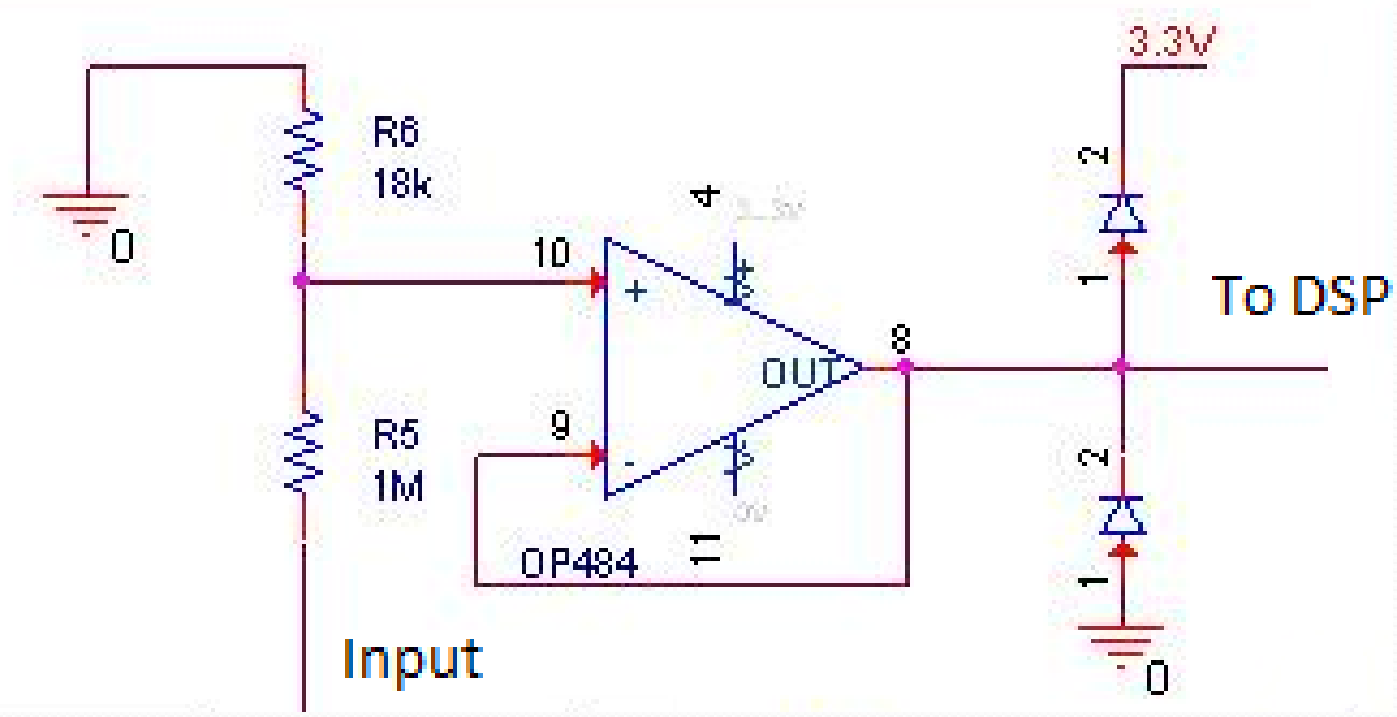
Implementation
PFC and Bi-Directional Converter



Functional Description

Interfacing & Protection Circuitry

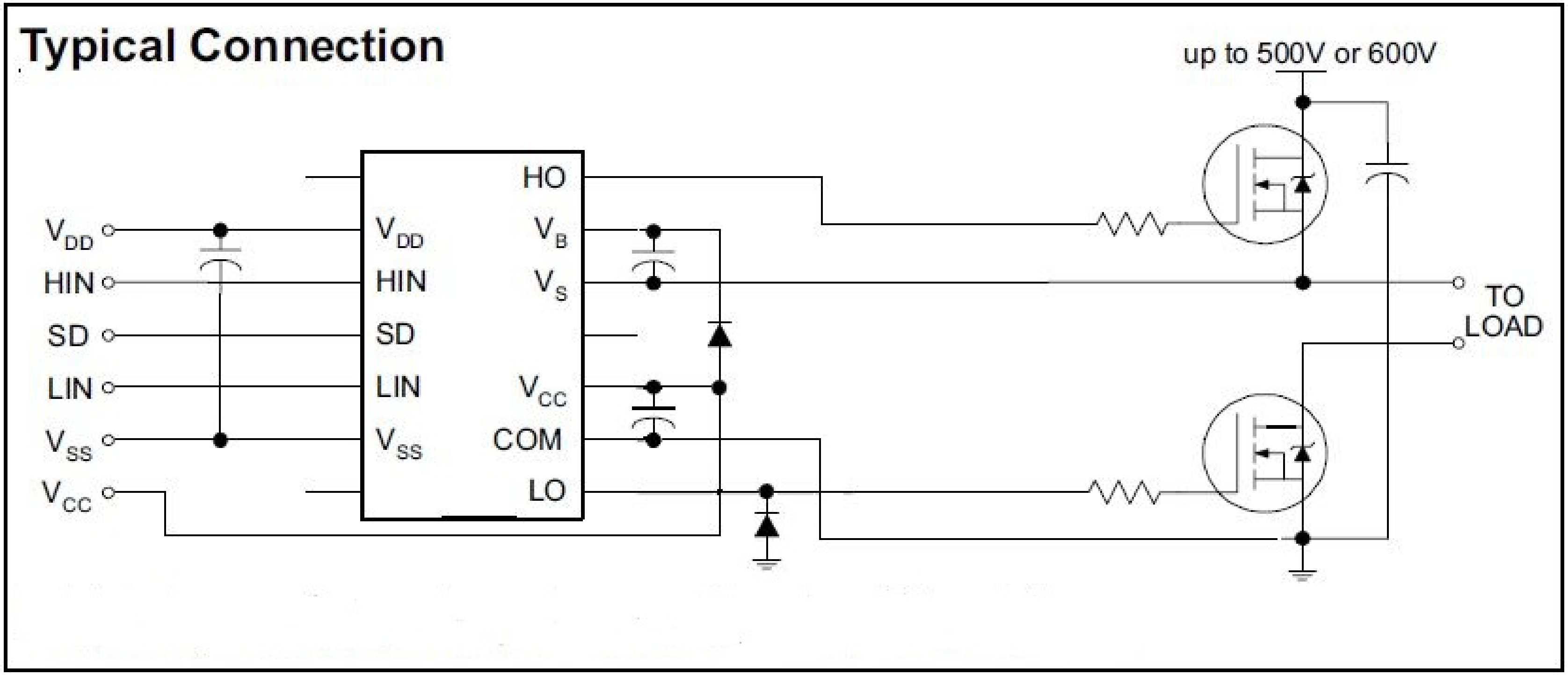
- To be used to sense voltage levels from various locations of the PHEV system, while providing isolation between the DSP and high voltage levels



Functional Description

Gate Driver

- Receives PWM input from DSP to control switching of MOSFETs
- Provides enough power to drive the converter's MOSFETs



Functional Description

Gate Driver

Bootstrap Capacitor

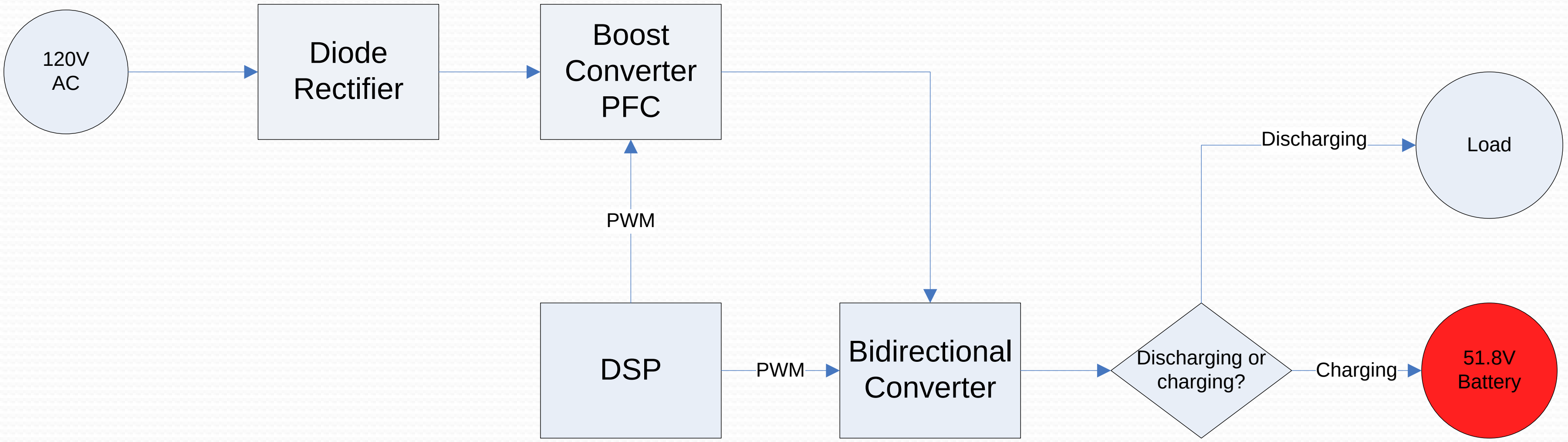
$$C \geq \frac{2\left[2Q_g + \frac{I_{qbs(\max)}}{f} + Q_{ls} + \frac{I_{Cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS} - V_{Min}}$$

$$I_g = \frac{Q_g}{T_s}$$

$$R_g = \frac{V_g}{I_g}$$

Q_g	= Gate Charge
f	= Frequency of Operation
$I_{qbs(max)}$	= Maximum V_{bs} Quiescent Current
Q_{ls}	= Level Shift Charge (5nC)
$I_{cbs(leak)}$	= Leakage Current
V_{cc}	= Logic Section Voltage Source
V_f	= Forward Voltage Drop Across Bootstrap Diode
V_{LS}	= Voltage Drop Across Low-Side FET
V_{min}	= Minimum Voltage Between V_b and V_s

Battery

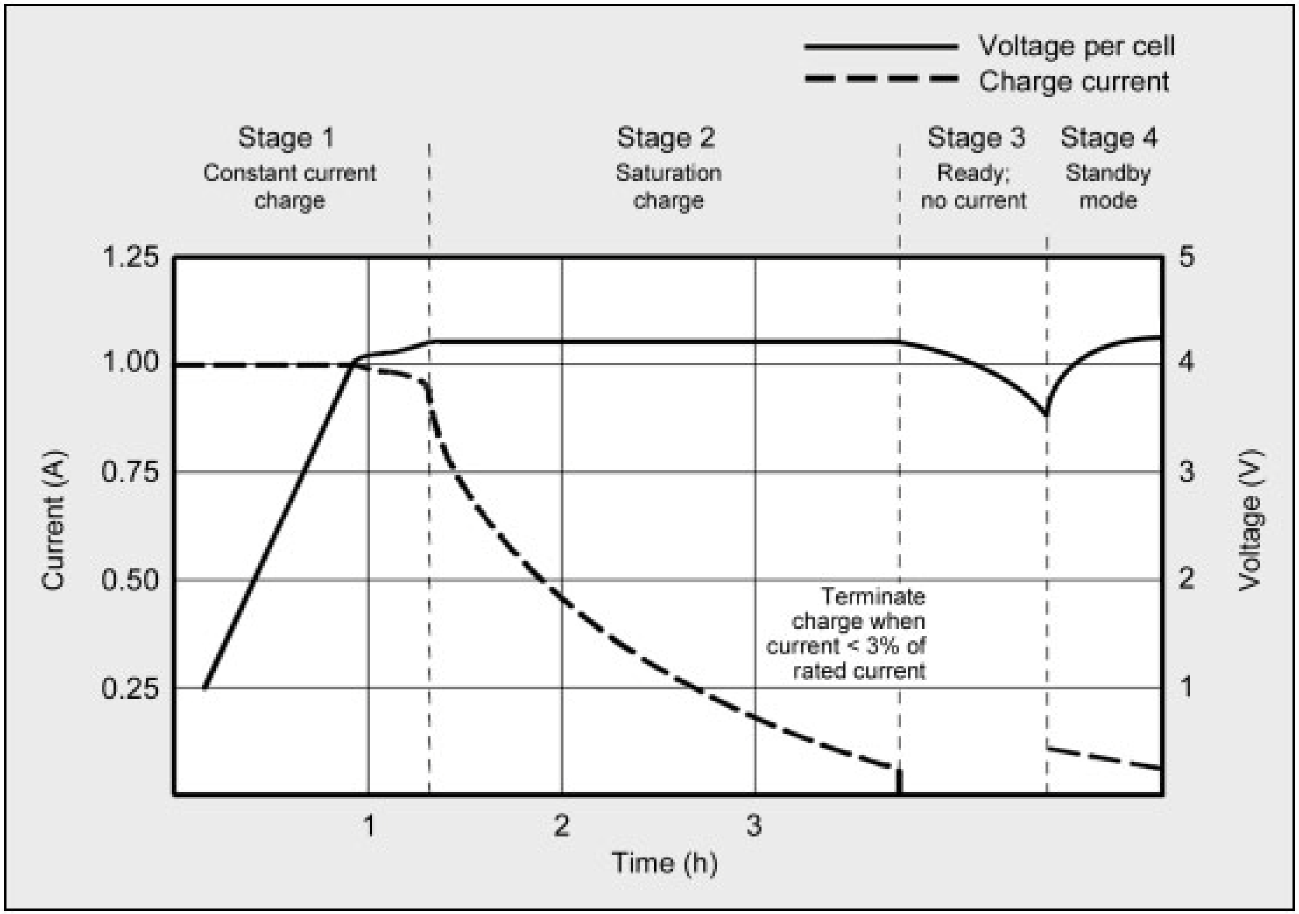

120V
AC
Diode
Rectifier
Boost
Converter
PFC
PWM
DSP
PWM
Bidirectional
Converter
Discharging or
charging?
Discharging
Load
Charging
51.8V
Battery

Functional Description

Battery

- Working Voltage=51.8[V]
- 14 Cell Polymer Li-Ion
- Capacity = 10Ah (518Wh)
- 40[A] Continuous Discharge Rate

Functional Description
Battery



Stage 1
Voltage rises at constant current

Stage 2
Voltage peaks, current decreases

Stage 3
Charge terminates

Stage 4
Occasional topping charge

Implementation

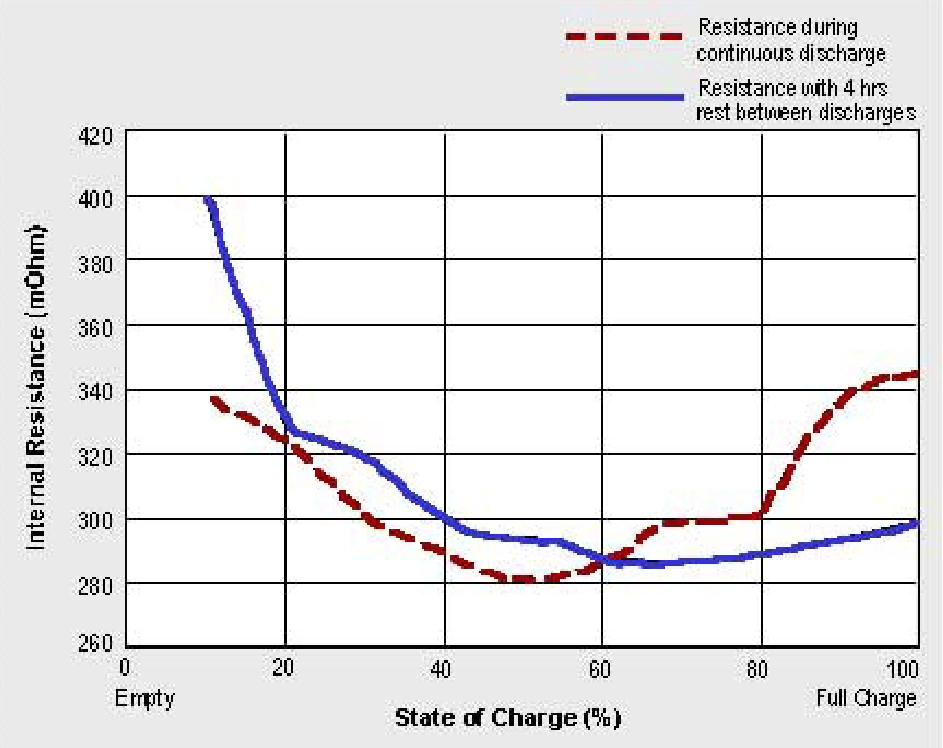
Charging Method

- Stage 1: Charge Rate: 0.8C
  - Constant Current Method
- Stage 2: 58.8[V]
  - Constant Voltage Method
  - Terminate at 3% Rated Current
- No Trickle Charge
  - Reduces battery life

Implementation

Battery Resistance

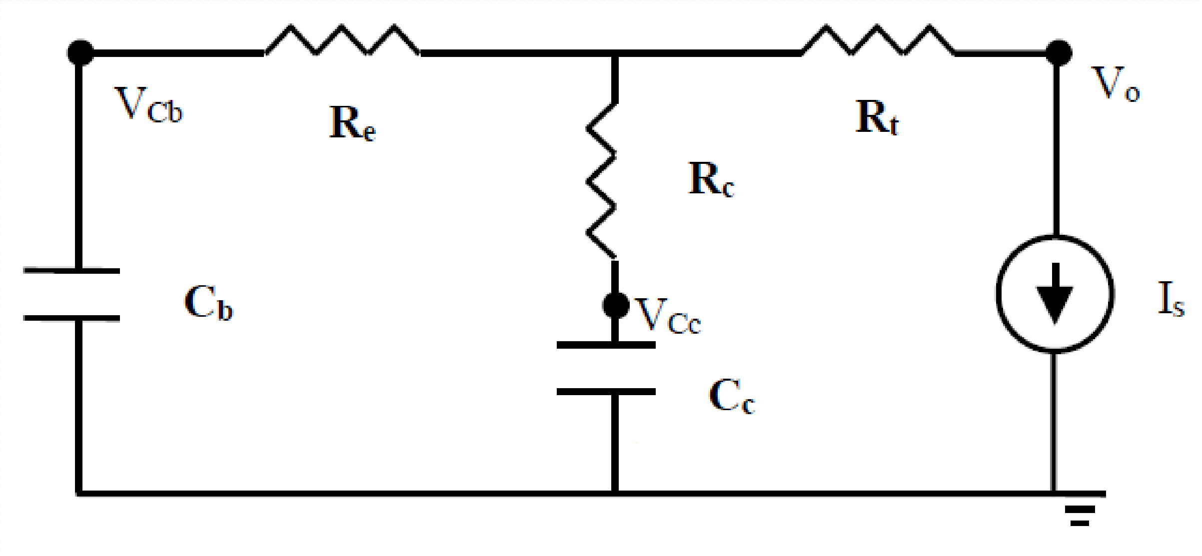
- Internal Resistance varies with State of Charge
- Actively Measure State of Charge
- Coulomb Counting
  - Requires Current Shunt



Implementation

Measuring Battery Resistance

- RC Battery Model
- Allows for Matlab simulation
- Resistance values are functions of SOC, T, and charge/discharge



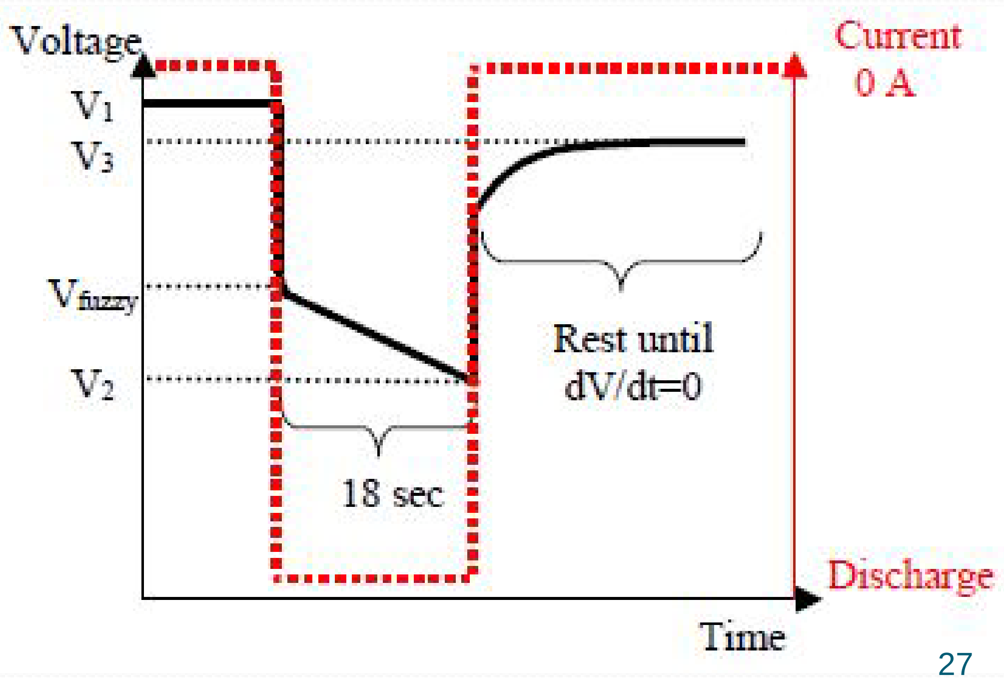
Implementation

Measuring Battery Resistance

- Internal Resistance seen from pulse discharge
- $R_{int} = 108m[\Omega]$

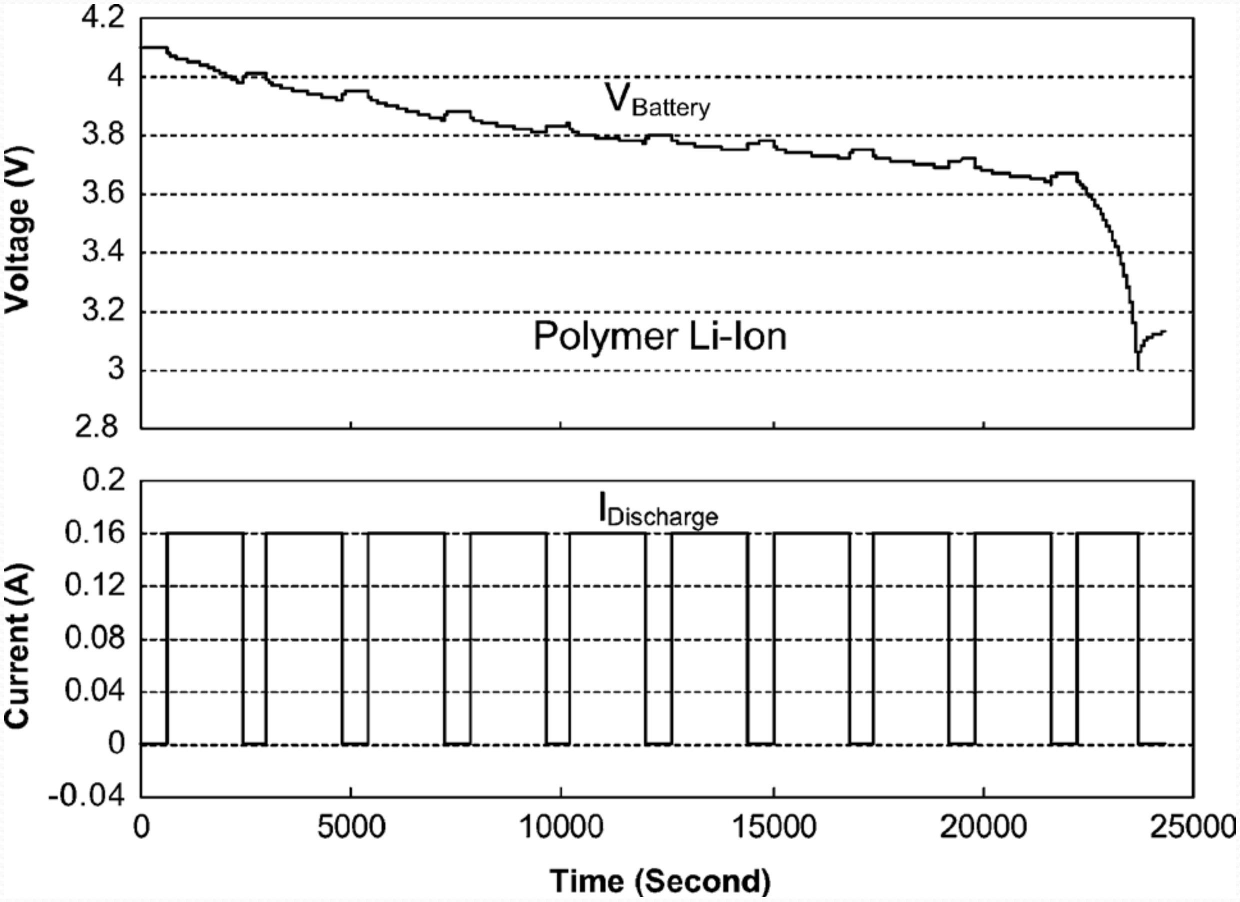
$$R = \frac{V_{oc} - V_{terminal}}{I} = \frac{V_3 - V_2}{I}$$

Vr	56.530
R	10.910
V1	57.850
V2	57.160
V3	57.720
I	5.181
Rint	0.108

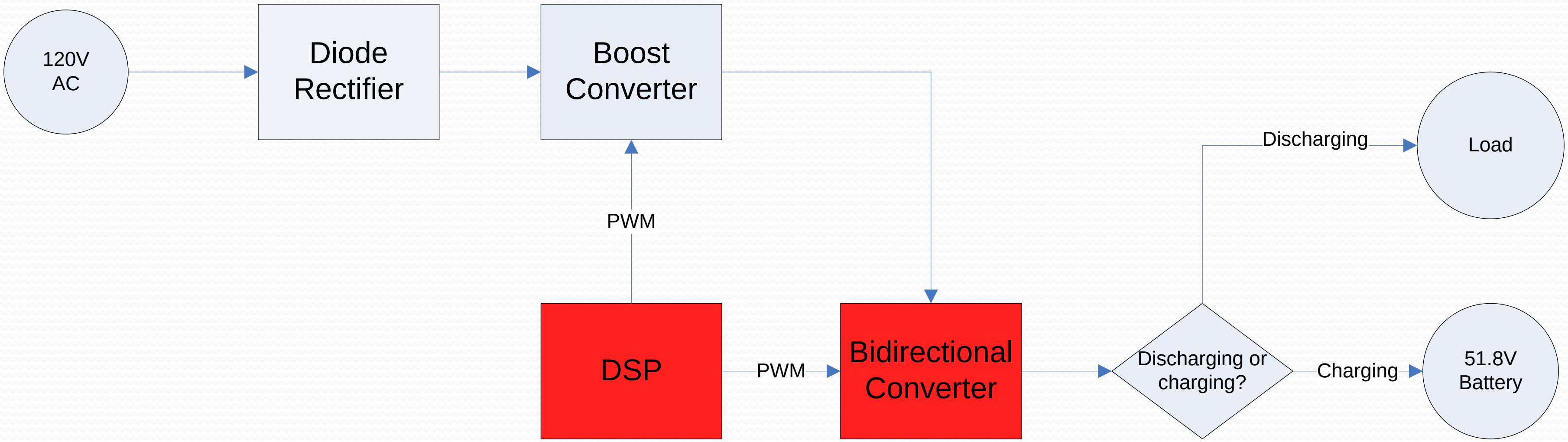


Implementation

Measuring Battery Resistance

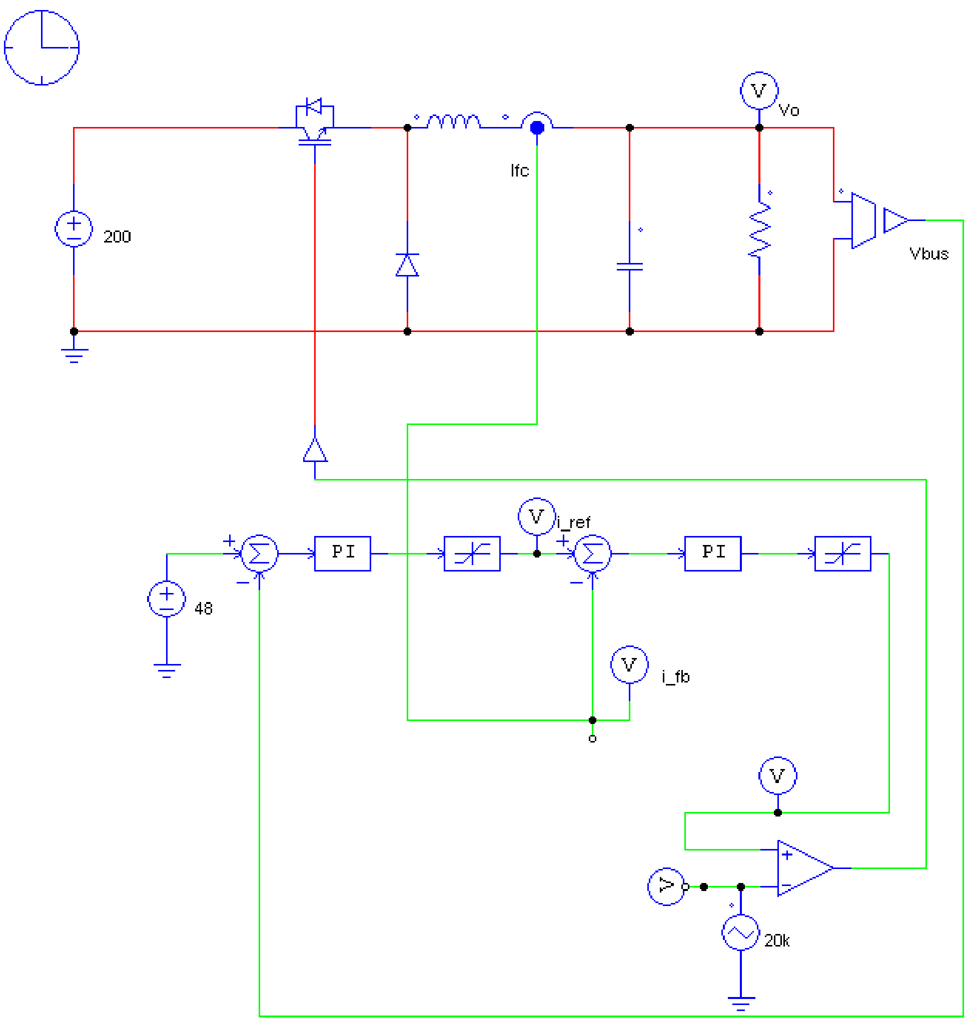


Bi-Directional Converter

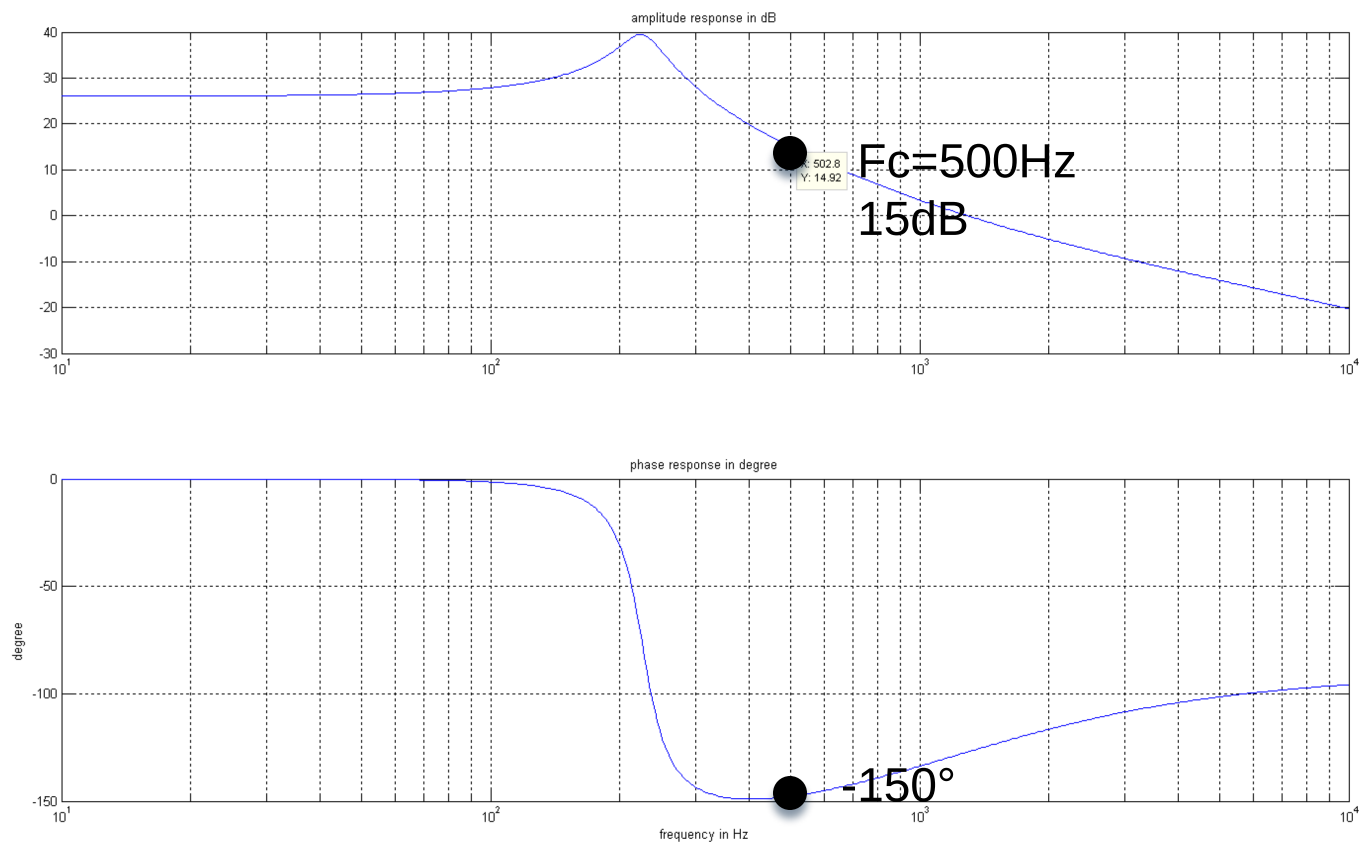


Schematics

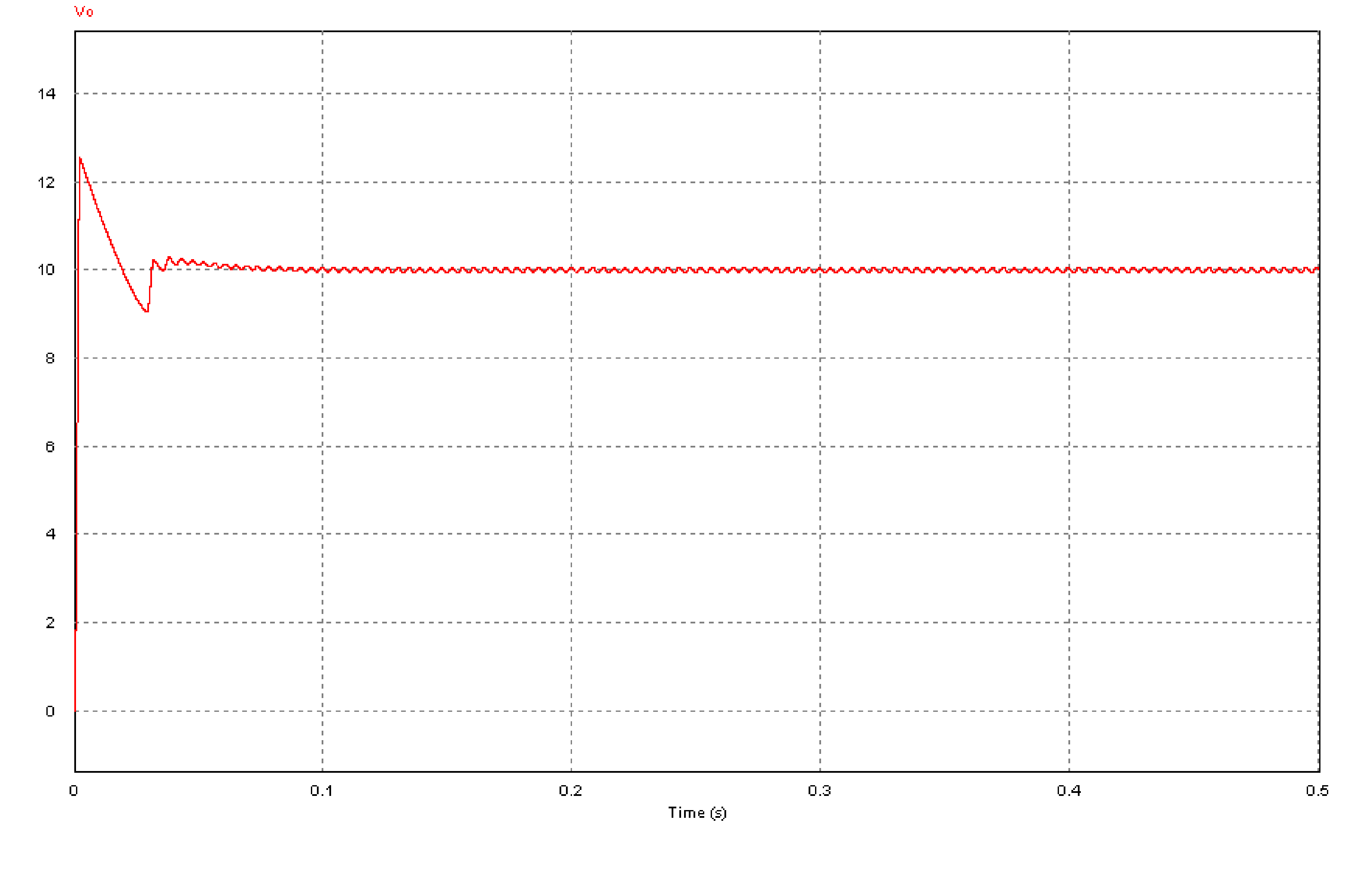
- Buck Converter



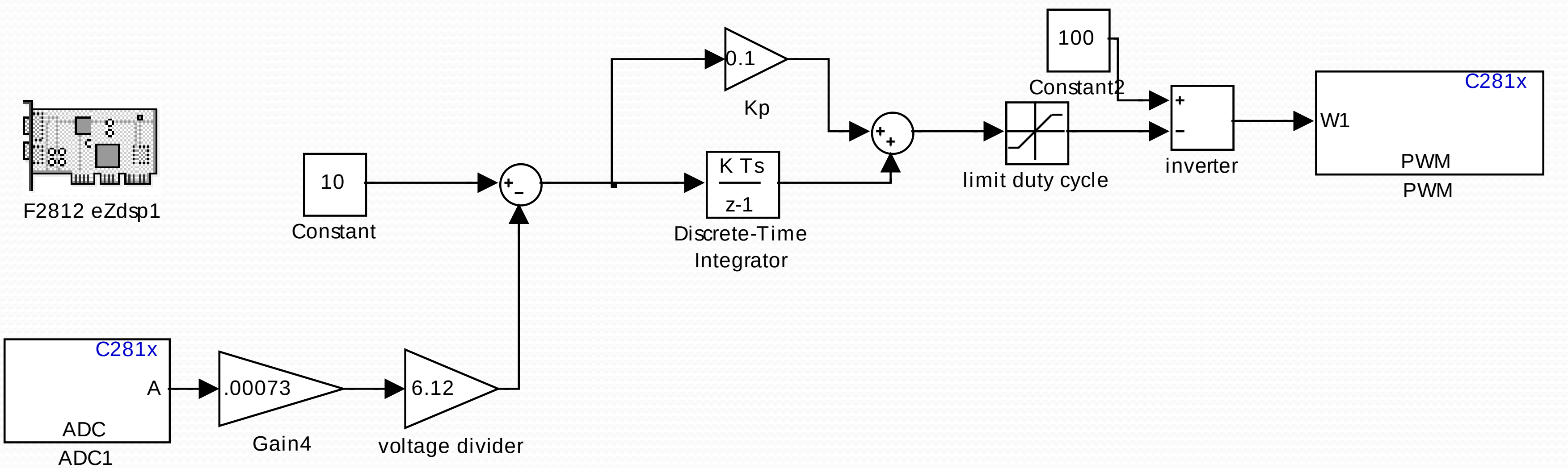
Calculating gains



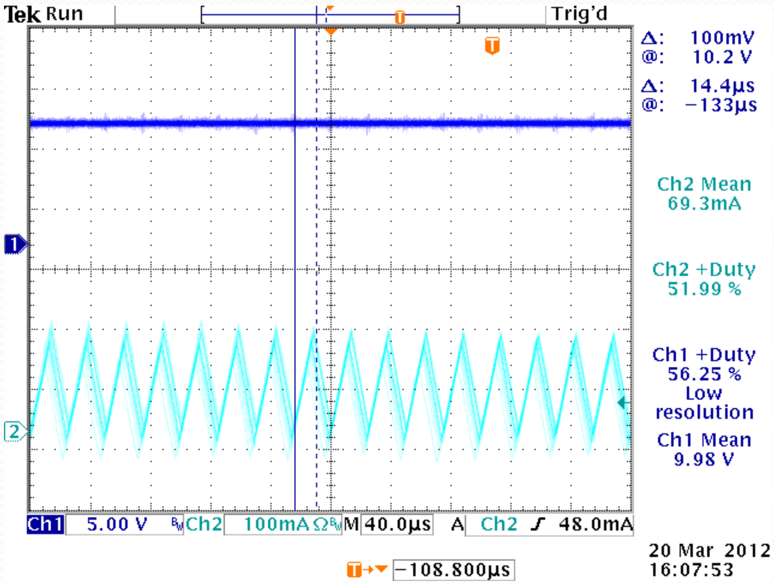
Psim output voltage

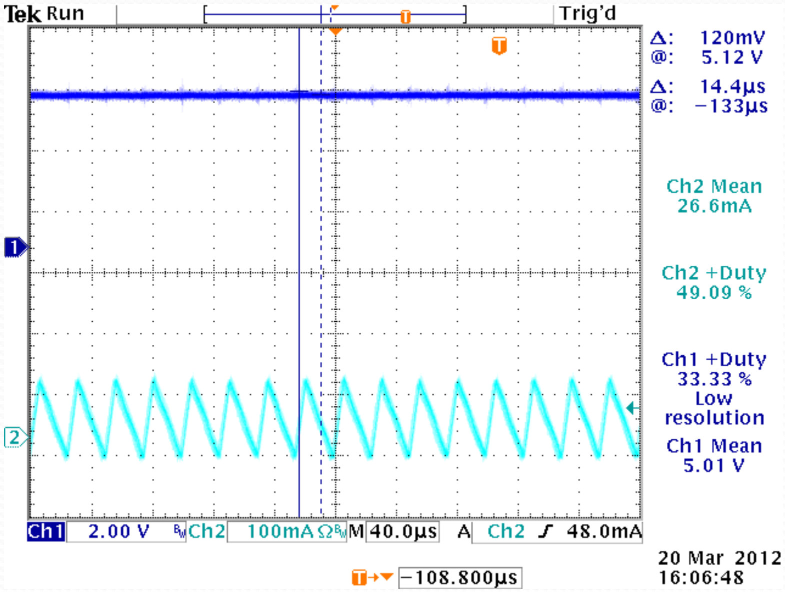


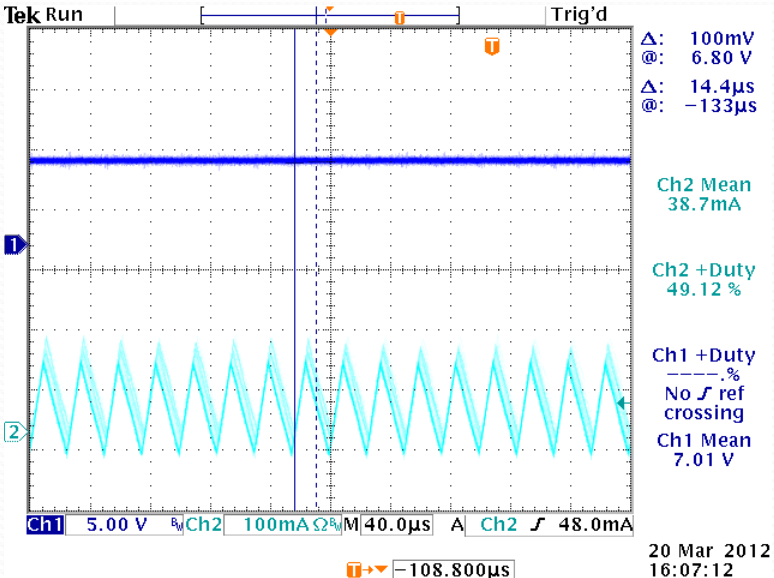
Buck Converter PI Control

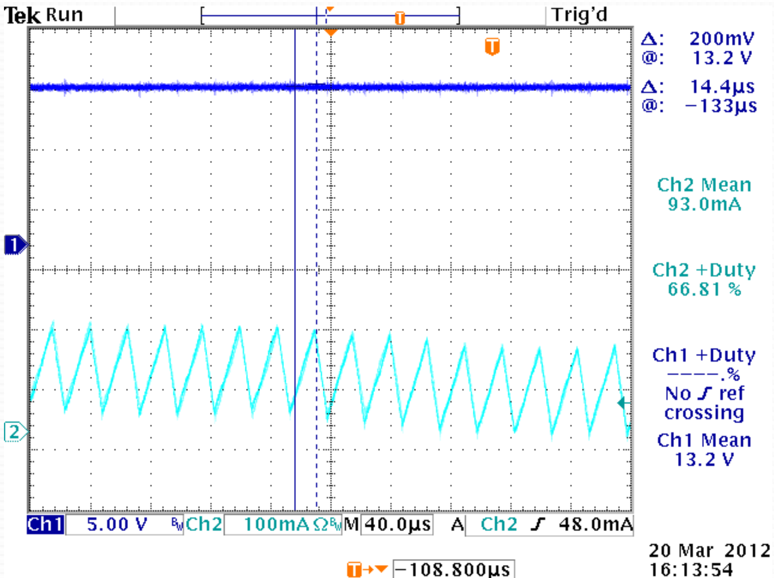


PI Control


Tek Run
Trig'd
Δ: 100mV
@: 10.2 V
Δ: 14.4µs
@: −133µs
Ch2 Mean
69.3mA
Ch2 +Duty
51.99 %
Ch1 +Duty
56.25 %
Low
resolution
Ch1 Mean
9.98 V
Ch1 5.00 V
Ch2 100mA Ω
M 40.0µs A Ch2 48.0mA
20 Mar 2012
16:07:53
−108.800µs

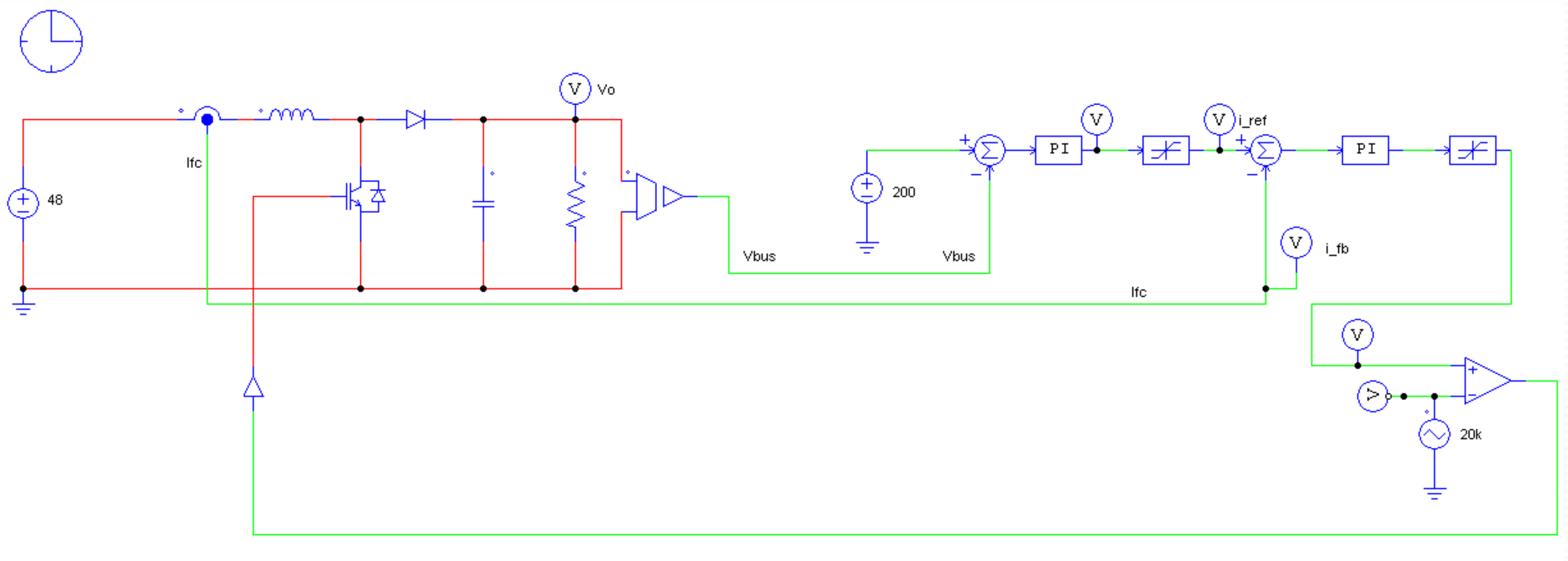

Tek Run
Trig'd
Δ: 120mV
@: 5.12 V
Δ: 14.4µs
@: −133µs
Ch2 Mean
26.6mA
Ch2 +Duty
49.09 %
Ch1 +Duty
33.33 %
Low
resolution
Ch1 Mean
5.01 V
Ch1 2.00 V
Ch2 100mA Ω
M 40.0µs A Ch2 48.0mA
20 Mar 2012
16:06:48
−108.800µs


Tek Run
Trig'd
Δ: 100mV
@: 6.80 V
Δ: 14.4µs
@: −133µs
Ch2 Mean
38.7mA
Ch2 +Duty
49.12 %
Ch1 +Duty
----.%
No ref
crossing
Ch1 Mean
7.01 V
Ch1 5.00 V
Ch2 100mA Ω
M 40.0µs A Ch2 48.0mA
20 Mar 2012
16:07:12
−108.800µs

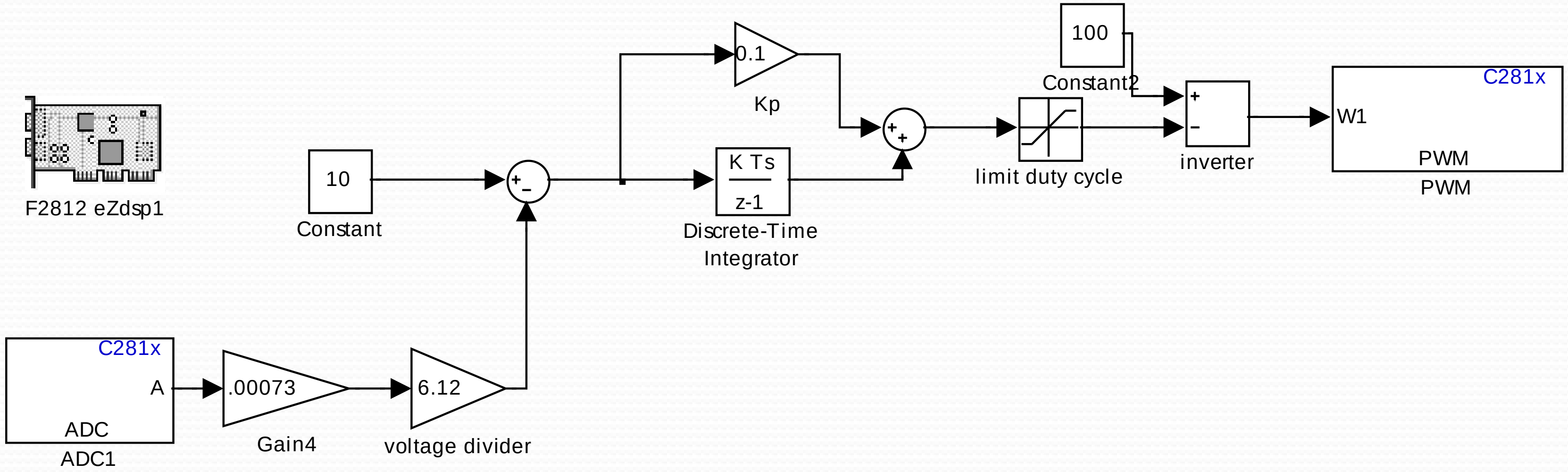

Tek Run
Trig'd
Δ: 200mV
@: 13.2 V
Δ: 14.4µs
@: −133µs
Ch2 Mean
93.0mA
Ch2 +Duty
66.81 %
Ch1 +Duty
----.%
No ref
crossing
Ch1 Mean
13.2 V
Ch1 5.00 V
Ch2 100mA Ω
M 40.0µs A Ch2 48.0mA
20 Mar 2012
16:13:54
−108.800µs

Schematics

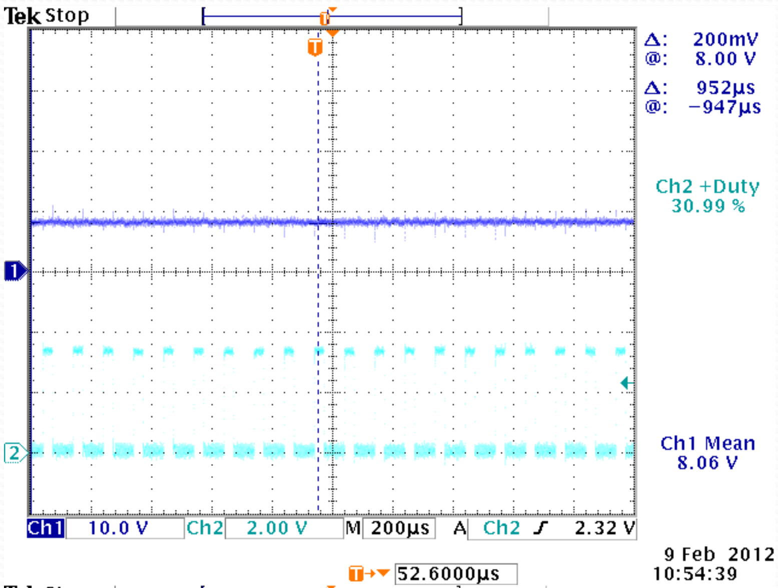
- Boost Converter

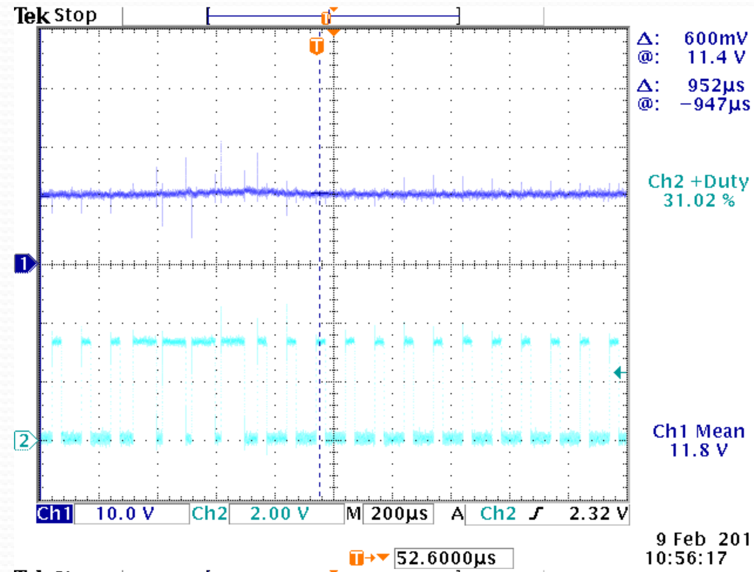


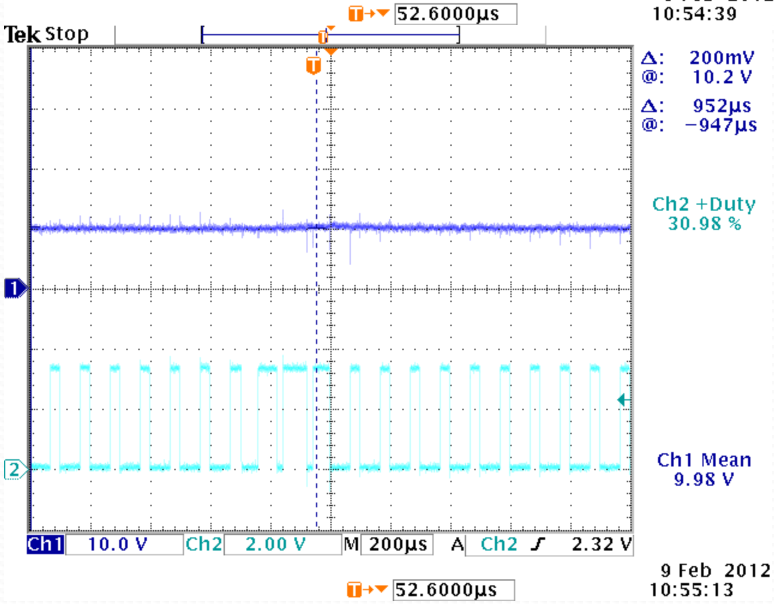
Boost Converter PI Control

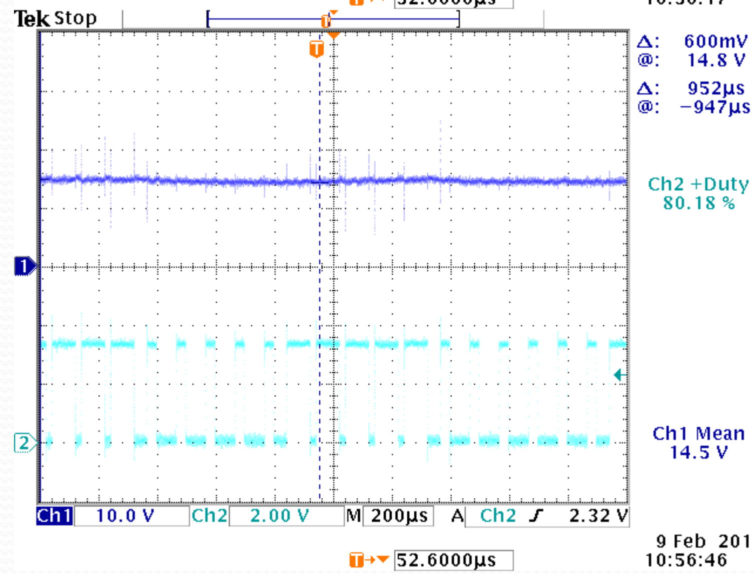


PI Control

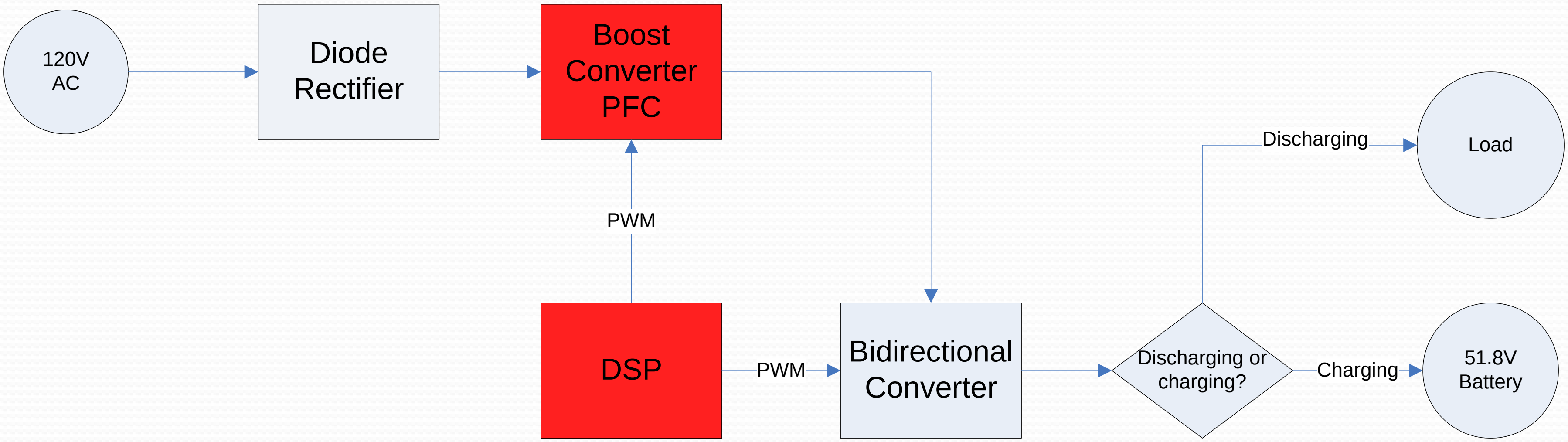

Tek Stop
Δ: 200mV
@: 8.00 V
Δ: 952µs
@: −947µs
Ch2 +Duty
30.99 %
Ch1 Mean
8.06 V
Ch1 10.0 V Ch2 2.00 V M 200µs A Ch2 ∫ 2.32 V
52.6000µs
9 Feb 2012
10:54:39


Tek Stop
Δ: 600mV
@: 11.4 V
Δ: 952µs
@: −947µs
Ch2 +Duty
31.02 %
Ch1 Mean
11.8 V
Ch1 10.0 V Ch2 2.00 V M 200µs A Ch2 ∫ 2.32 V
52.6000µs
9 Feb 2012
10:56:17


Tek Stop
Δ: 200mV
@: 10.2 V
Δ: 952µs
@: −947µs
Ch2 +Duty
30.98 %
Ch1 Mean
9.98 V
Ch1 10.0 V Ch2 2.00 V M 200µs A Ch2 ∫ 2.32 V
52.6000µs
9 Feb 2012
10:55:13

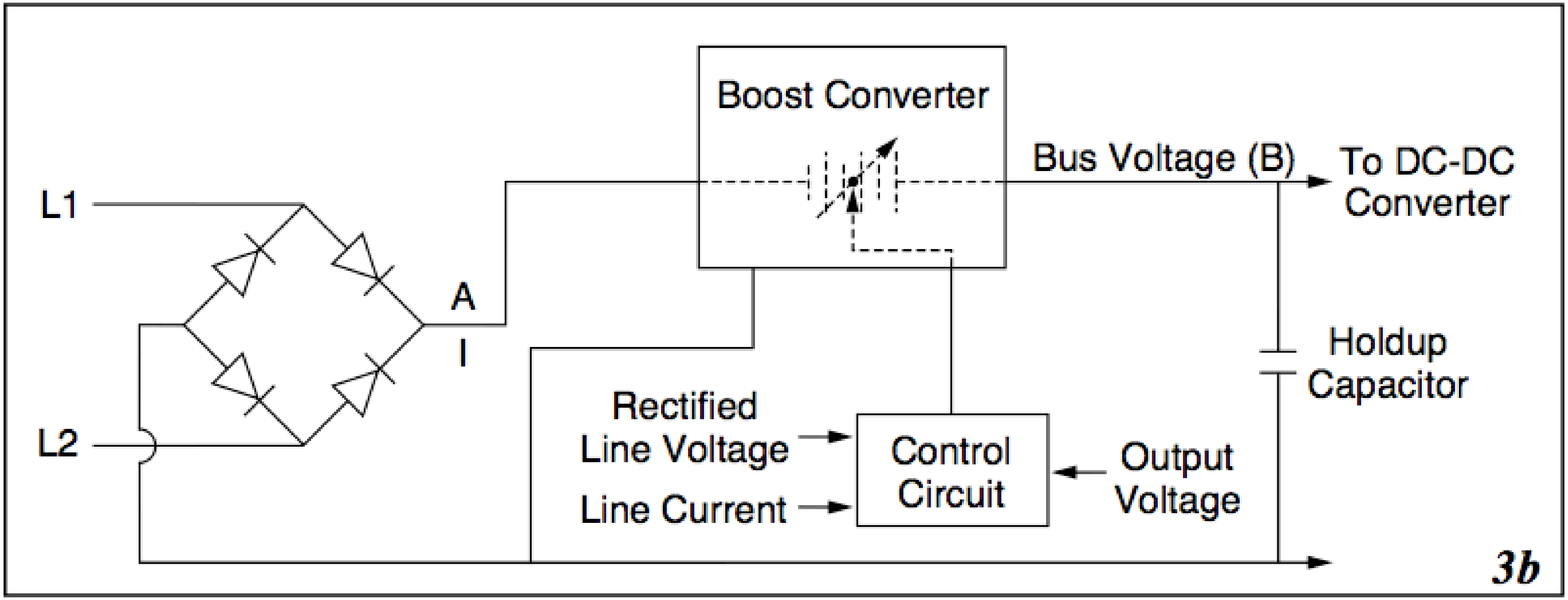

Tek Stop
Δ: 600mV
@: 14.8 V
Δ: 952µs
@: −947µs
Ch2 +Duty
80.18 %
Ch1 Mean
14.5 V
Ch1 10.0 V Ch2 2.00 V M 200µs A Ch2 ∫ 2.32 V
52.6000µs
9 Feb 2012
10:56:46

Power Factor Correction



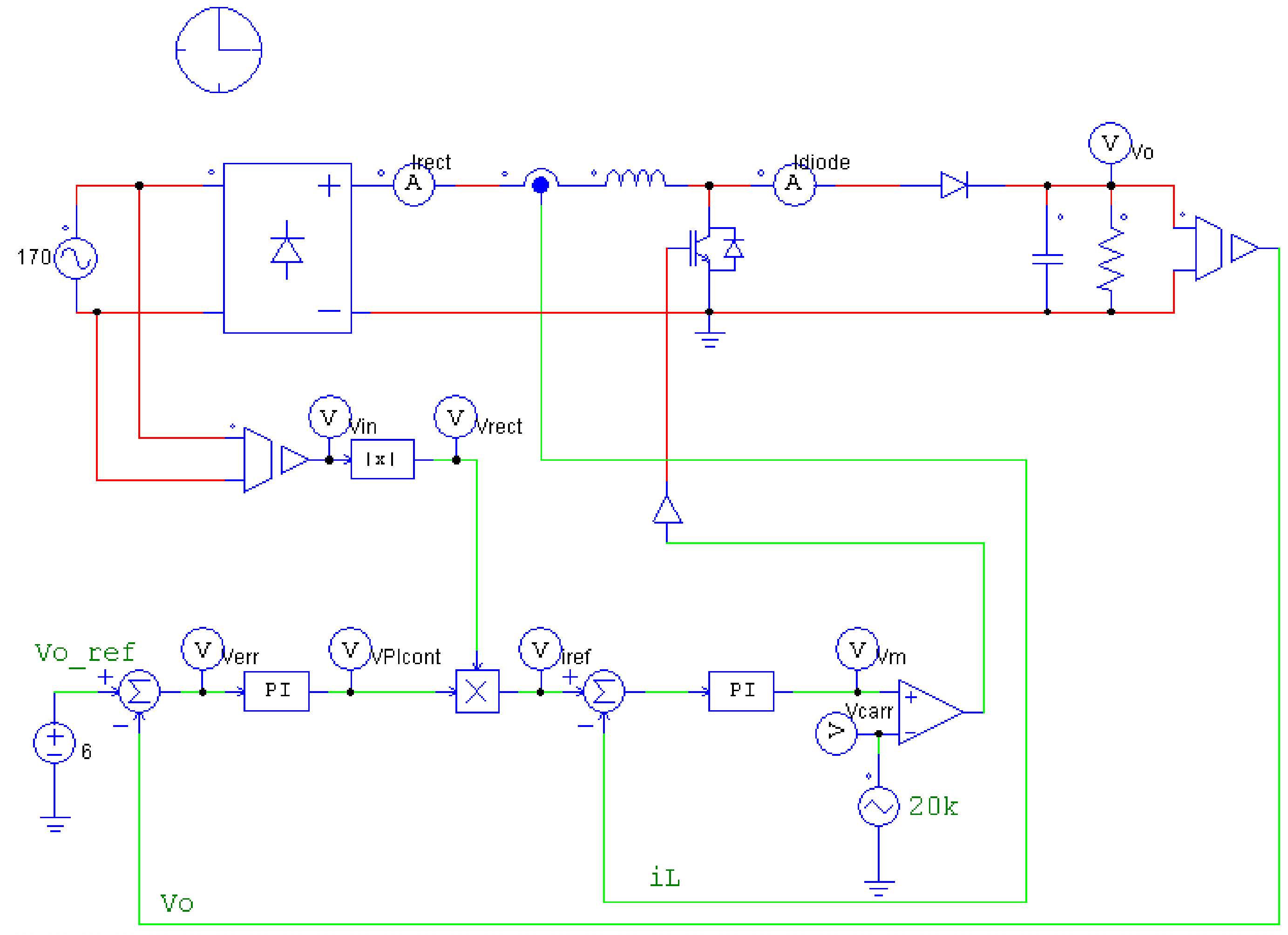
Power Factor Correction

- How it works:

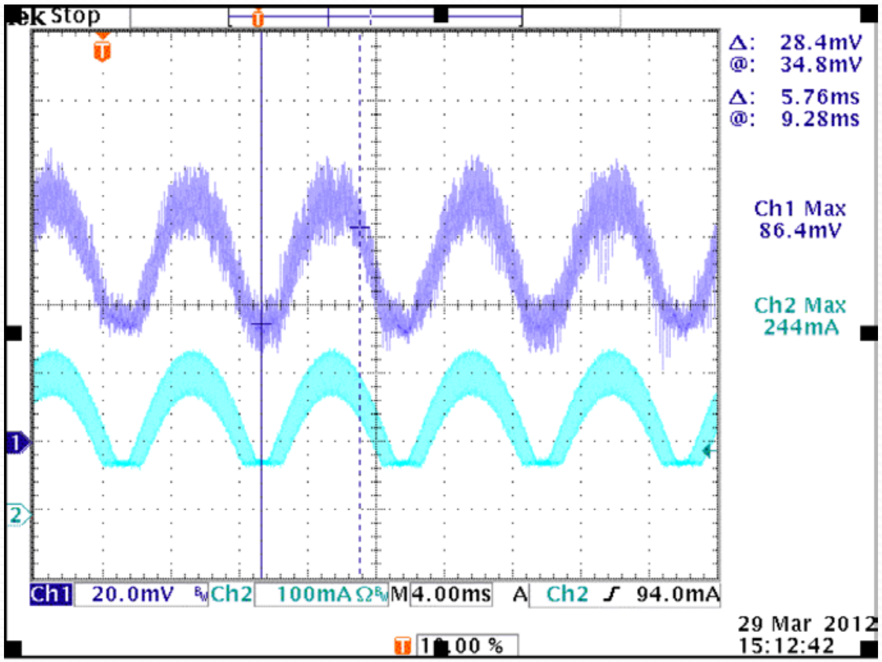


Schematics

Power Factor Correction



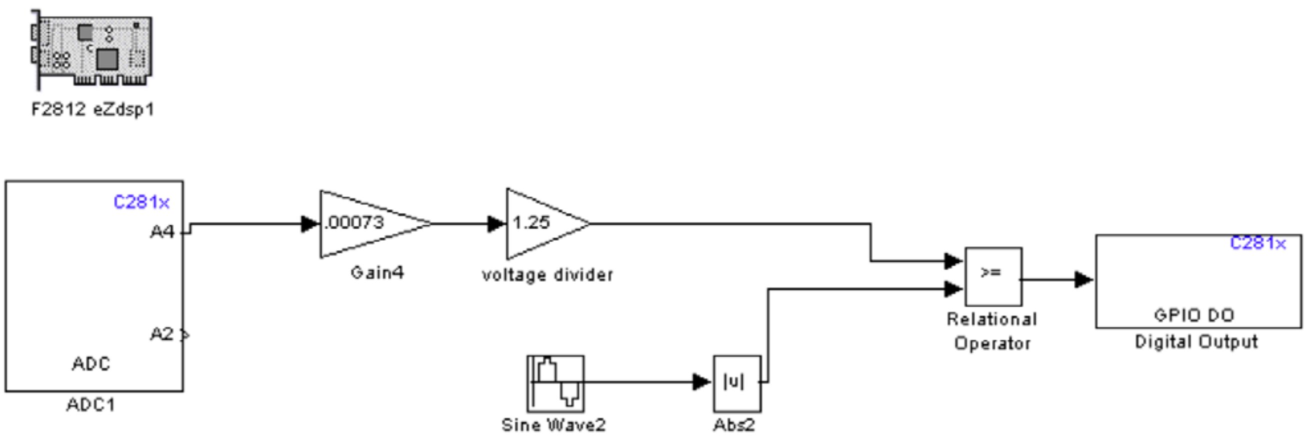
PFC Testing



- Channel 1: output of current sensing circuitry and op amp input to the dsp
- Channel 2: output of current probe

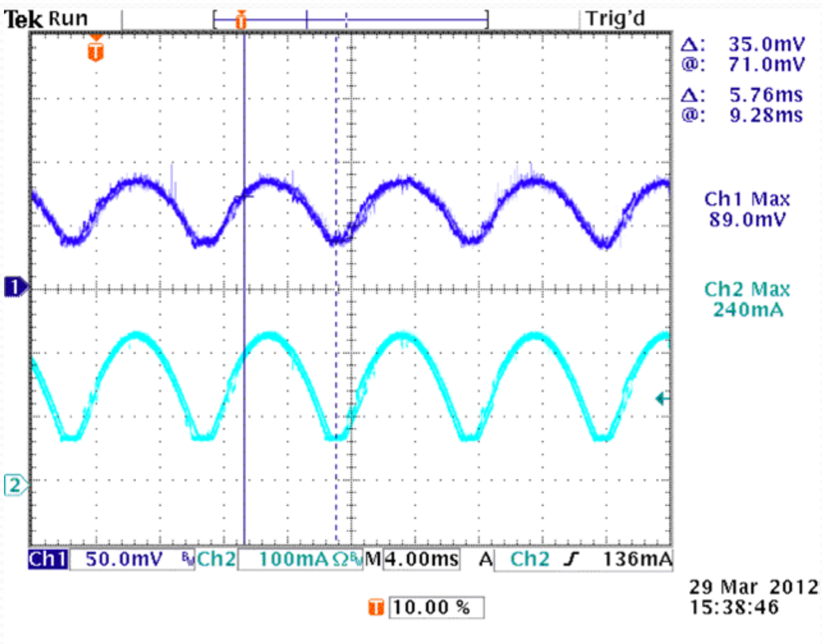
- Open loop control, 50% duty cycle
- 80mV out of the op amp can be converted by multiplying by the 1.25 voltage divider, then multiply by 50/4 for the current sensor, and divide by 5 to factor in the 5 loops around the current sensor gives you 250mV which the current probe is showing.

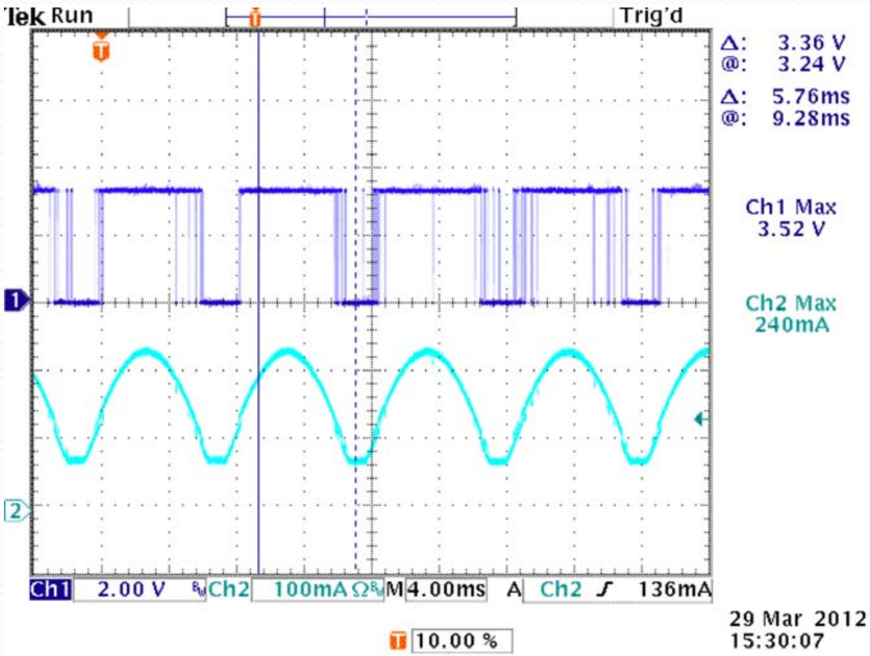
PFC Testing



- Because the current being measured by the DSP is a rectified sign wave with an amplitude of approximately 80mV, I simulated this in Simulink as the reference current to match.

PFC Testing

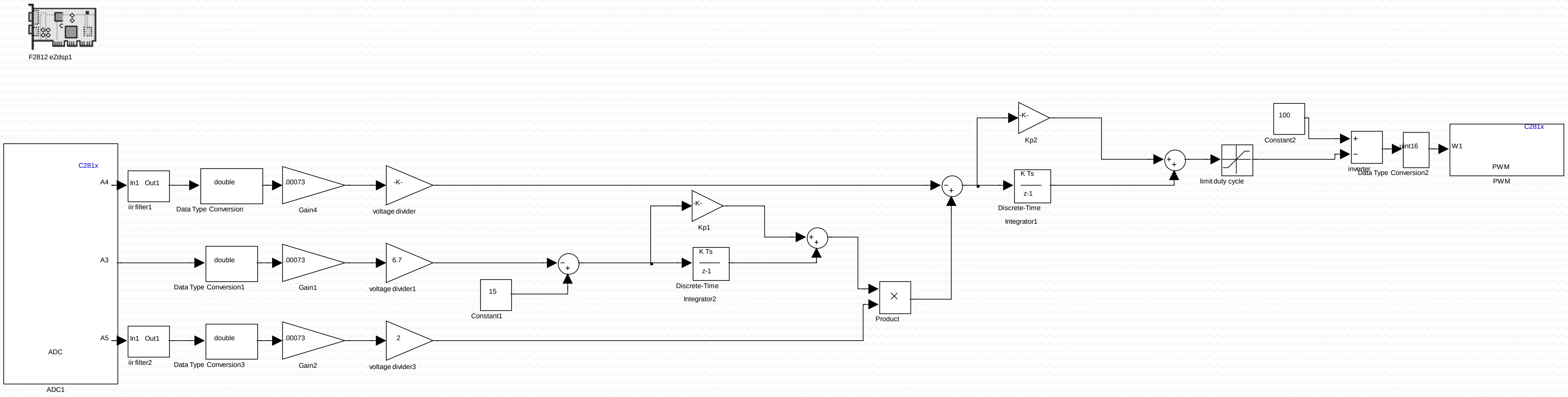




- 1: output of current sensing circuit opamp into DSP
- 2: current probe measuring current through inductor

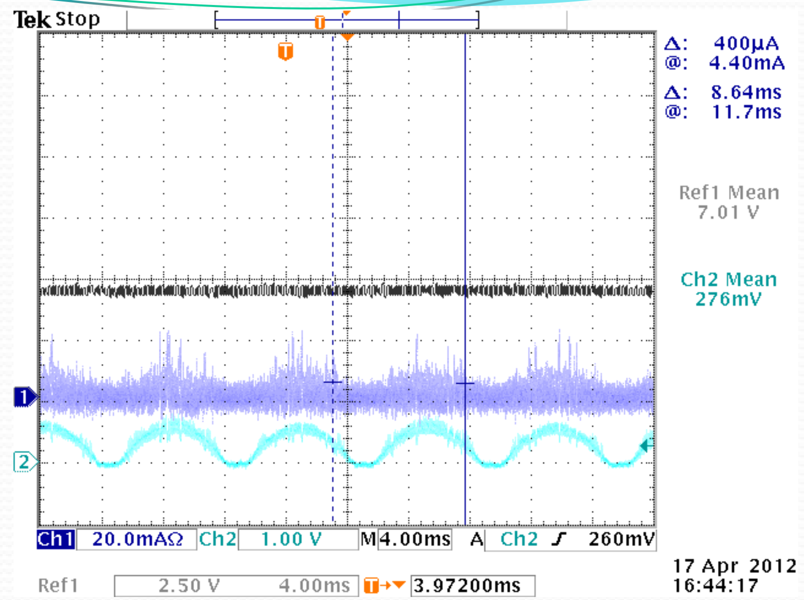
- 1: constantly adjusting pwm

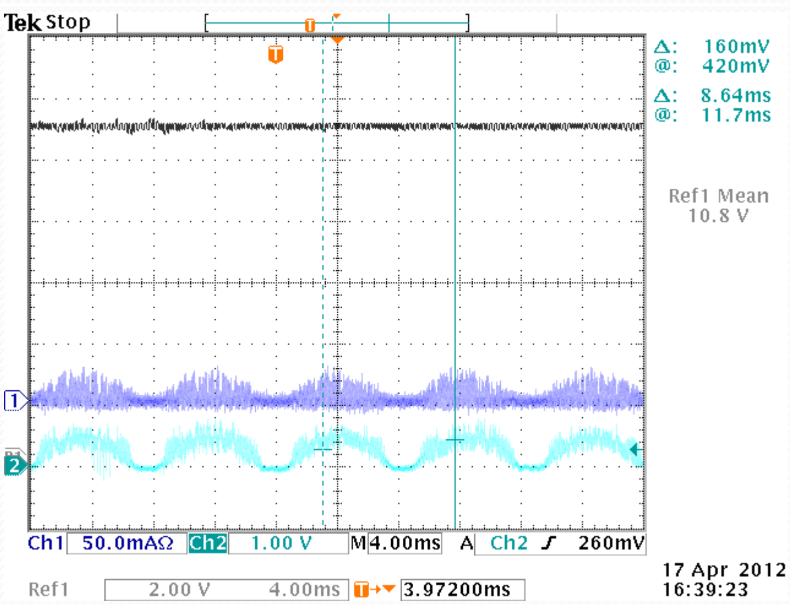
PFC PI Control

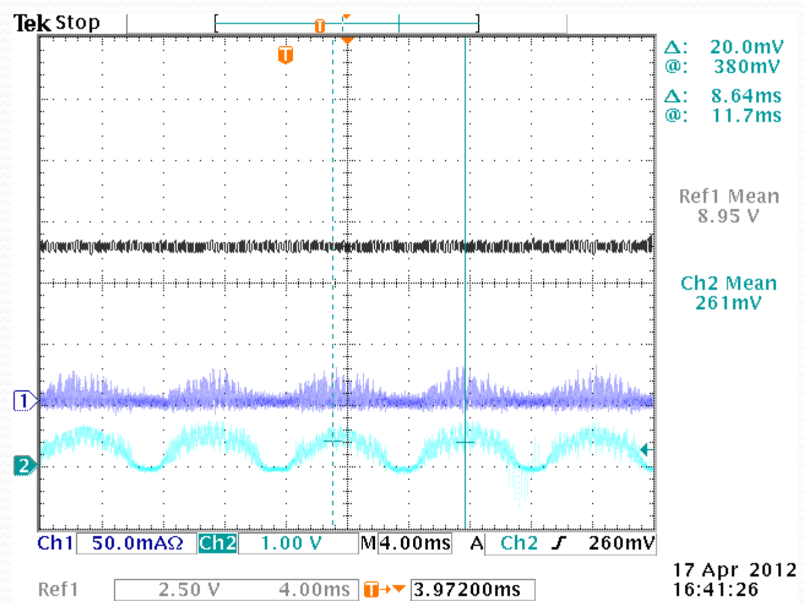


PFC PI Control

- Circuit in discontinuous mode







Completed Work

- Designed full scale system
- Controls functioning
  - Full scale boost converter
  - Full scale buck converter
  - Small scale PFC

Future

- Use system to charge battery
- Acquire detailed parameters for battery
- Discharge battery through inverter to run a variable load
- Implement regenerative braking
- Utilize ultra-capacitors for regenerative braking energy storage

Questions?

Converter Equations

Capacitor and Inductor Calculation Equations for PFC and Bi-Directional Converter

$$L = \frac{V_{out}}{4\, f_{swi\, max}\, \Delta I}$$

$$C = \frac{V_M I_M}{2\, \Delta V_{out}\, \omega\, V_{out}}$$

Boost Converter

$$\frac{V_o}{V_i} = \frac{1}{1-D}$$

Voltage Divider

$$V_{out} = \frac{R2}{R1 + R2} \cdot V_{in}$$

Buck Converter

$$(V_i - V_o)DT - V_o(1-D)T = 0$$

$$\Rightarrow V_o - DV_i = 0$$

$$\Rightarrow D = \frac{V_o}{V_i}$$

Controller Equations

$$\frac{\tilde{v}_o}{\tilde{d}} = \frac{V_{in}}{LC} \frac{1 + srC}{s^2 + s\left(\frac{1}{RC} + \frac{r}{L}\right) + \frac{1}{LC}} \qquad \text{(Buck)}$$

$$\frac{\tilde{v}_o}{\tilde{d}} = \frac{V_{in}}{(1-D)^2}\left(1 - s\frac{L_e}{R}\right)\frac{1 + srC}{L_eC\left(s^2 + s\left(\frac{1}{RC} + \frac{r}{L_e}\right) + \frac{1}{L_eC}\right)} \qquad \text{(Boost)}$$

$$\left|G_L(s)\right|_{f_c} = \left|G_C(s)\right|_{f_c} \times \left|G_{PWM}(s)\right|_{f_c} \times \left|G_{PS}(s)\right|_{f_c} \times k_{FB} = 1$$

$$K_{boost} = \sqrt{\frac{\omega_p}{\omega_z}} \qquad K_{boost} = \tan\left(45^o + \frac{\phi_{boost}}{4}\right)$$

$$\phi_{boost} = -90^o + \phi_{PM} - \angle G_{PS}(s)\Big|_{f_c}$$

$$f_z = \frac{f_c}{K_{boost}} \qquad f_p = K_{boost}\, f_c$$

$$k_c = \left|G_C(s)\right|_{f_c} \frac{\omega_z}{K_{boost}}$$

MOSFET vs. IGBT