EE155/255 Green Electronics

Grid, Power Factor, Inverters, and Batteries

10/30/17

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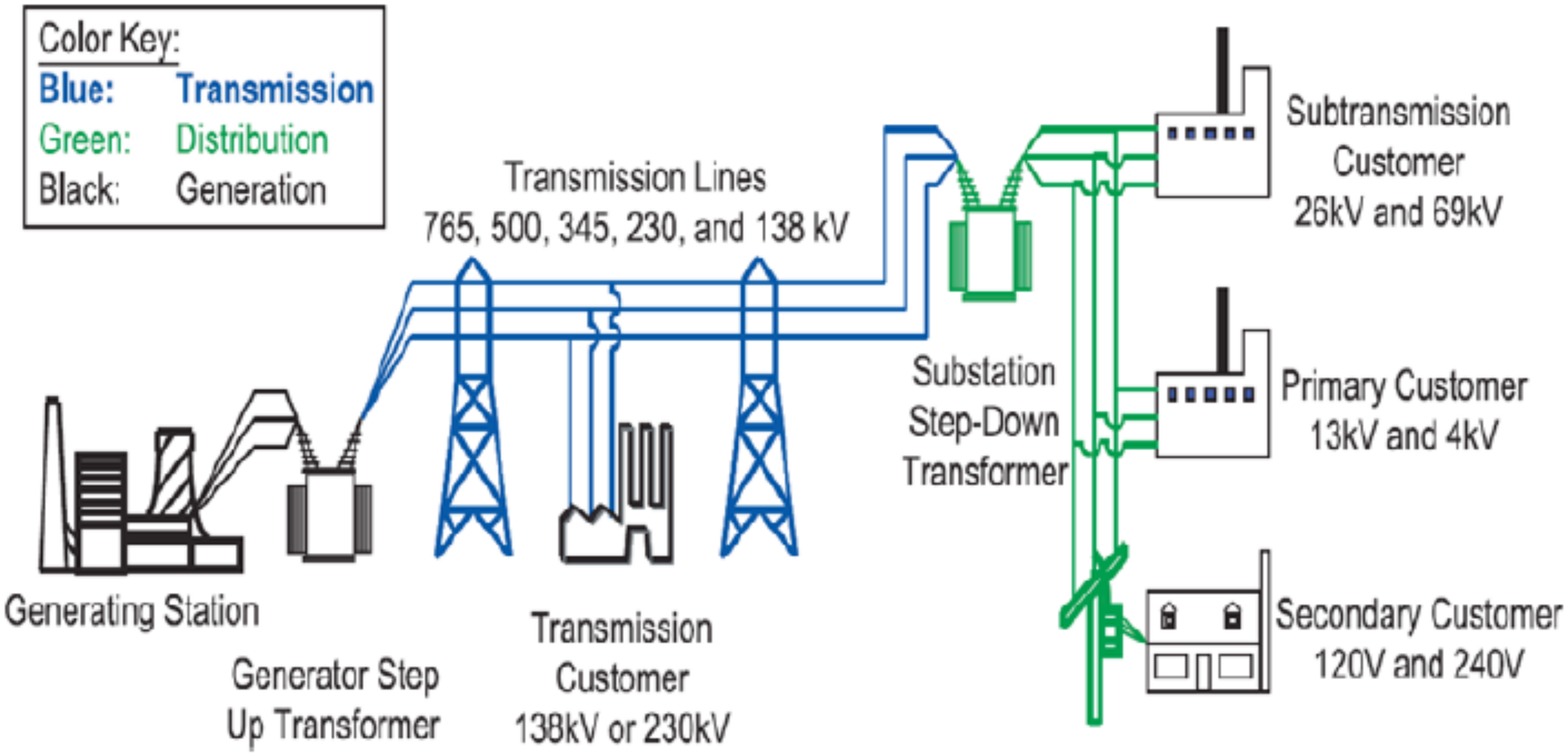
ENGINEERING

YAH

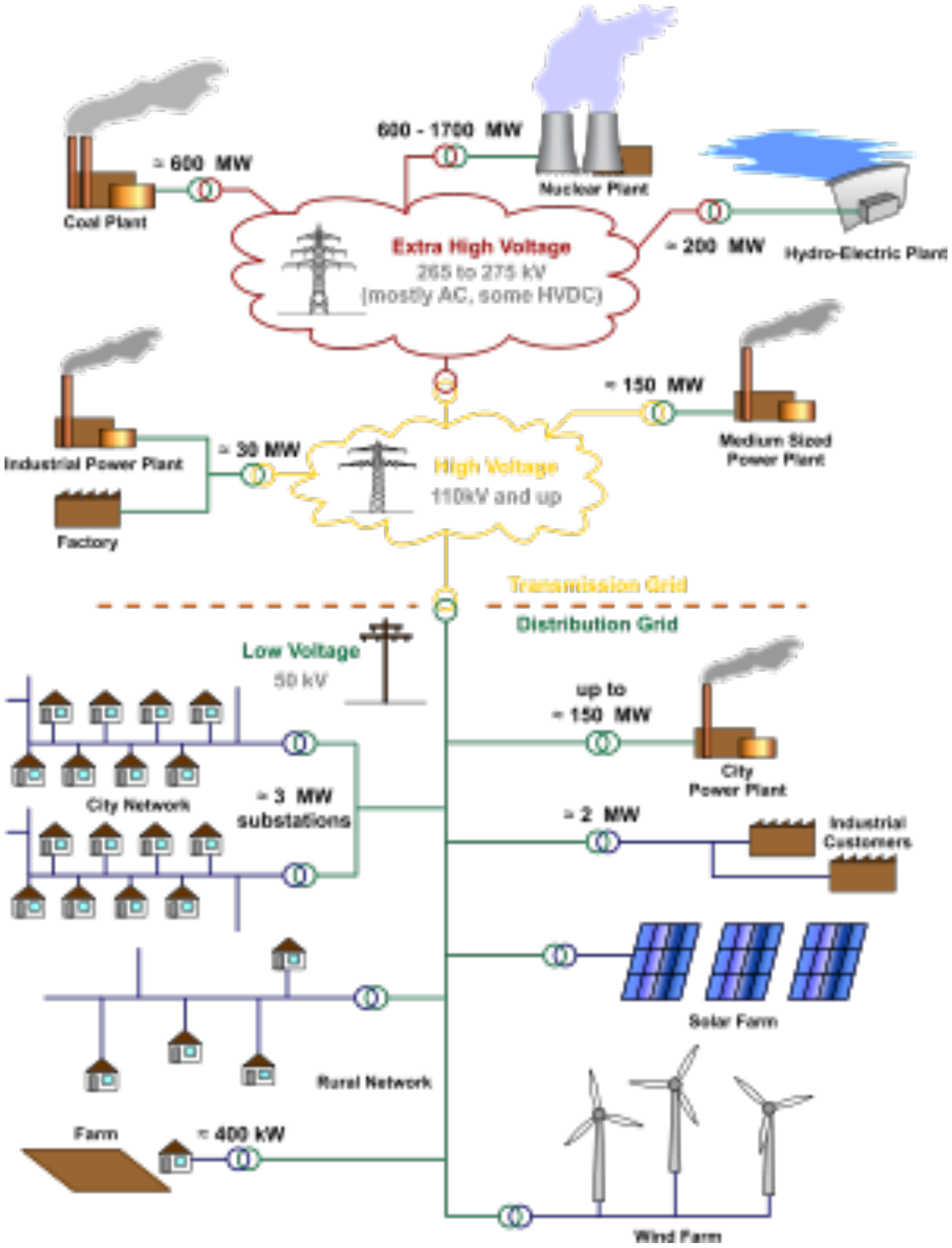
No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Inverters, Grid, PF, and Batteries	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Thermal & EMI		6	P	6	Project	
14	11/8/17	Soft Switching						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class				C4		
	TBD	Project presentations			P			
	12/15/17	Project webpage due						

60Hz AC

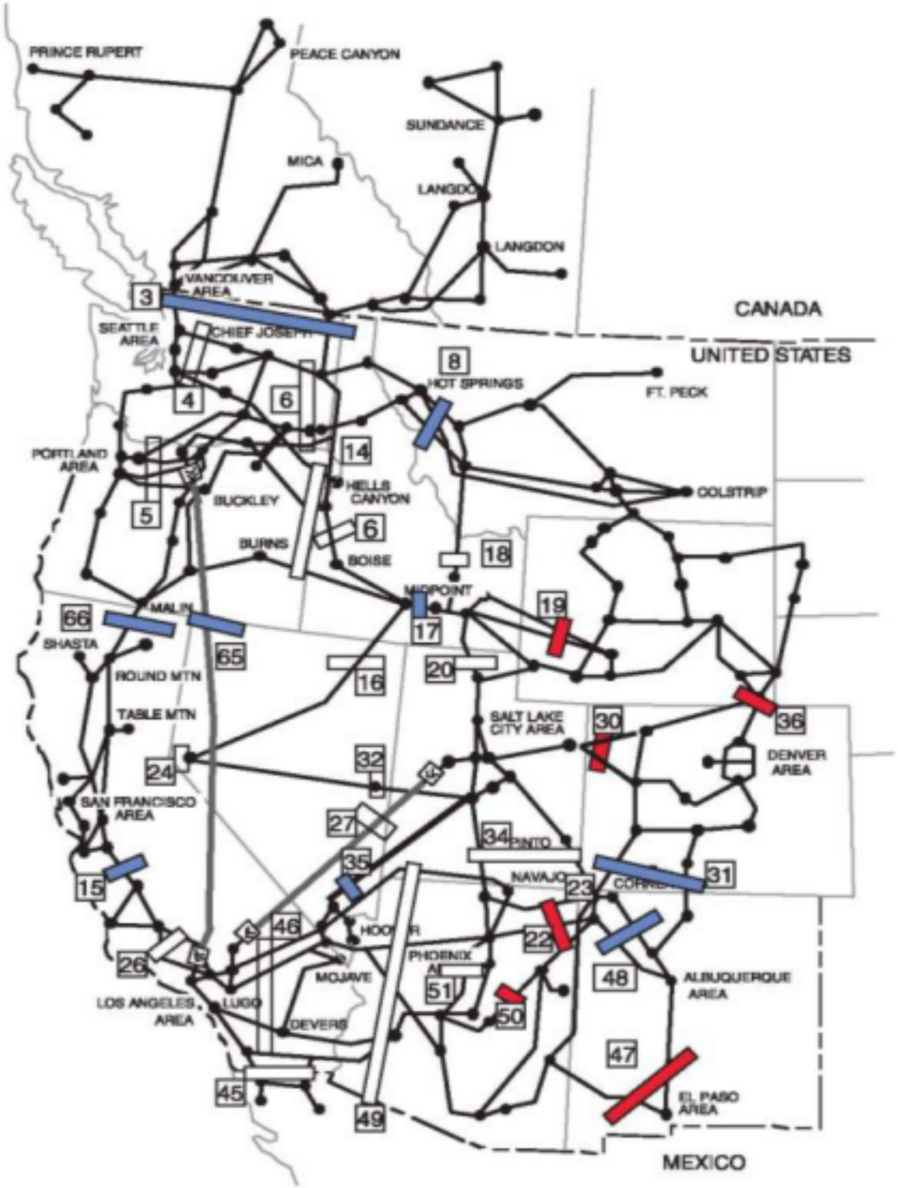
Basic Structure of the U.S. Electric Grid



Source: U.S. Canada Power System Outage Task Force



- Grid itself is largely passive
- Control is by varying generation or demand
- Transient loads cause frequency variation
  - Instantaneous energy provided by kinetic energy of generator
  - Only 0.5Hz variation allowed
- Fast response generation and storage needed
  - Spinning reserves (oil, gas)
  - Pumped water, Flywheels, Batteries
- Renewables have variable generation
- Free market for generation, transmission, and distribution
  - 4 second pricing
  - Payment for fast response reserves



Transmission line (or lines). White or colored bars "bundle" the lines they cross or touch into a numbered transmission path.

The number alongside each bar is the WECC number for that path.

🟥 Actual Flow > 75% of OTC greater than 50% of time on path

🟦 Actual Flow > 75% of OTC between 25% and 50 % of time on path

⬜ Actual Flow > 75% of OTC between 0% and 25% of time on path

Why not Make the Grid DC?

- Pros
  - More efficient transmission
  - Better control of energy flow
  - Lower cost with modern electronics
- Cons
  - Inertia
  - Historical cost of energy conversion
    - No longer the case
  - Hard to make a DC circuit breaker
  - Need to be compatible with AC devices
    - Have to be AC at the outlet (for a while at least)
  - Less reliable (historically)

Dealing with the AC Line

- 60Hz AC is just slowly moving DC
- Make voltage follow 60Hz sine wave to synthesize AC
- Unity power factor requires current proportional to voltage
  - i = kV
  - Driving or loading the AC line

Three Cases

- Power factor corrector (PFC)
  - AC input, DC output
  - Make AC current proportional to voltage (unity power factor)
  - Need to store energy
- Grid tied inverter
  - DC input, AC output
  - Grid defines voltage
  - Drive current to be proportional to voltage (unity power factor)
  - Need to store energy
  - Just a PFC with energy going into the grid
- Free-standing inverter
  - Synthesize 60Hz sine wave

Power Factor

Energy Star Regulations

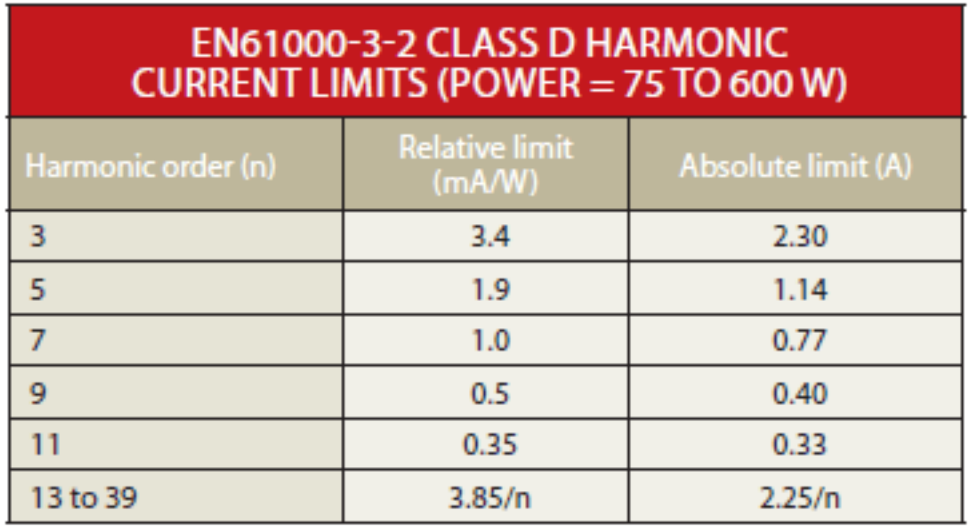
3) **<u>Energy Efficiency and Power Management Criteria</u>:** Computers must meet the requirements below to qualify as ENERGY STAR. The Version 5.0 effective date is covered in Section 5 of this specification.

(A) Power Supply Efficiency Requirements - Requirements are applicable to all product categories covered by the ENERGY STAR Computer Specification:

> **Computers Using an Internal Power Supply:** 85% minimum efficiency at 50% of rated output and 82% minimum efficiency at 20% and 100% of rated output, with Power Factor ≥ 0.9 at 100% of rated output.

Power Factor >= 0.9 at 100% rated output

IEC/EN61000-3-2



EN61000-3-2 CLASS D HARMONIC CURRENT LIMITS (POWER = 75 TO 600 W)

Harmonic order (n)	Relative limit (mA/W)	Absolute limit (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 to 39	3.85/n	2.25/n

Definition

$$PF = \frac{Real\ Power}{Apparent\ Power}$$

Apparent Power = V_{rms} x I_{rms}

$$PF = \frac{P}{\sqrt{P^2 + Q^2}}$$

$$PF = \frac{1}{\sqrt{1 + THD^2}} = \frac{I_{1,rms}}{I_{rms}}$$

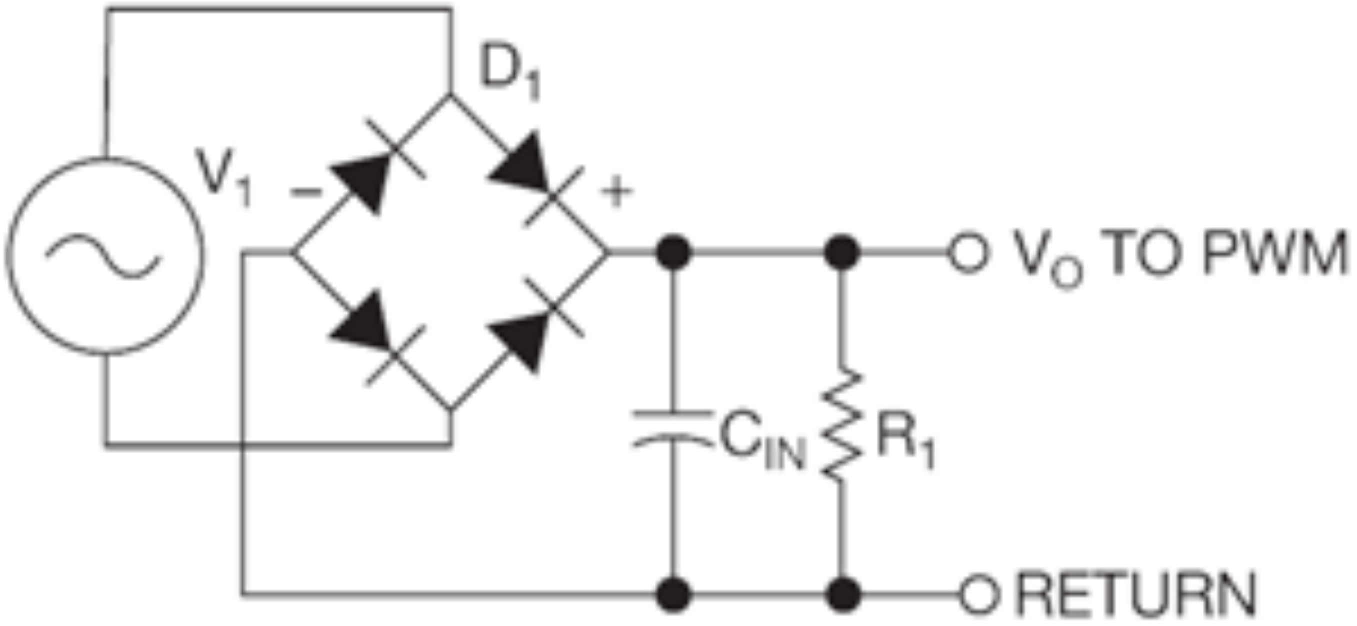


Figure 1 The SMPS presents a nonlinear load to the ac-power line.

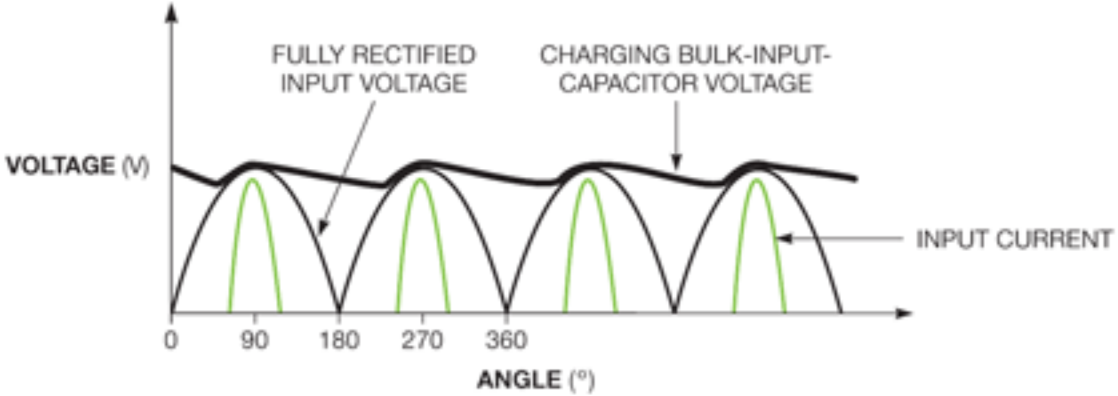
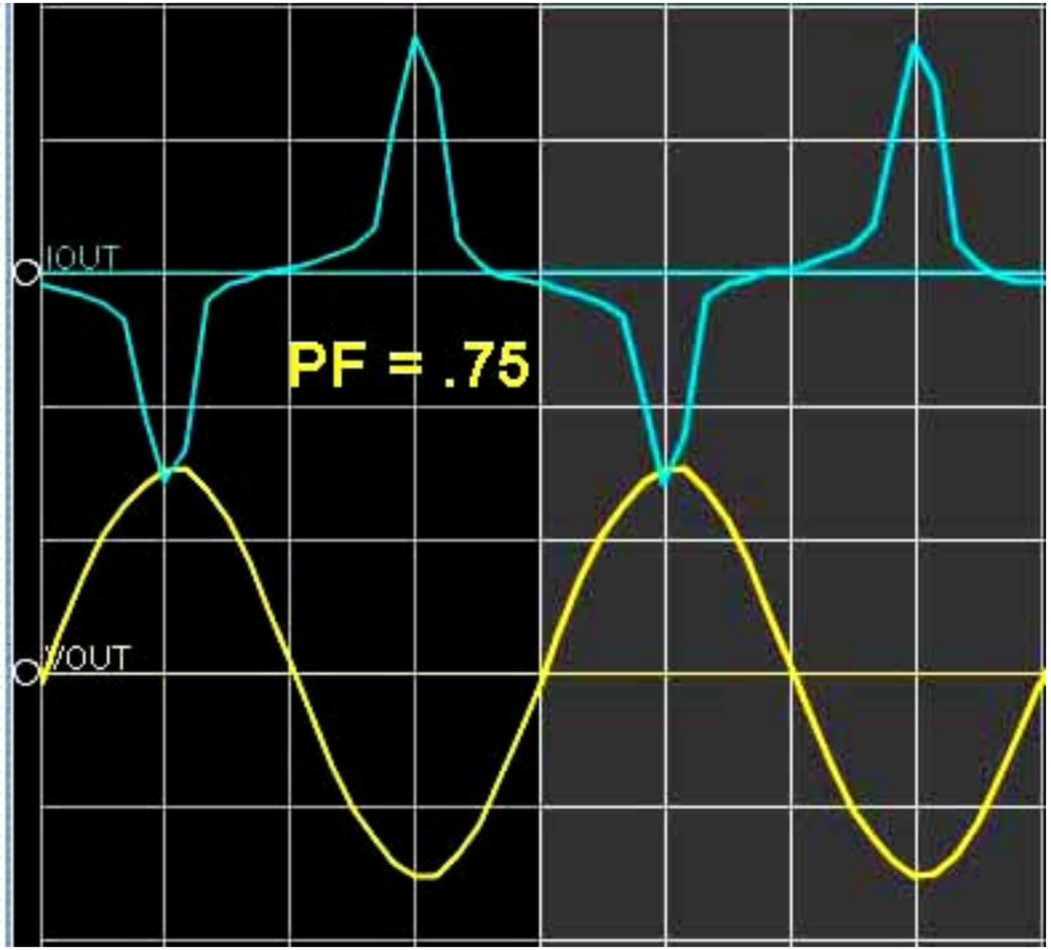
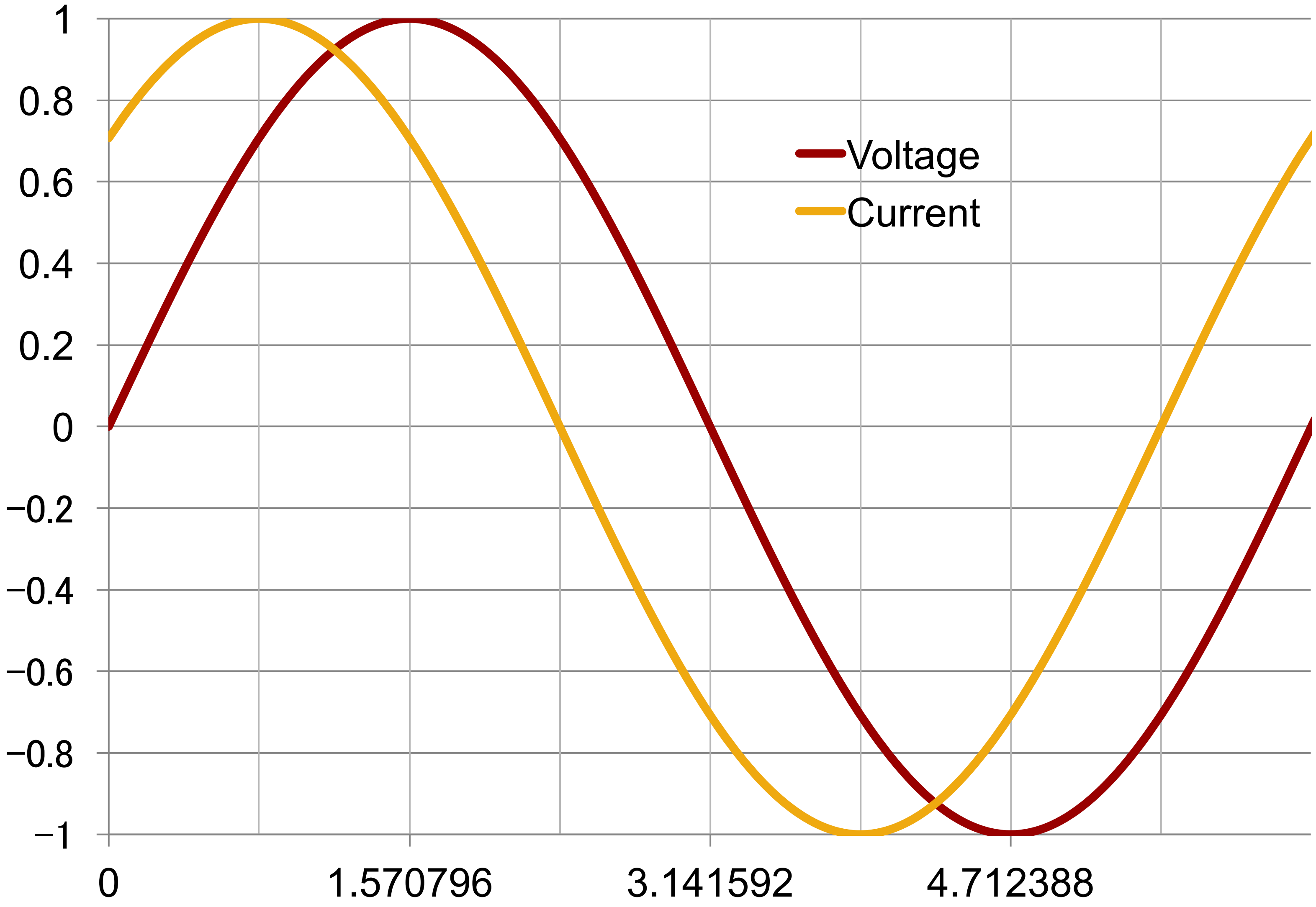


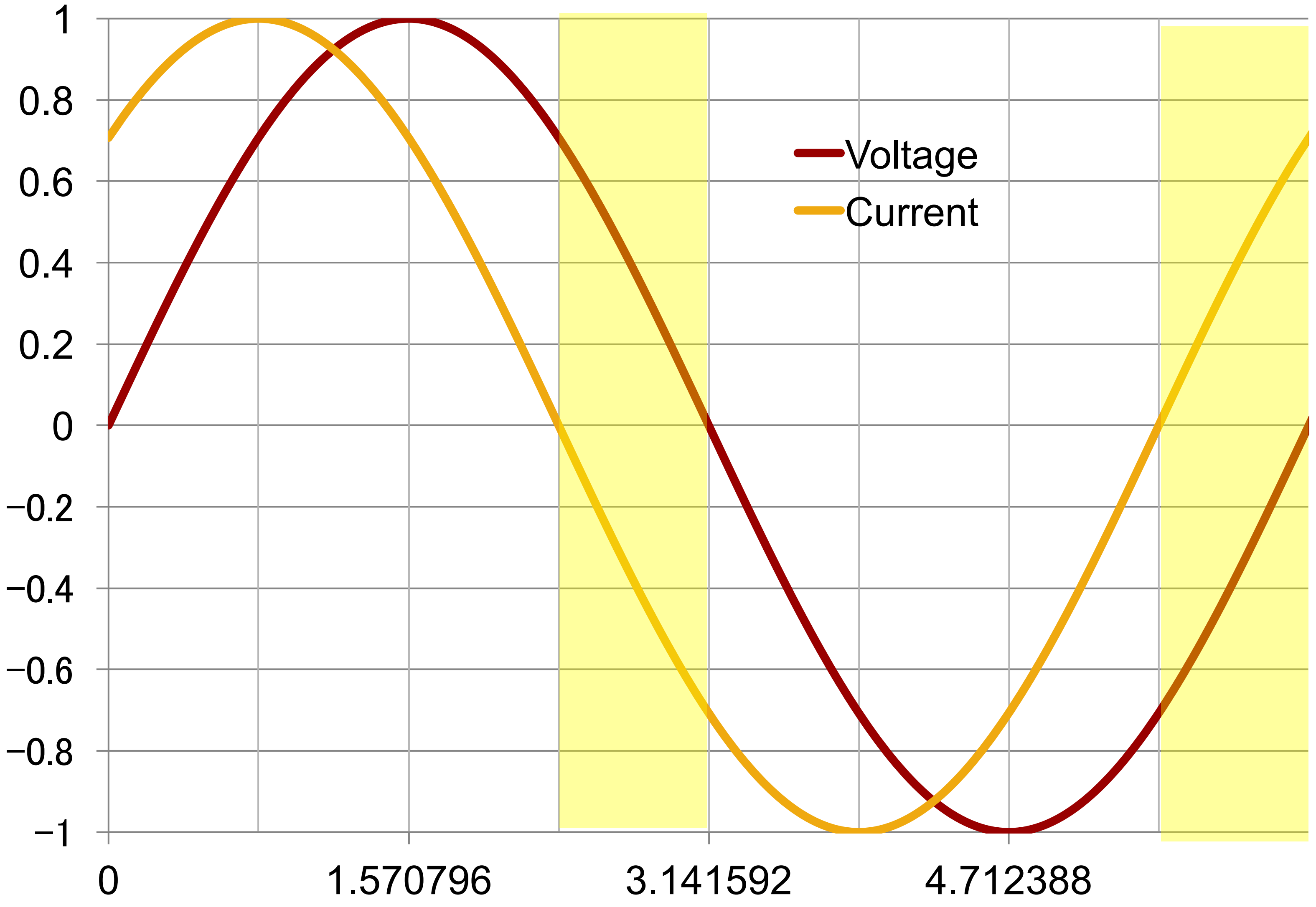
Figure 2 Superimposing the current over the voltage for the circuit in Figure 1 shows the need for a PFC to shape the current.

IOUT
VOUT
PF = .75

PF = 0.707


1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
1.570796
3.141592
4.712388
Voltage
Current

PF = 0.707



1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
1.570796
3.141592
4.712388
Voltage
Current

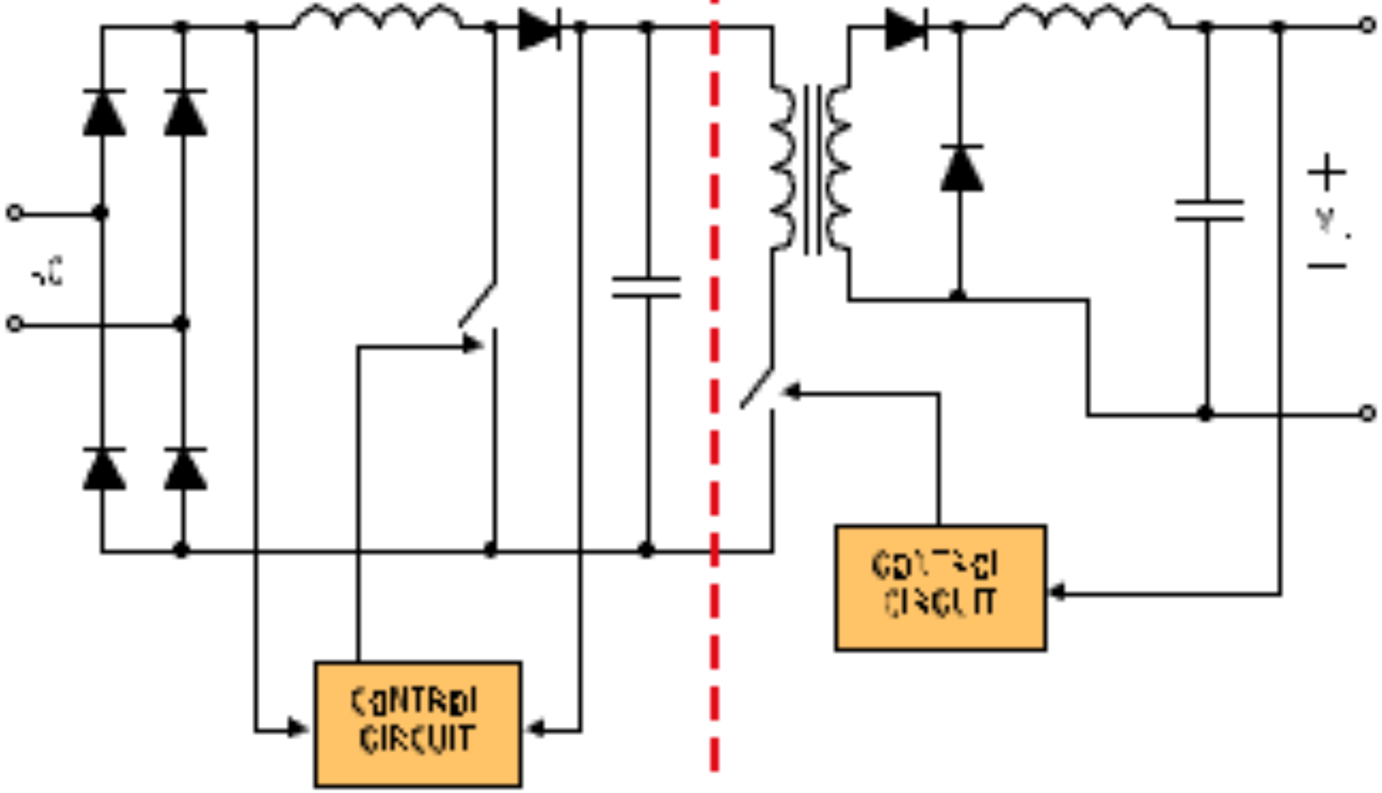
PFC

Power Factor Correction

- Correct power factor by regulating input current
  - To be instantaneously proportional to input voltage
    - I = kV
  - Makes circuit “look” like a resistor
  - May change the constant k over time
- Often done in a separate input stage
- Trivially achieved with DCM boost input stage
- Can be accomplished with CCM boost input stage and current-mode control

AC current in – DC current out

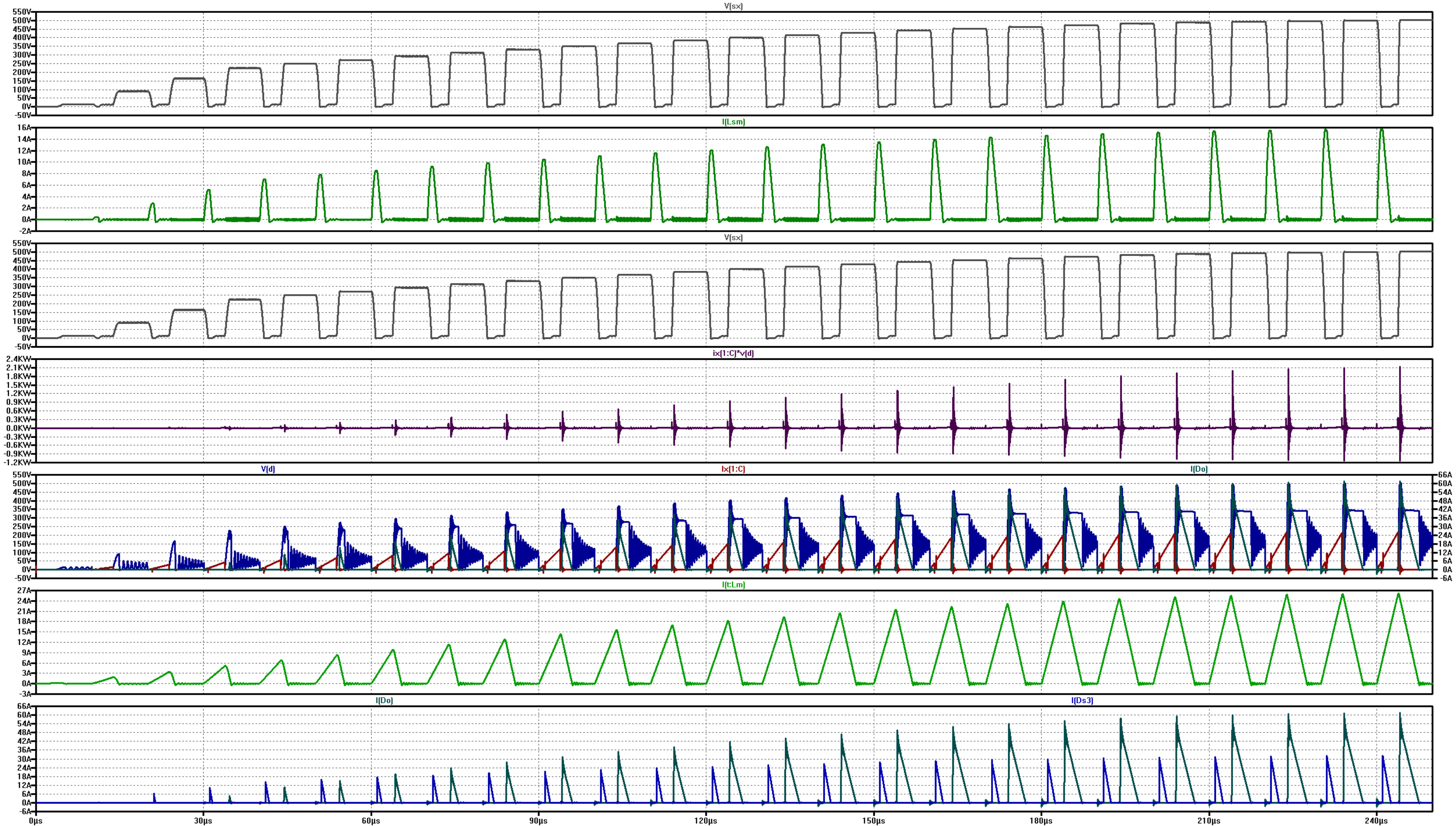
PFC Input Stage

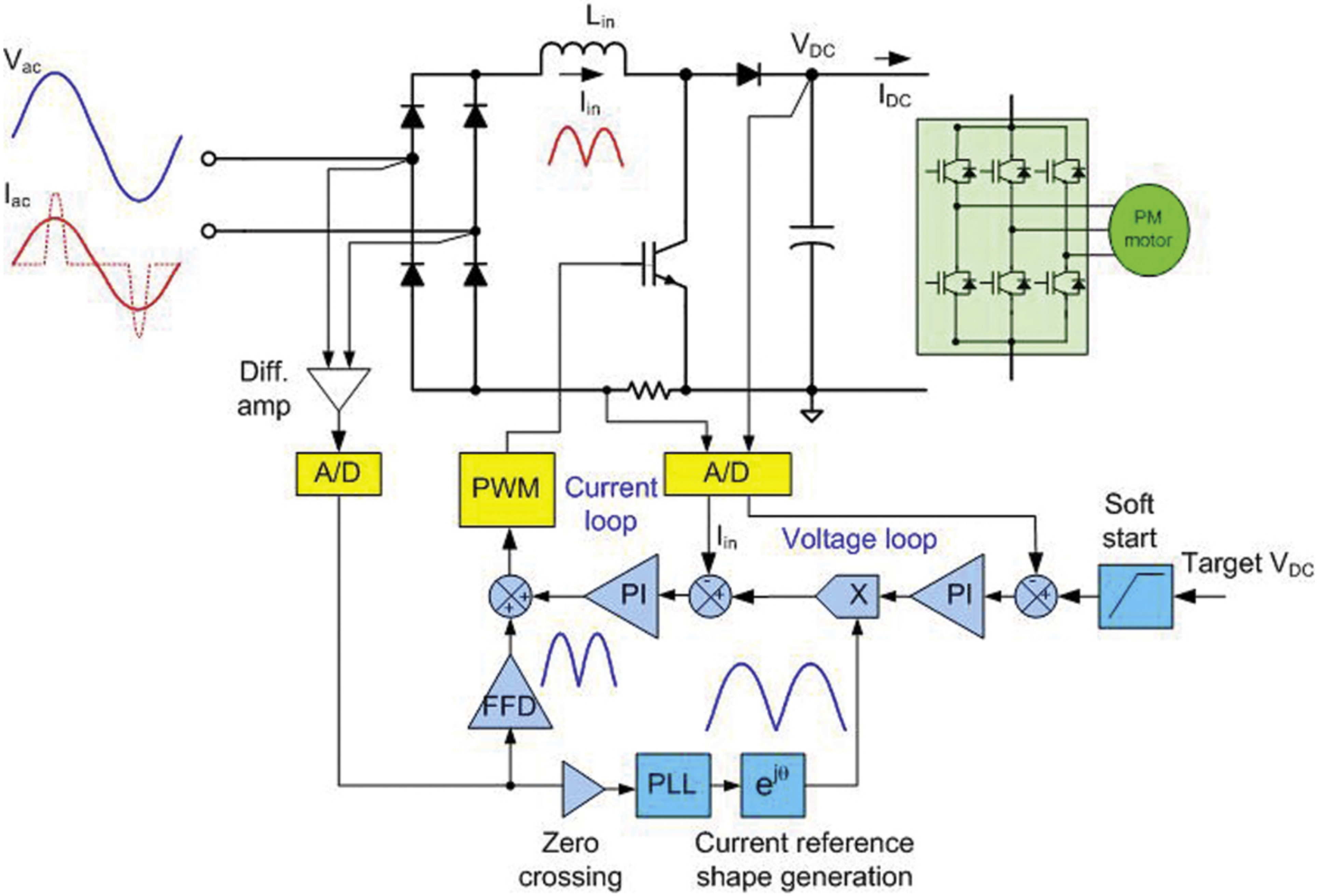


PFC Boost

Forward Output Stage

DCM of Flyback
1kHz Input Frequency
Constant Pulse Width




V_{ac}
I_{ac}
L_{in}
I_{in}
V_{DC}
I_{DC}
PM motor
Diff. amp
A/D
PWM
Current loop
A/D
I_{in}
Voltage loop
Soft start
Target V_{DC}
PI
X
PI
FFD
PLL
$e^{j\theta}$
Zero crossing
Current reference shape generation

Summary of PFC

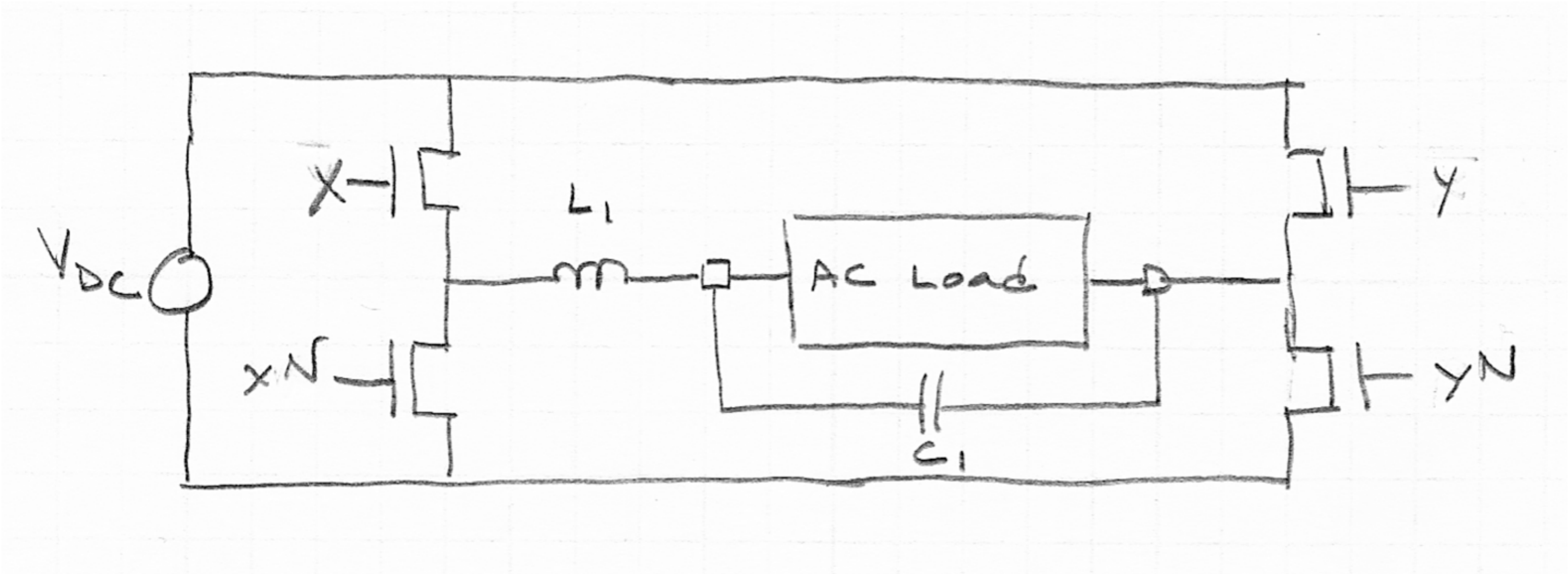
- Input current must be proportional to input voltage
  - Harmonics limited by regulation
- PFC input stage regulates input current
  - DCM – constant pulse width
  - CCM – multiply input voltage by voltage error signal and regulate current to this value
- Feedback tracks
  - Input current – to make it proportional to input voltage
  - Output voltage – sets constant of proportionality

Inverters

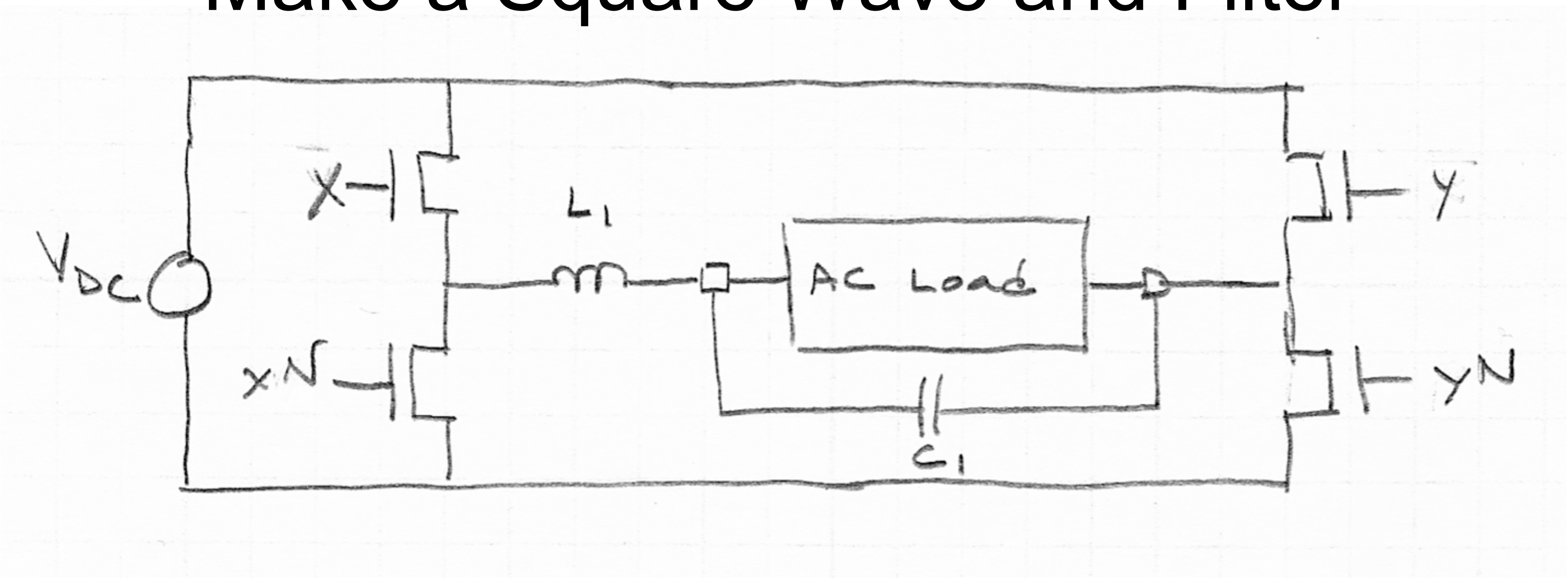
Inverter

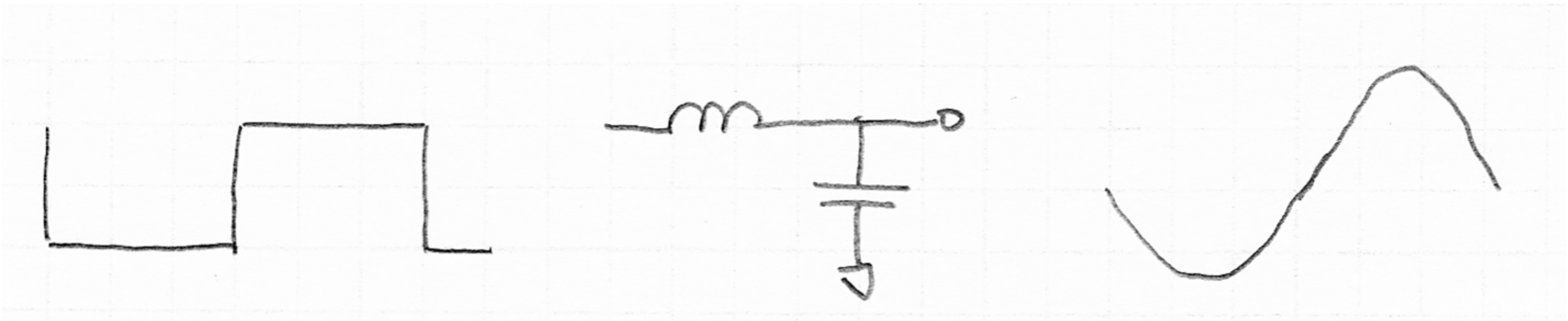
- PFC regulates an AC input current
  - Converts AC power to DC power
- Inverter regulates an AC output voltage
  - Converts DC power to AC power
  - Particularly useful for motor drives

Basic Inverter
Make a Square Wave and Filter

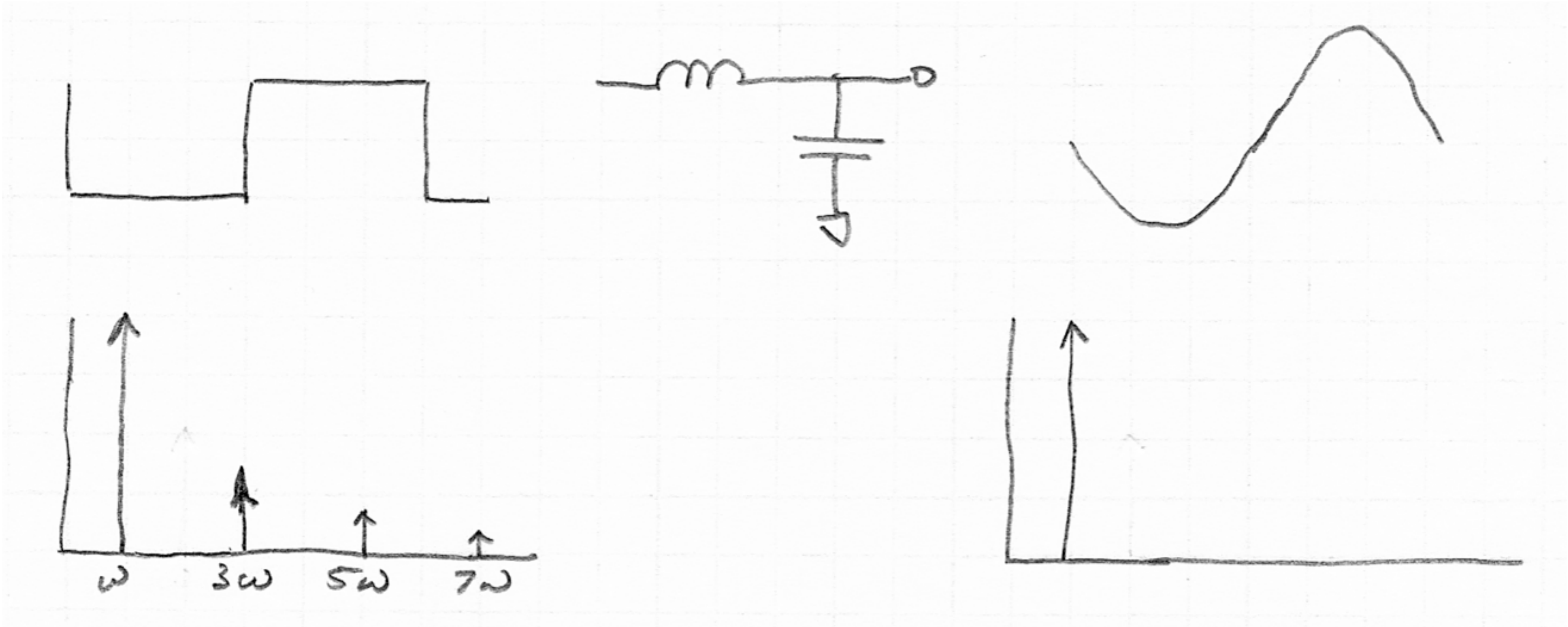


Basic Inverter
Make a Square Wave and Filter

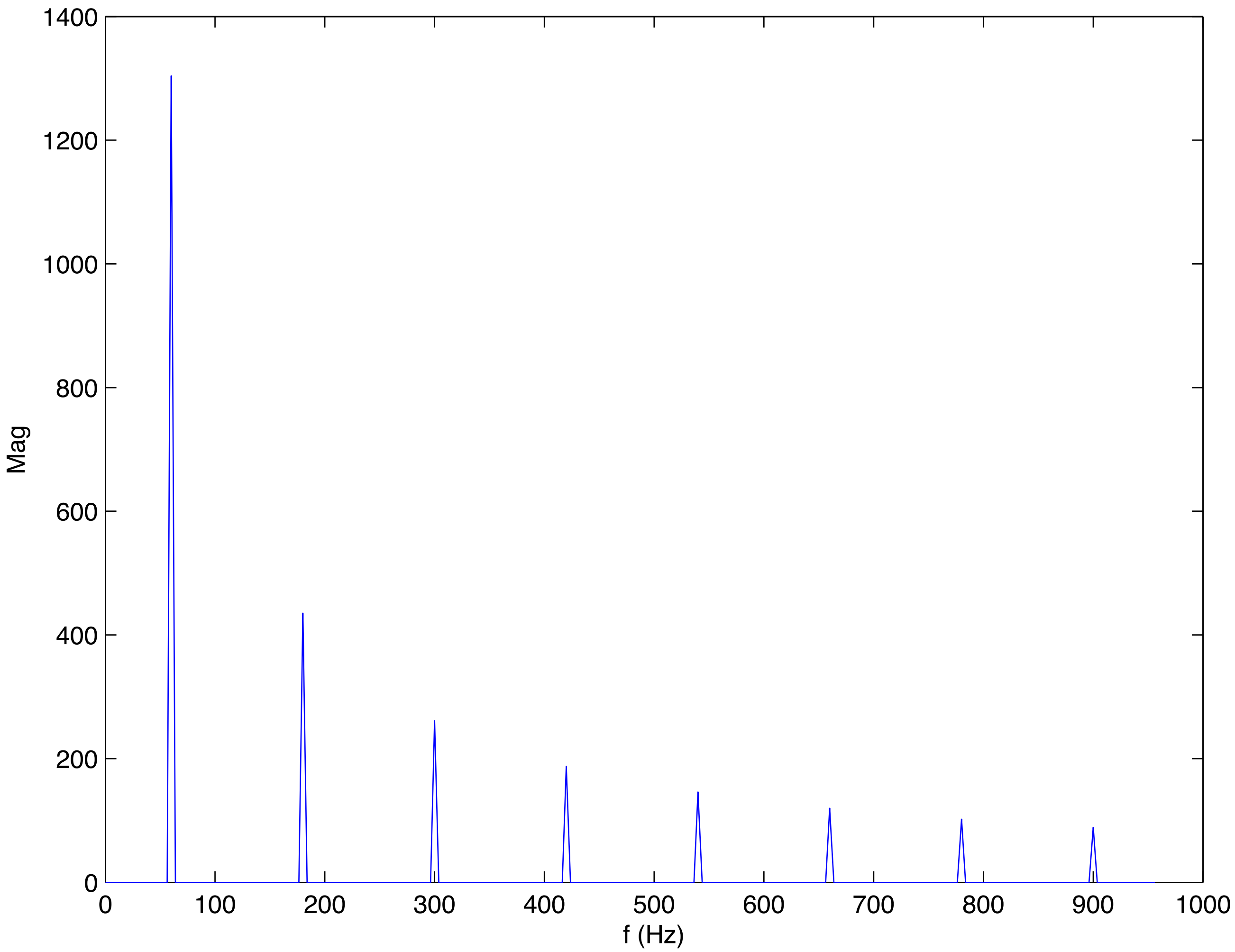




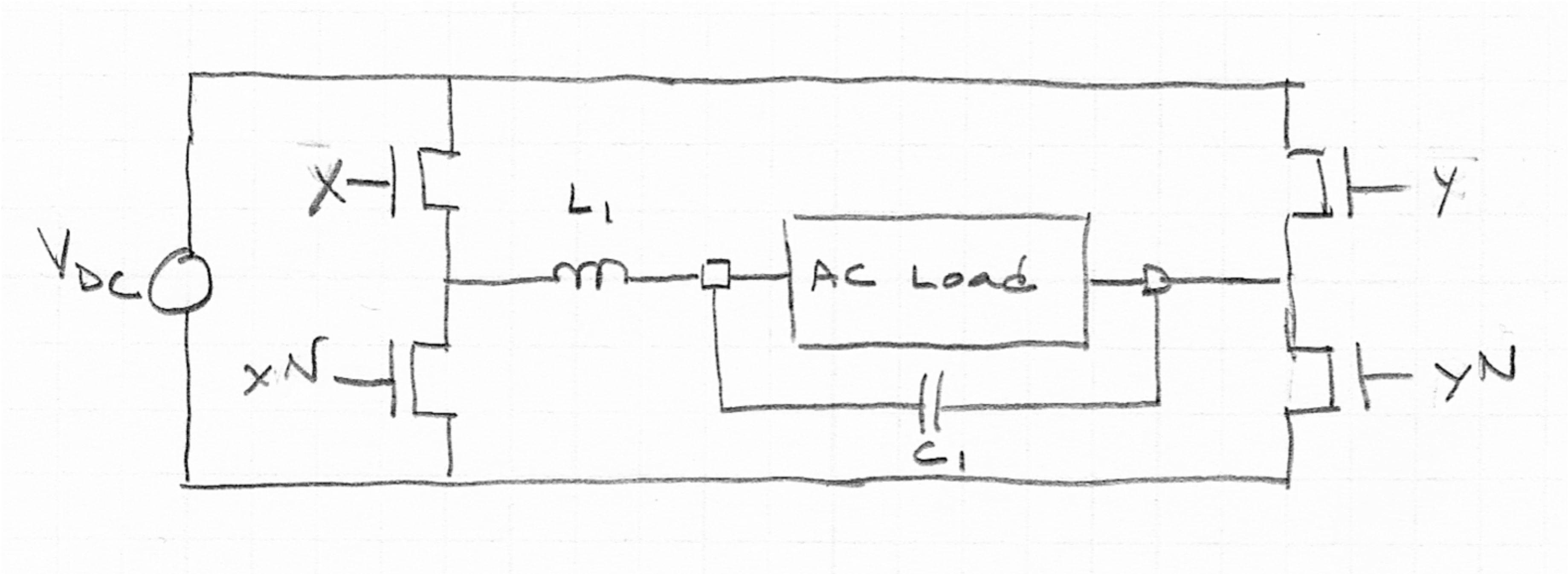
But Filtering a 60Hz Square Wave is Hard



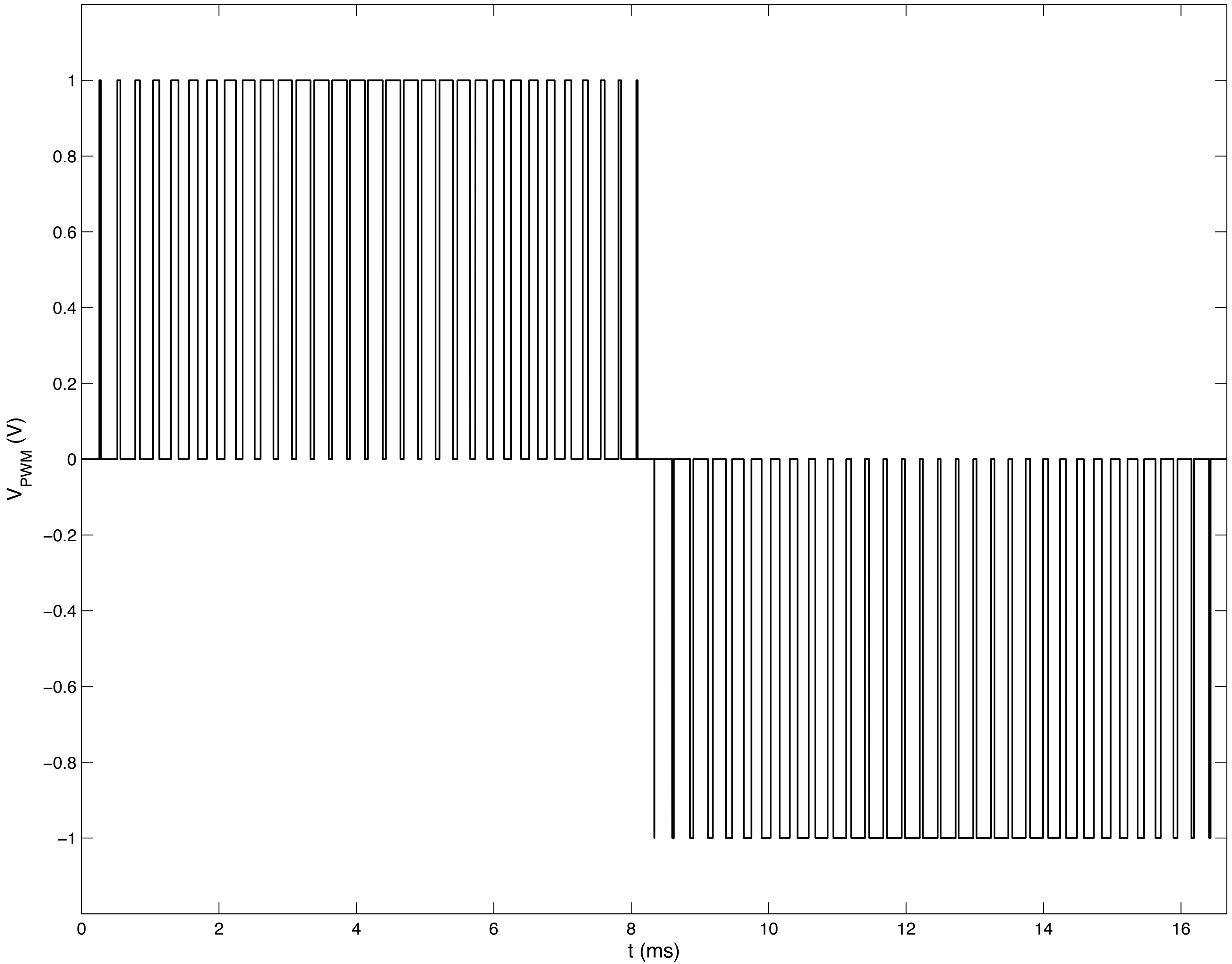
Spectrum of a 60Hz Square Wave



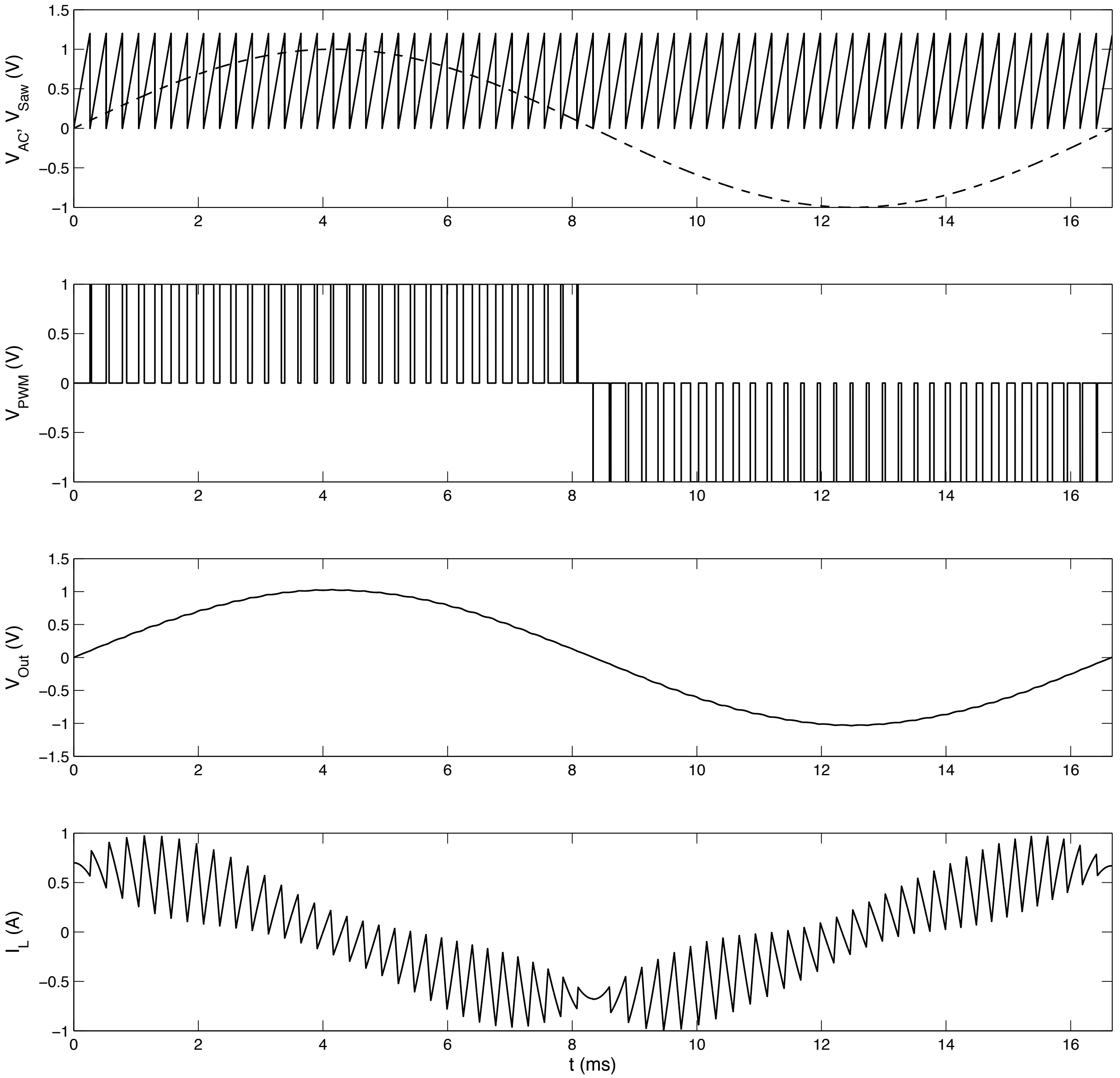
Make a PWM Sine Wave and Filter



PWM Waveform



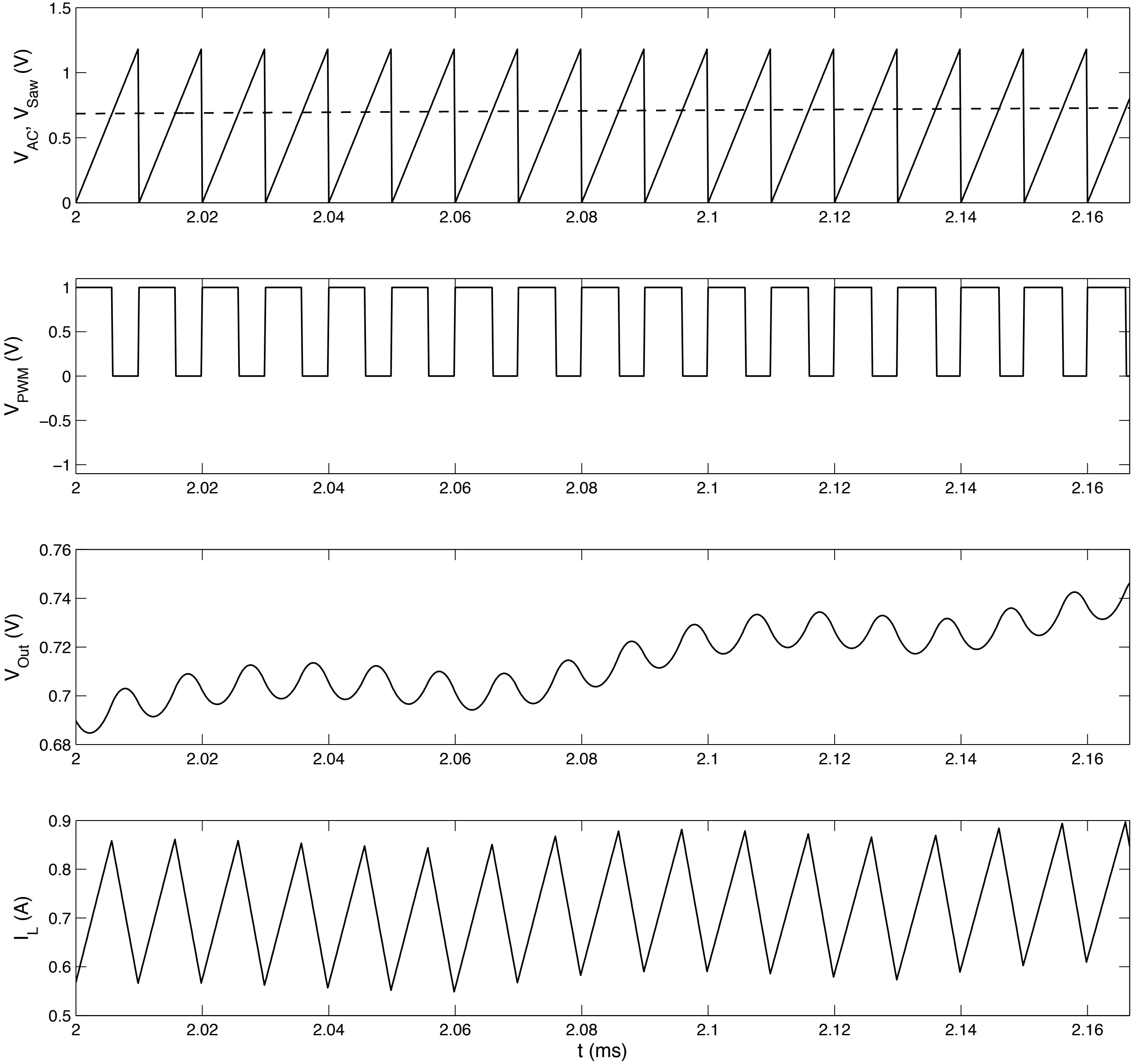
PWM Synthesis



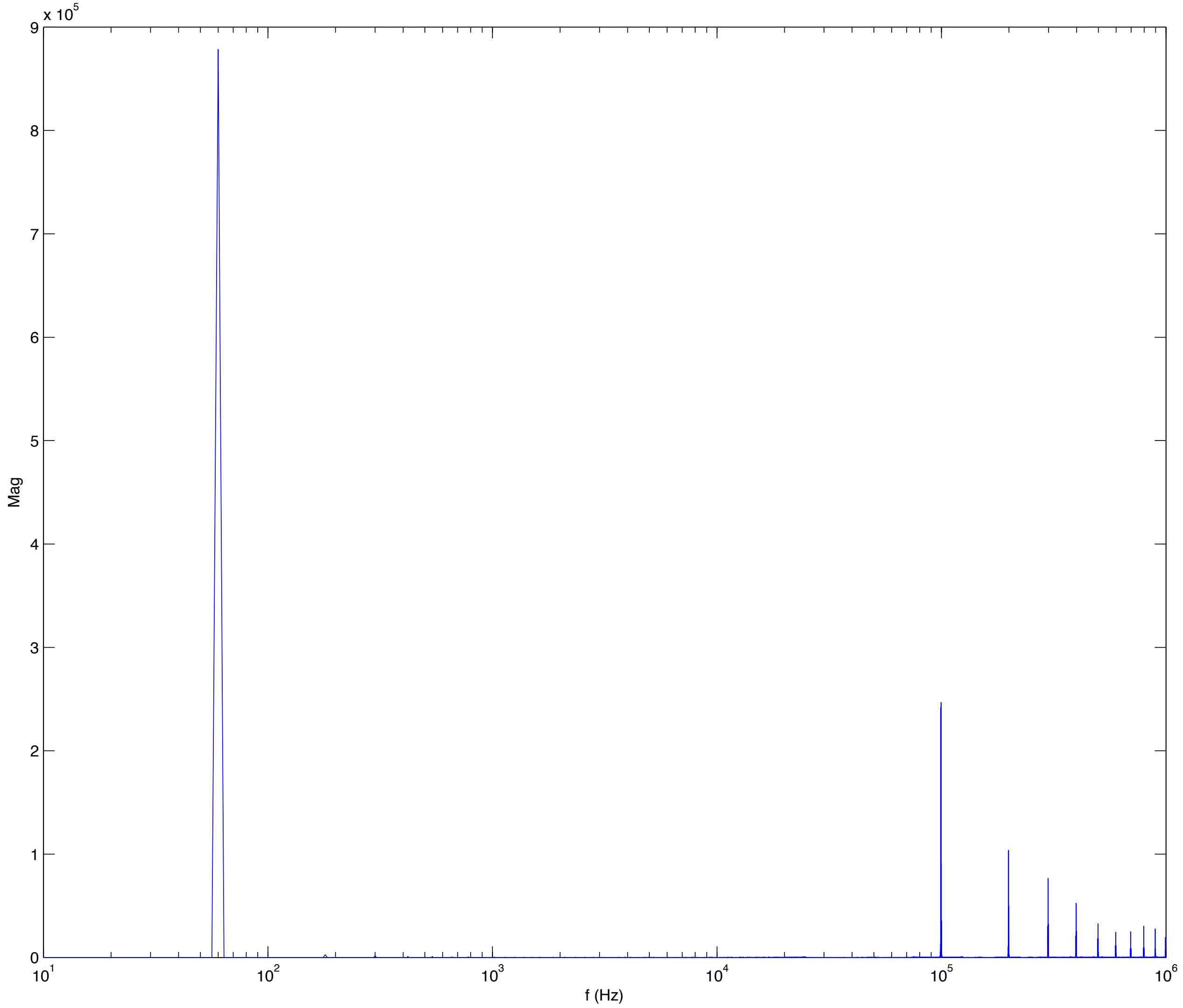
x = sine > saw
y = -sine > saw

Digitally generate sine with quarter-wave table

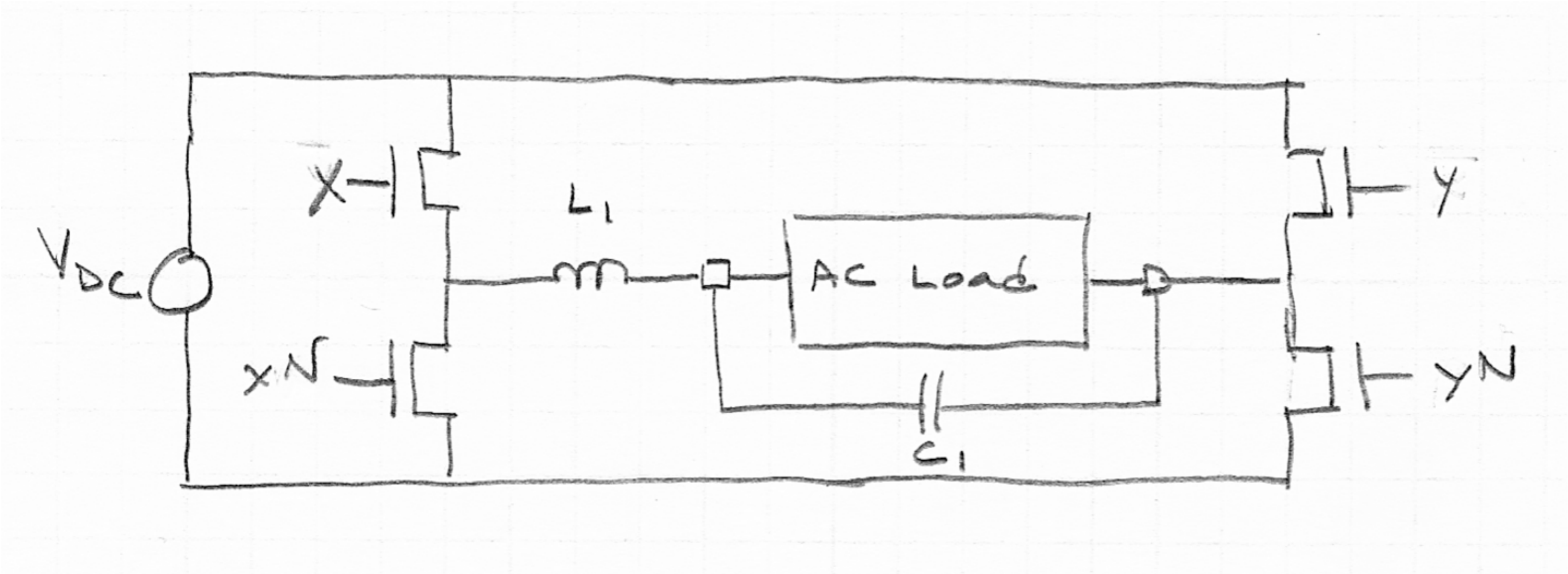
100kHz PWM, 60Hz Sine (1667:1)



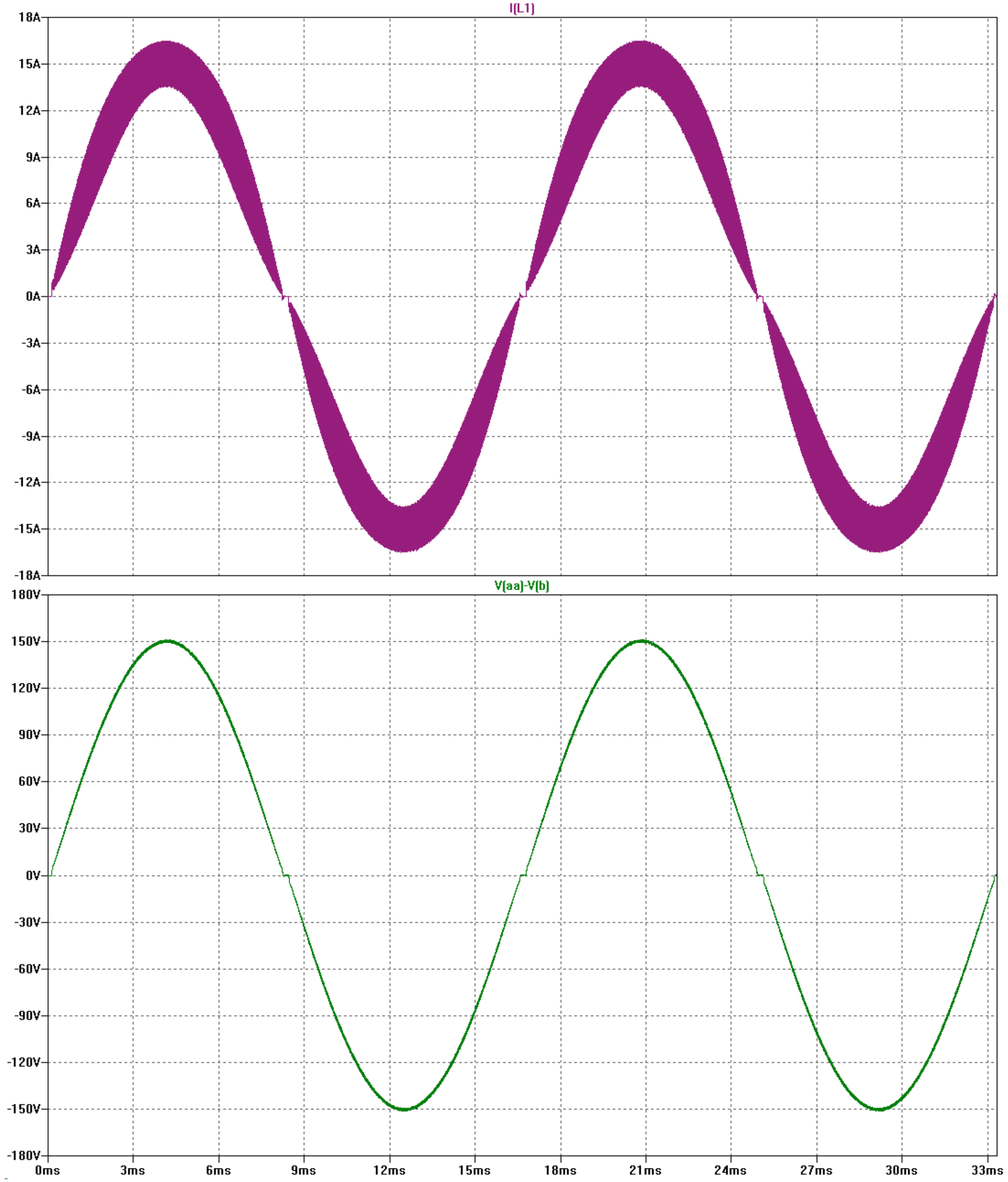
Spectrum of 100kHz PWM Signal



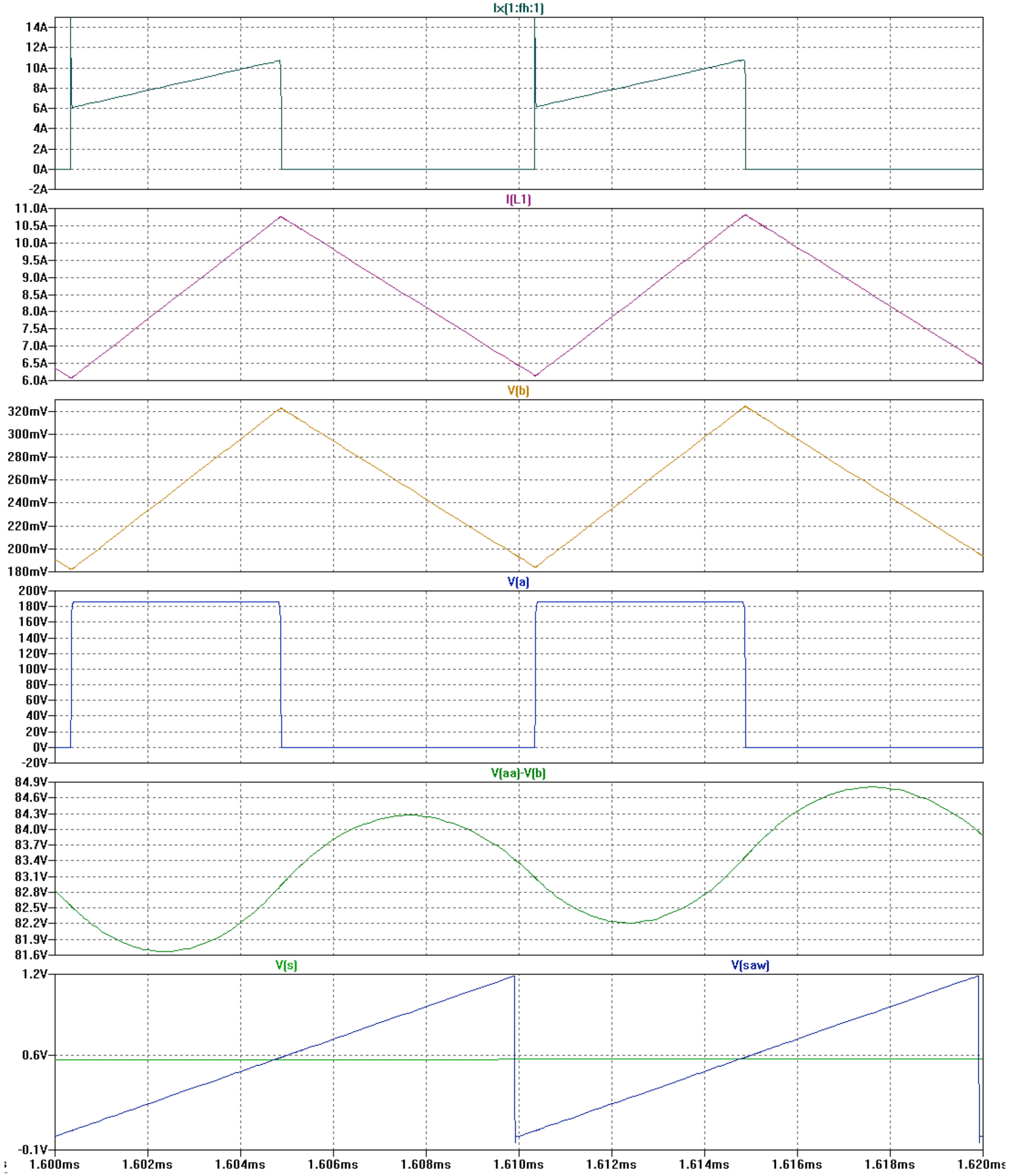
Circuit Simulation



SPICE Waveforms



Close Up of 2 PWM Cycles



Inverter Details

- Can operate independently or drive the grid.
  - Grid connected inverters use the AC line as a “sine-wave” reference.
    - This gives the proper phase
    - It also compensates for distortion of the sine wave
- Current-mode control often used
  - To give close to unity power factor into AC line
  - This is the same as a PFC circuit but the current is flowing the other way

Anti-Islanding

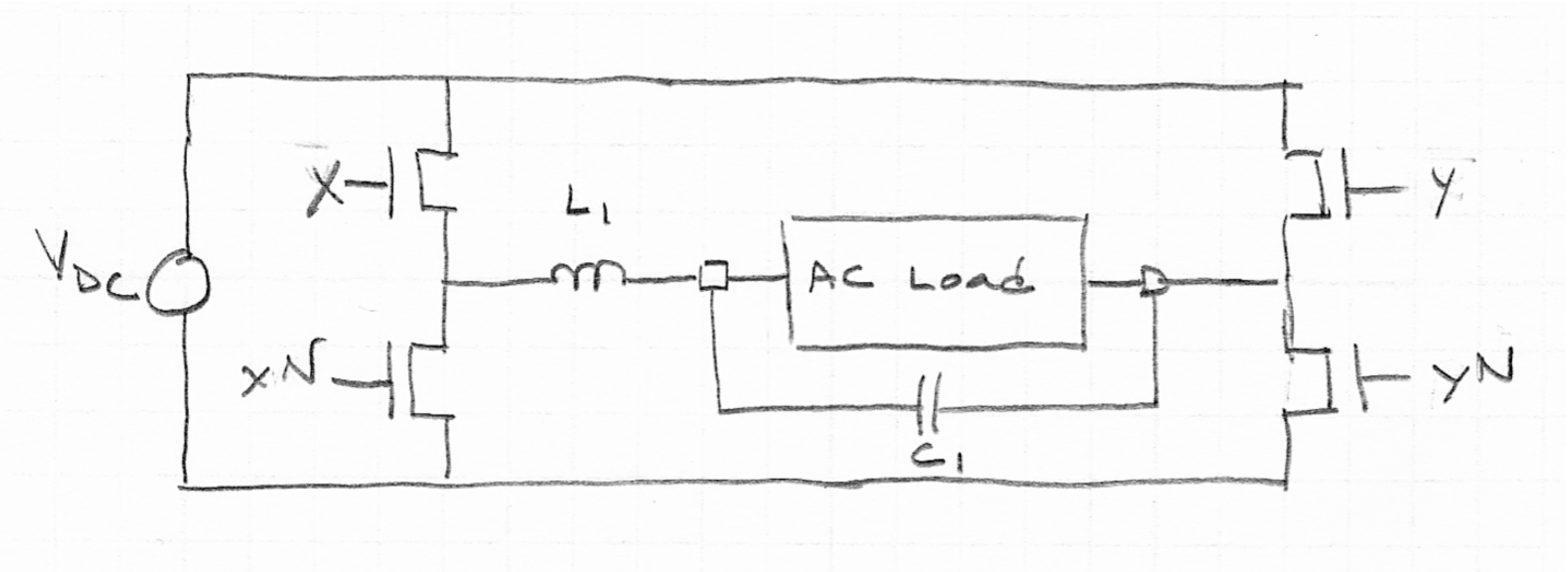
- Grid-connected inverters need to turn off when the grid goes down.
- Safety issue for firemen, linemen, etc…
- How do you detect when the grid goes down?

Anti-Islanding

- Line monitoring
  - Voltage limits, frequency limits.
  - Rate of change of frequency
  - Rapid phase shift
- Active detection
  - Impedance measurement
  - Forced phase shift/frequency shift

Inverters Summary

- Convert a DC Voltage to an AC Voltage
- AC is just slowly changing DC
- Use a full-bridge to generate a PWM Sine Wave
  - Pulse width proportional to sin(x)
- LC Filter to reject high frequencies



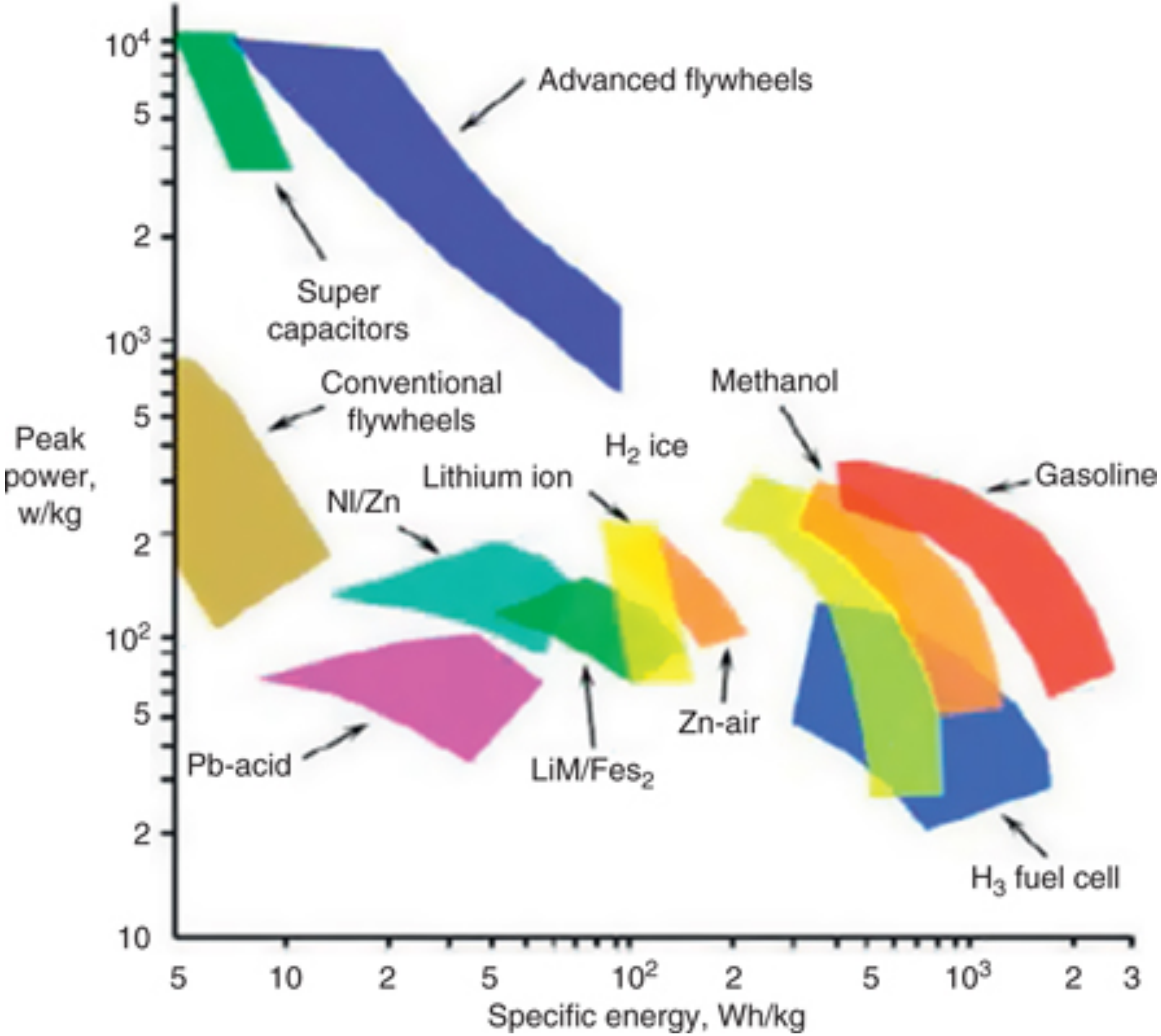
Batteries

Energy Storage Devices

Device	Specific Energy (MJ/Kg)	Rate (Hz)
Capacitor	0.002	10^9
Super Capacitor	0.01	100
Ferrite Inductor	10^{-5}	10^6
Flywheel	0.4	0.1
Battery (Li-ion)	0.9	10^{-3}
Gasoline*	44	0.1

*Requires an oxidizer

Ragone Chart

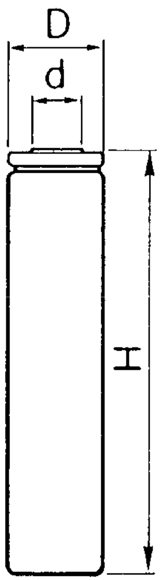


18650 Cell

Panasonic 18650

Lithium ion
Rechargeable battery

Cell Type NCR18650B



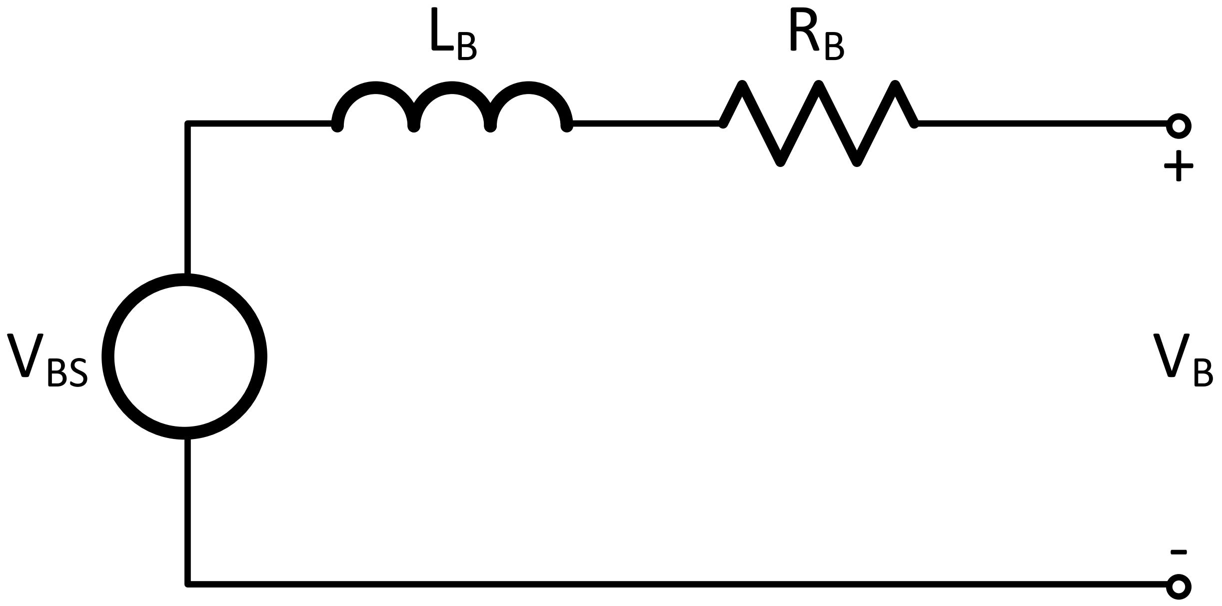
Dimensions(Typ.) of Bare Cell		
	H	64.93mm
	D	18.2mm
	d	7.9mm

Discharged State after Assembling

Specifications

Rated Capacity (at 20℃)		Min.3200mAh
Nominal Capacity (at 25℃)		Min.3250mAh Typ.3350mAh
Nominal Voltage		3.6V
Charging Method		Constant Current -Constant Voltage
Charging Voltage		4.2V
Charging Current		Std.1625mA
Charging Time		4.0hrs.
Ambient Temperature	Charge	+10～+45℃
	Discharge	-20～+60℃
	Storage	-20～+50℃
Weight (Max.)		47.5g
Dimensions (Max.) Maximum size without tube	(D)	18.25mm
	(H)	65.10mm
Volumetric Energy Density		676Wh/l
Gravimetric Energy Density		243Wh/kg

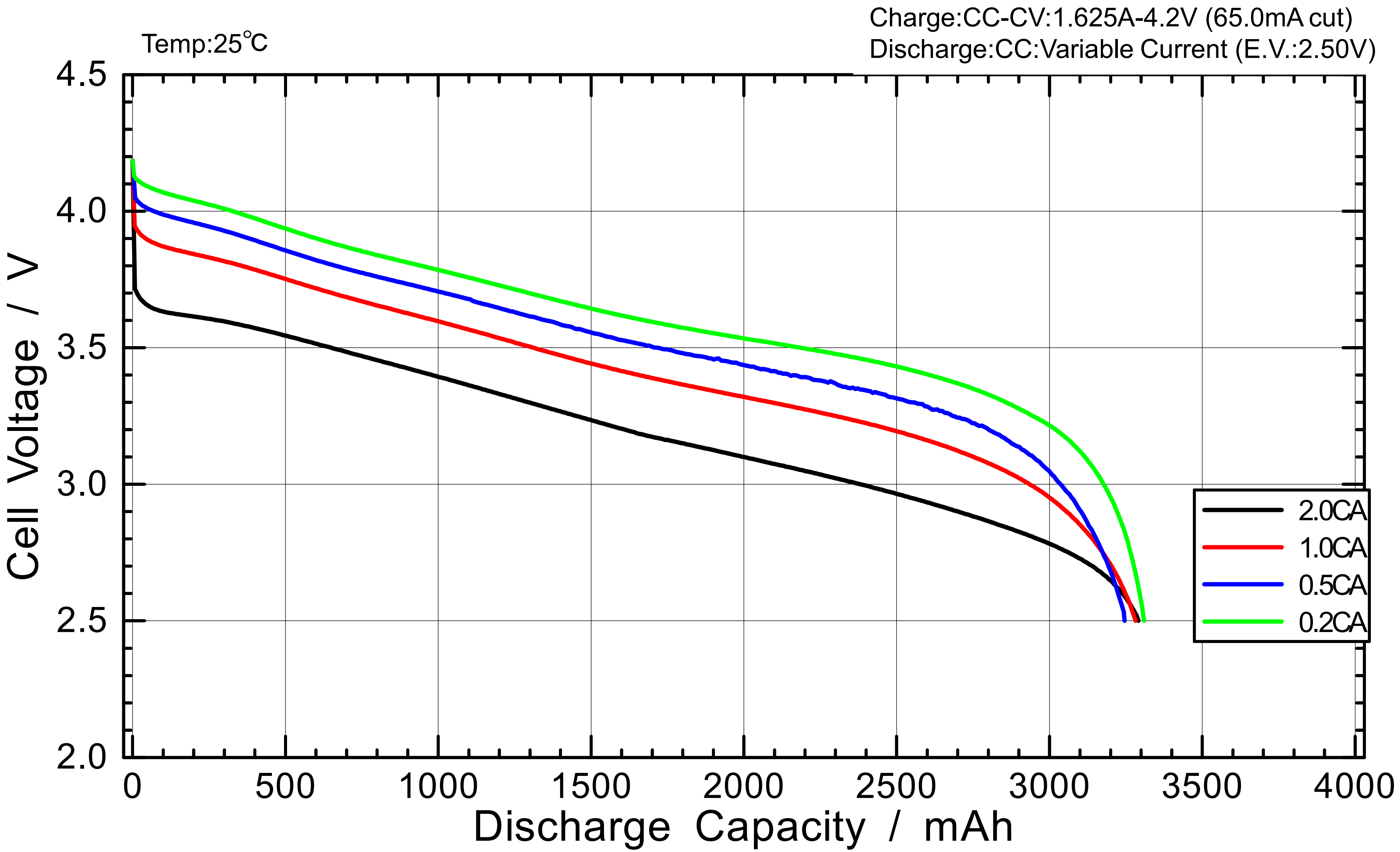
Battery Model



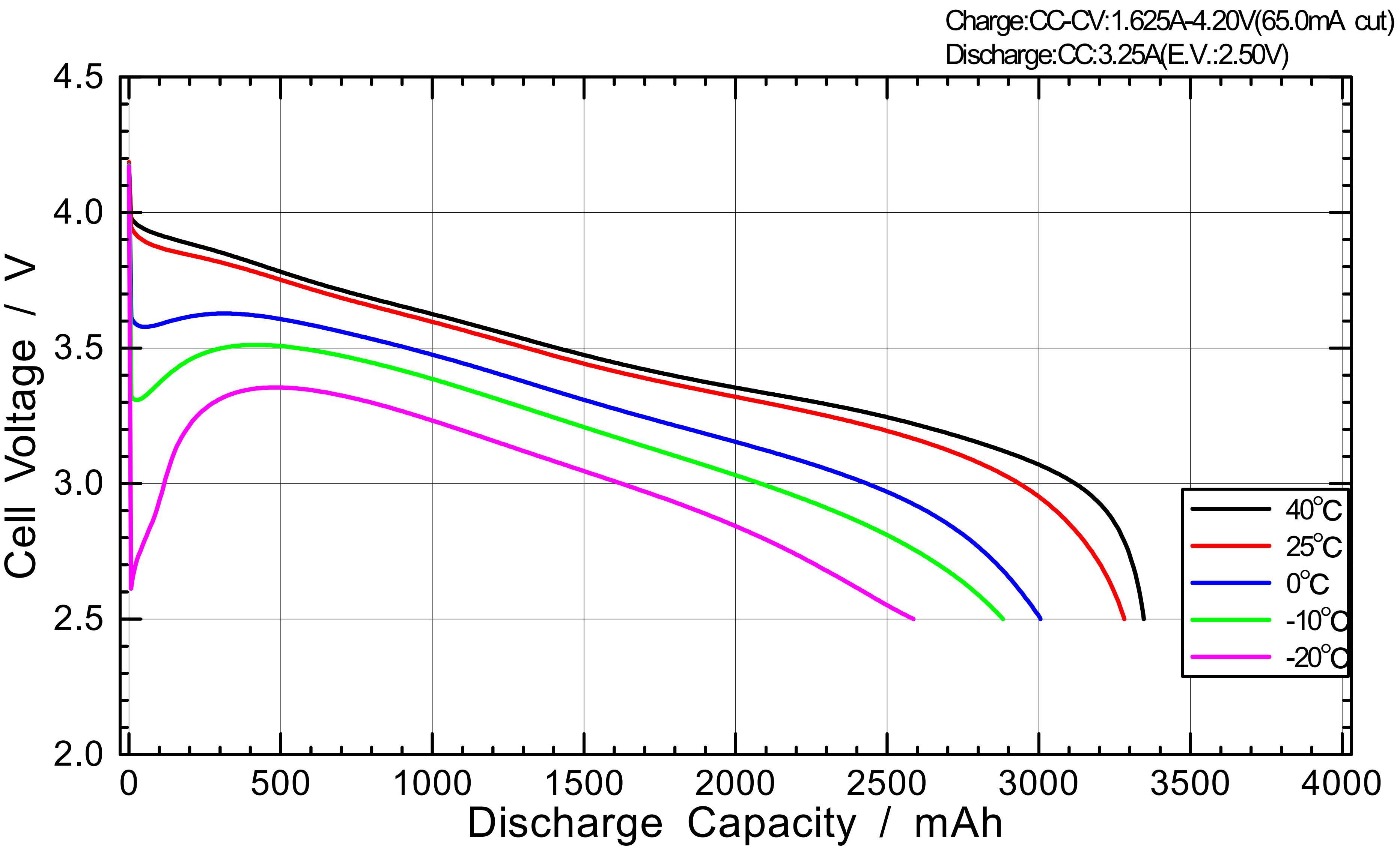
V_{BS} depends on state of charge and temperature
L_B is negligible at typical charge/discharge rates
R_B models rate dependent voltage drop

Gives linear charging curve with displacement based on rate

Discharge Rate Characteristics for NCR18650B

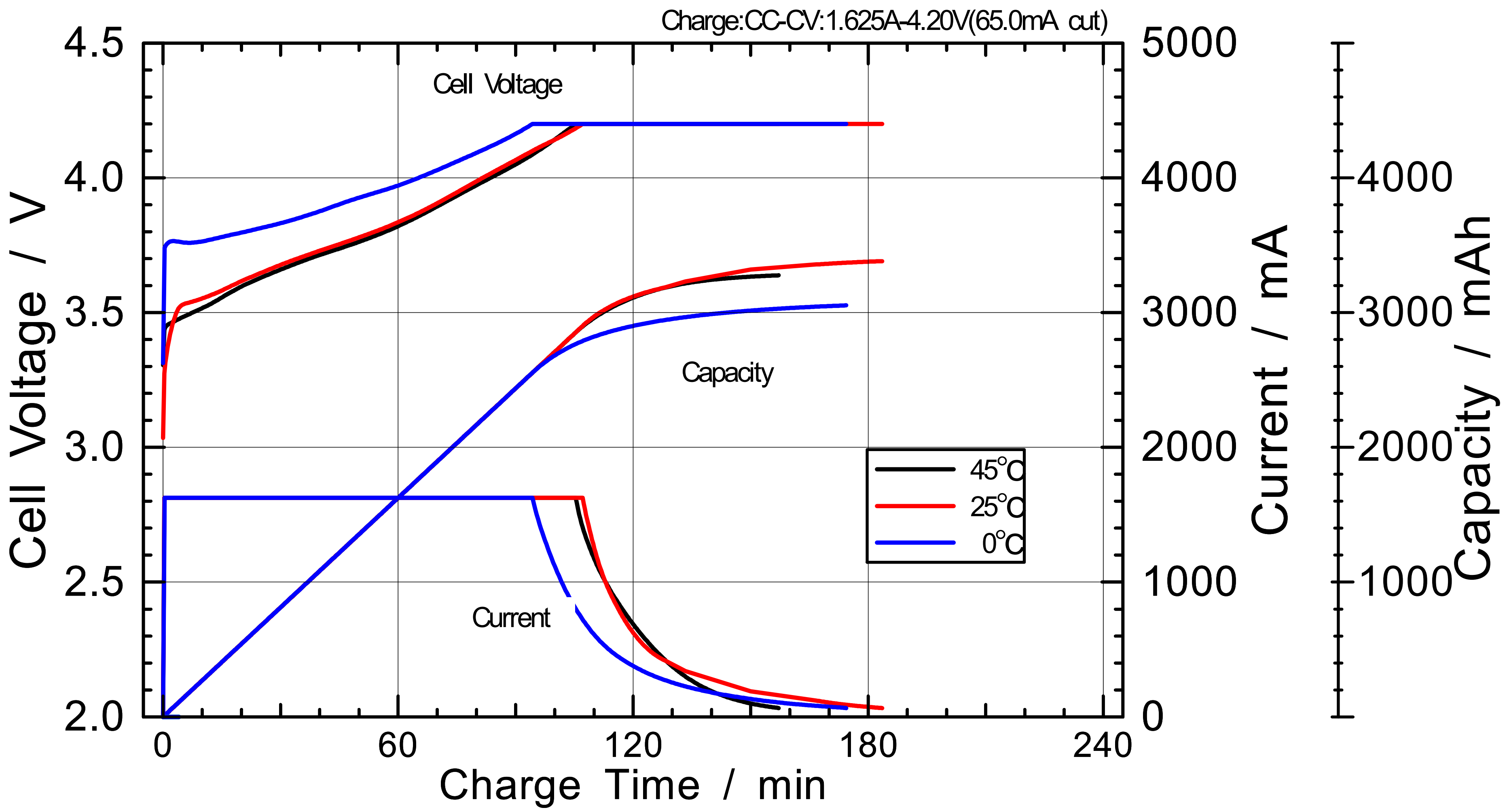


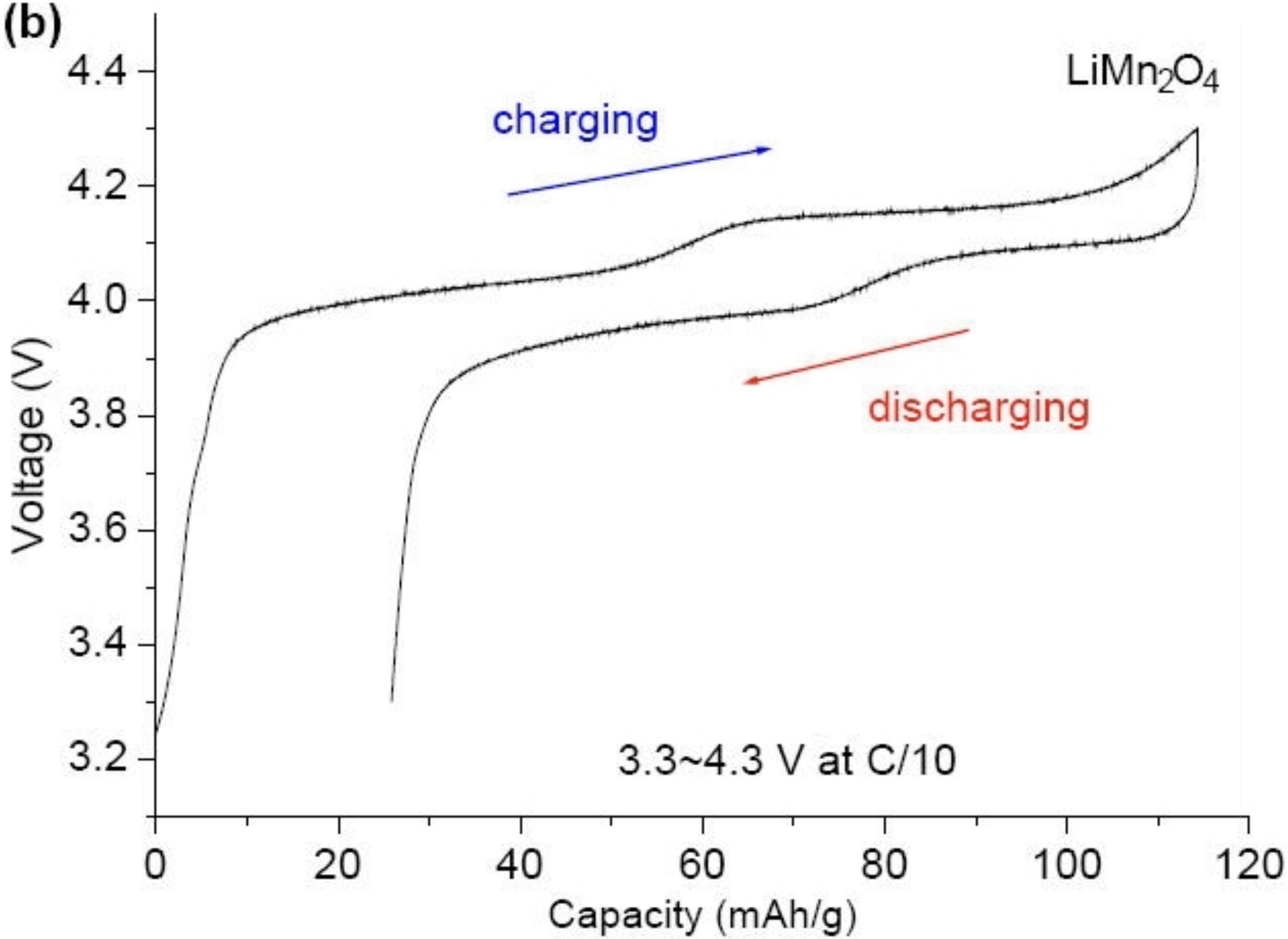
Discharge Temperature Characteristics for NCR18650



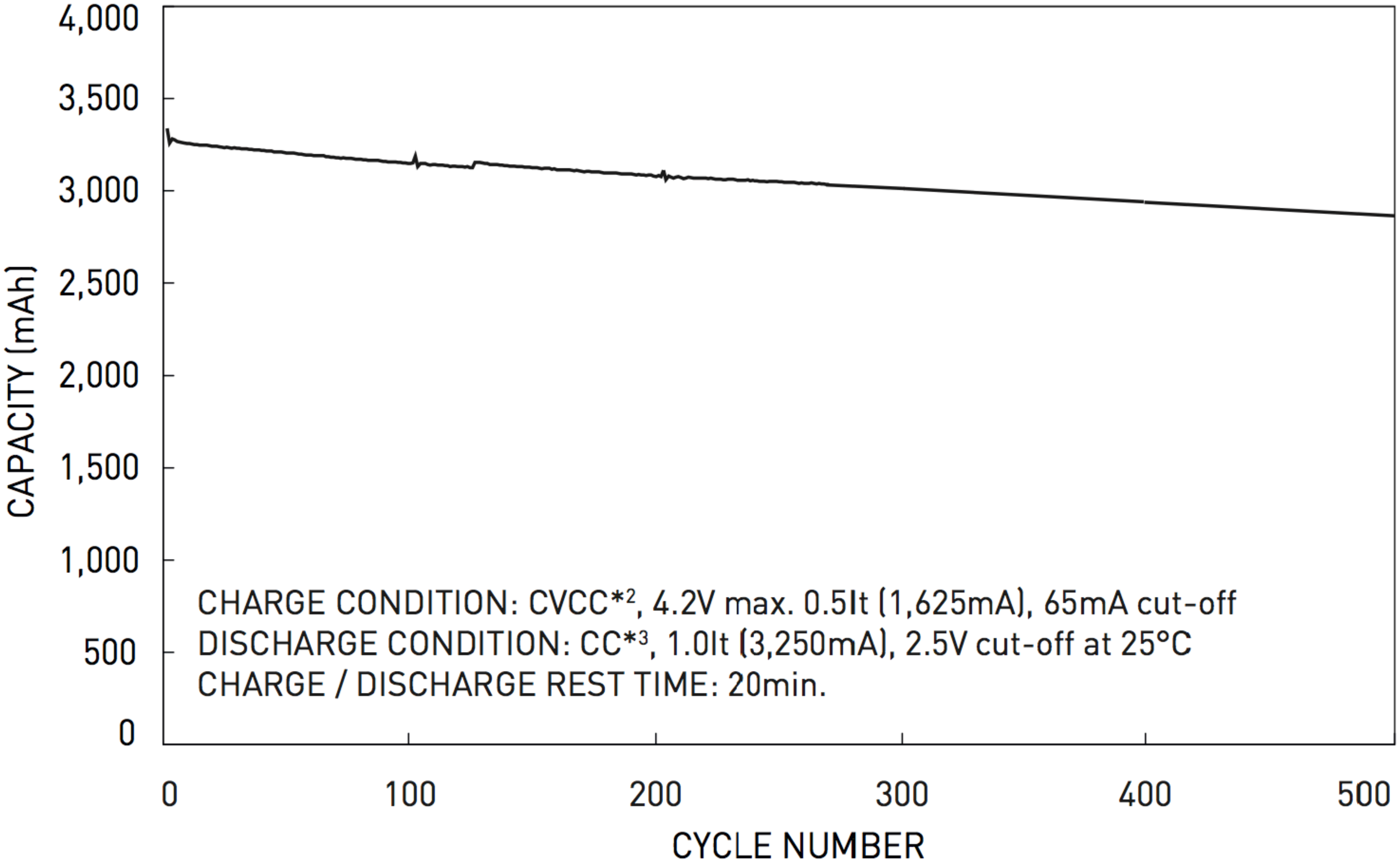
Charge:CC-CV:1.625A-4.20V(65.0mA cut)
Discharge:CC:3.25A(E.V.:2.50V)

Charge Characteristics for NCR18650B

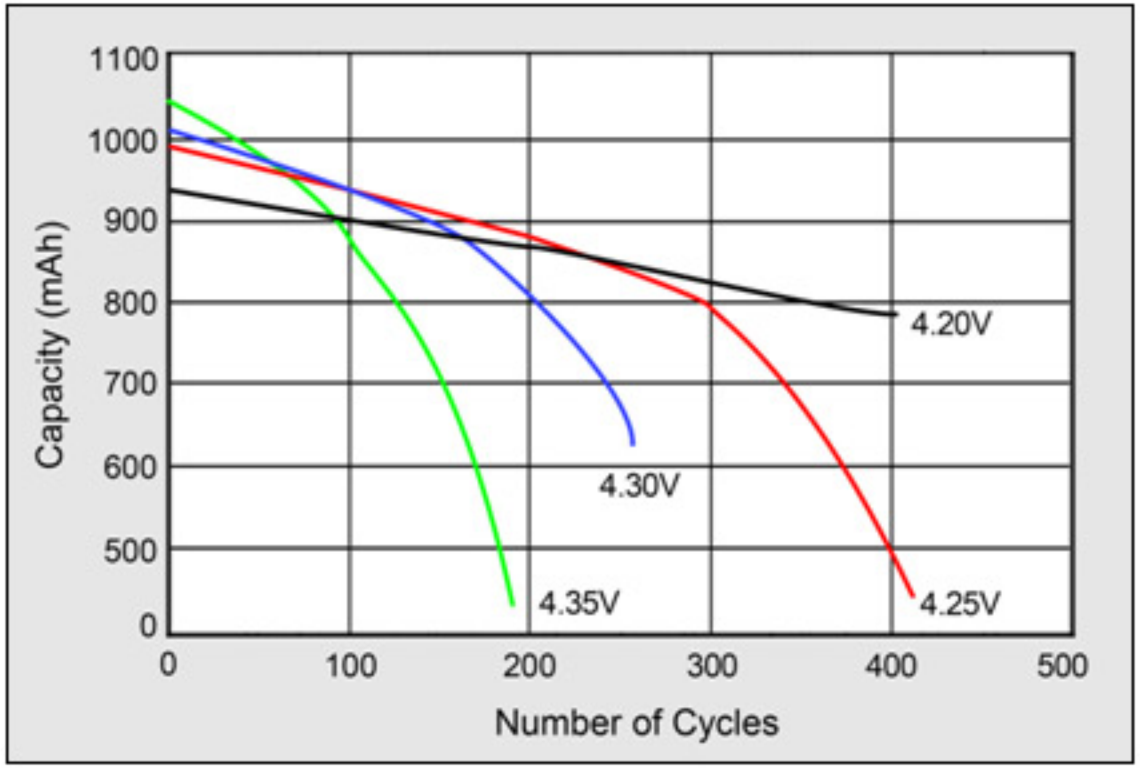



(b)
LiMn$_2$O$_4$
charging
discharging
3.3~4.3 V at C/10
Voltage (V)
4.4
4.2
4.0
3.8
3.6
3.4
3.2
Capacity (mAh/g)
0
20
40
60
80
100
120

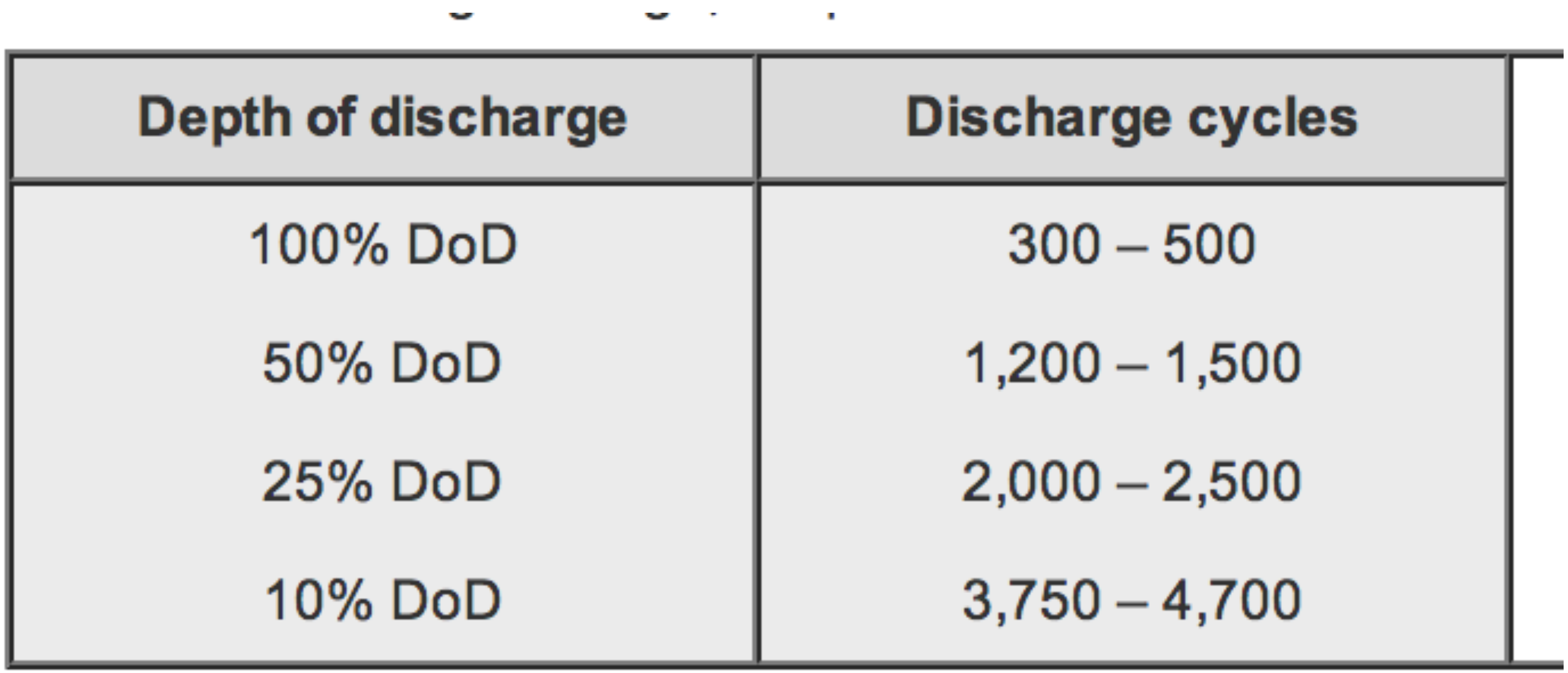
TYPICAL CYCLE CHARACTERISTICS



High Charge Voltage Reduces Life

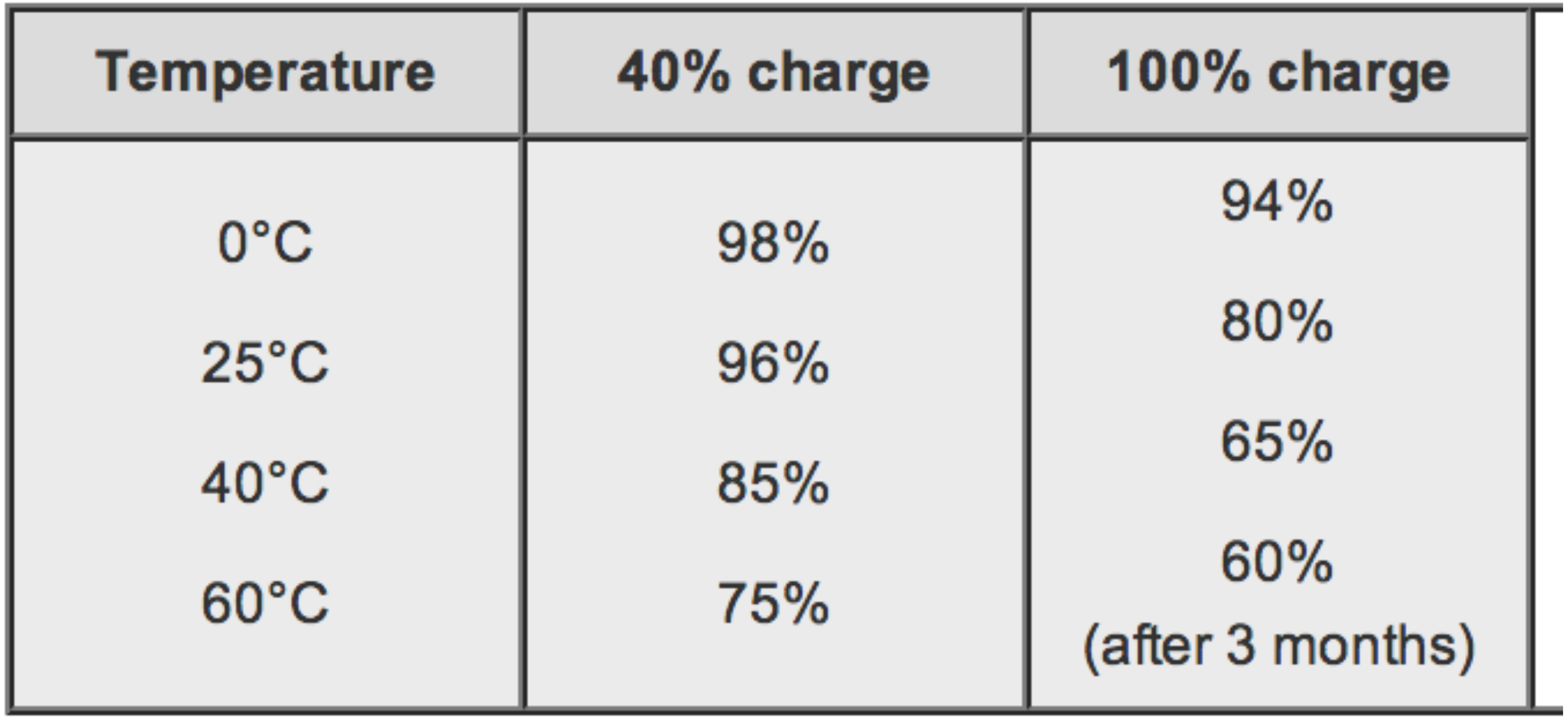


Deep Discharge Reduces Life



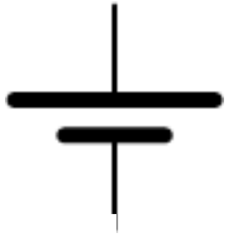
Depth of discharge	Discharge cycles
100% DoD	300 – 500
50% DoD	1,200 – 1,500
25% DoD	2,000 – 2,500
10% DoD	3,750 – 4,700

High Temperature Reduces Life Particularly at high SOC



Temperature	40% charge	100% charge
0°C	98%	94%
25°C	96%	80%
40°C	85%	65%
60°C	75%	60% (after 3 months)

Cells

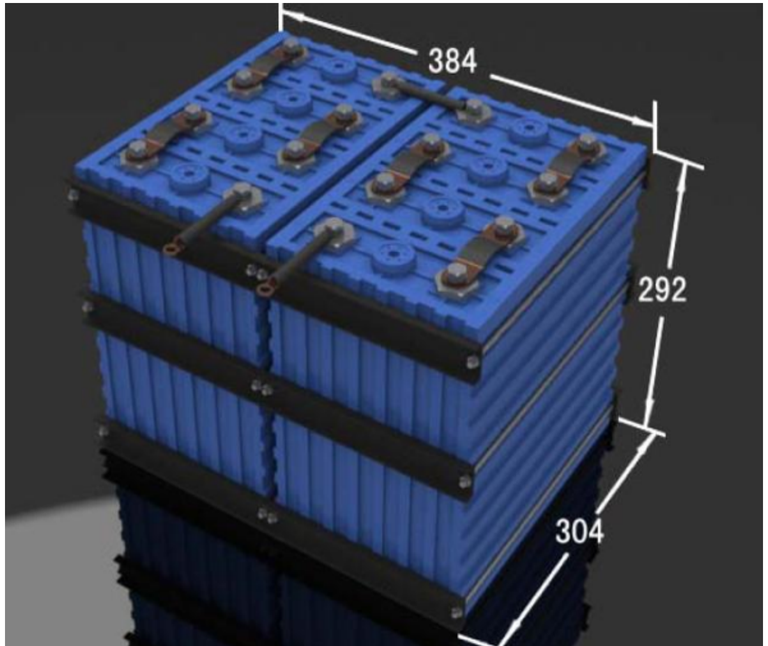


One Cell
~2.0V for lead-acid
~3.2V for $LiFePO_4$
~3.7V for LiCo

Capacity depends on volume
0.4Ah to 200Ah or more

1.28Wh to 640Wh

Series Connection Increases Voltage
Ah remains the same

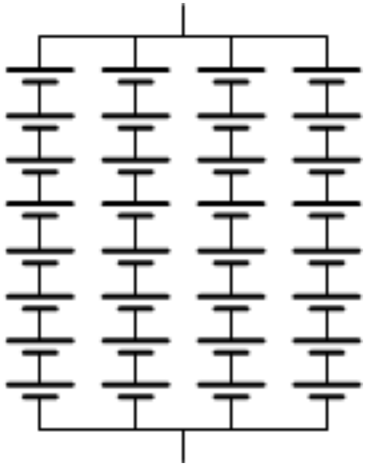


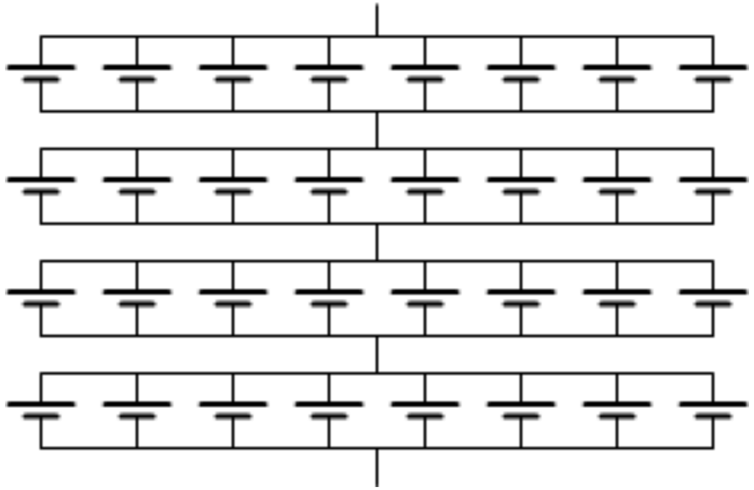
100 LiFePO4 cells is about 320V (280-360)

Capacity (in Ah) the same as one cell

128Wh (0.4Ah cells) to 64kWh (200Ah cells)

Series Parallel vs Parallel Series



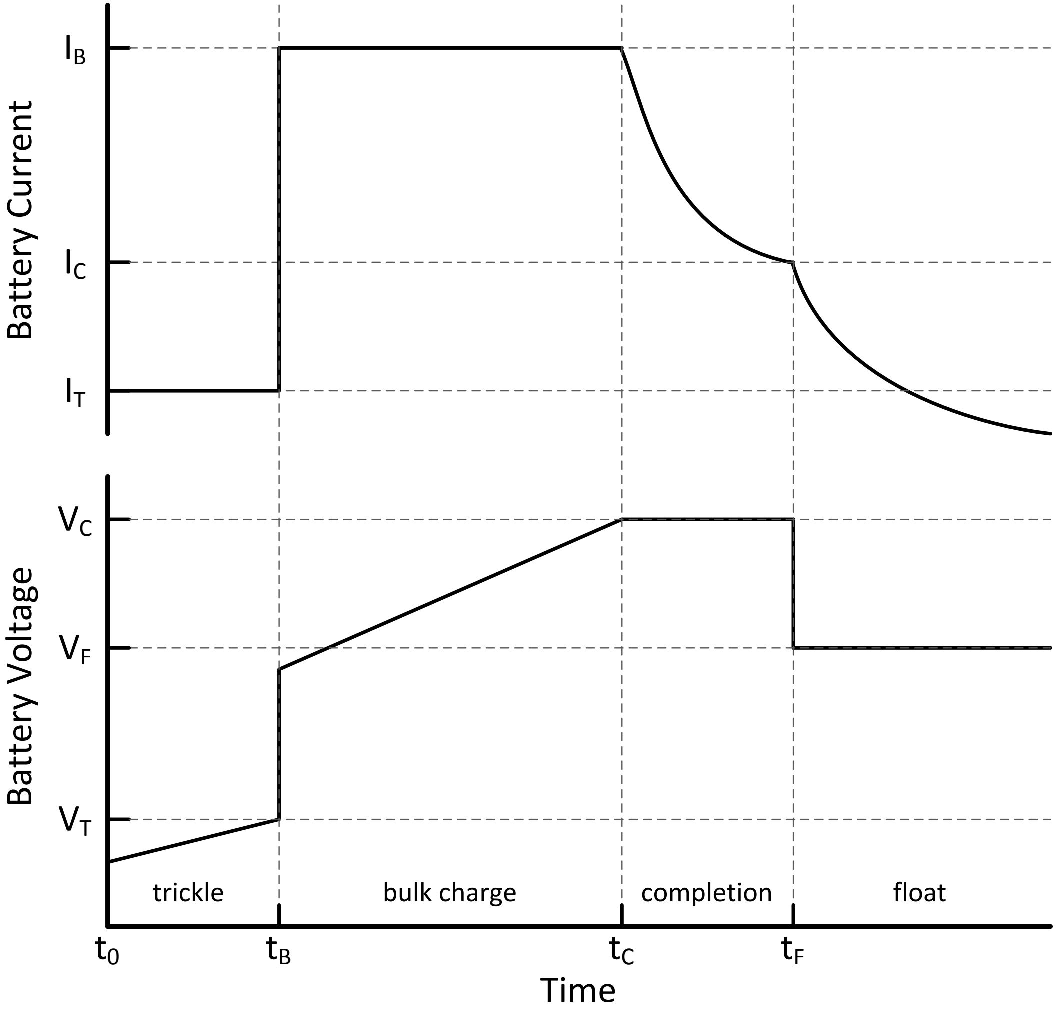


Which is preferred (assuming same Volts and Ah)?

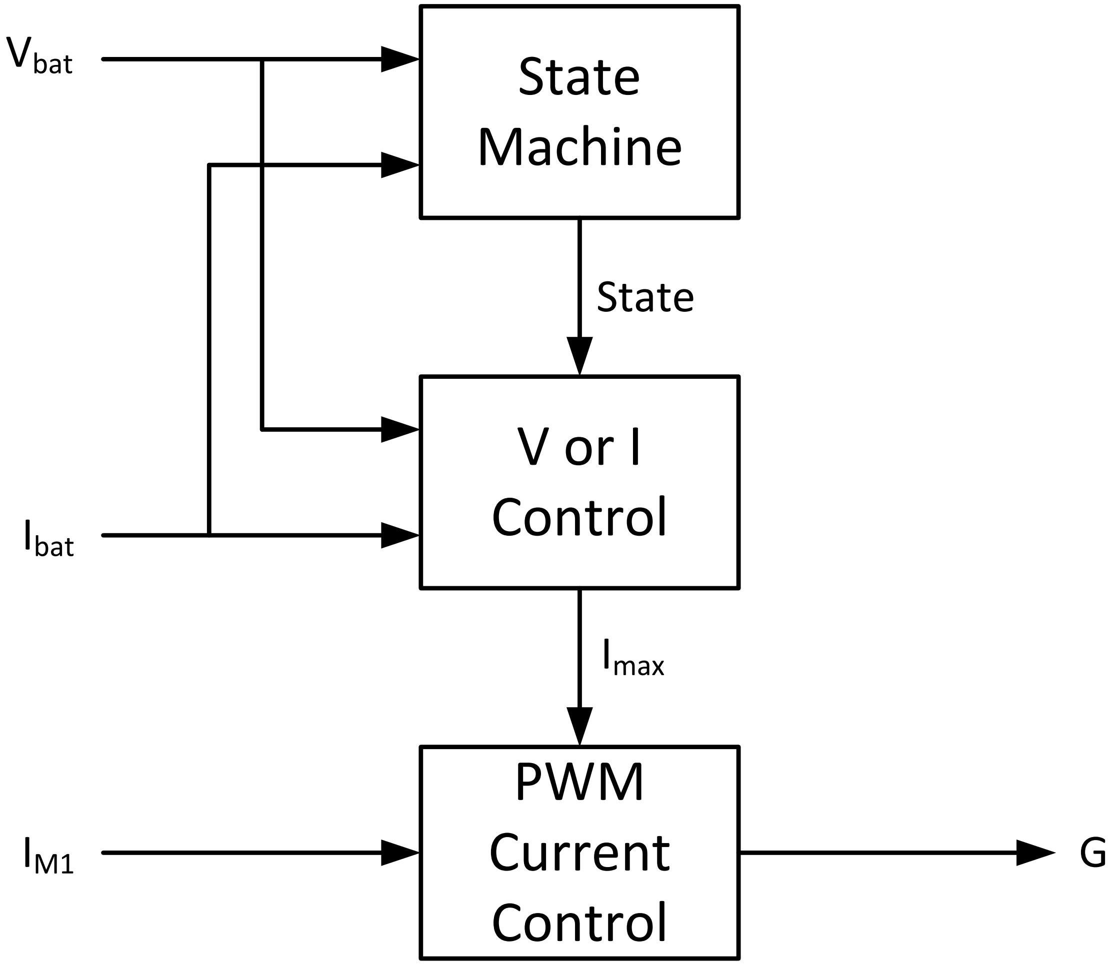
Battery Management Tasks

- Charge control
  - CC, CV profile
  - Cell balancing
  - Temperature monitoring/control
- SOC (state of charge) estimation
  - Fuel gauge
  - Integrate power
  - Estimate from voltage, current, and temperature
- Lifetime extension
  - Avoid deep discharge
  - Avoid high-charge, high-temperature storage

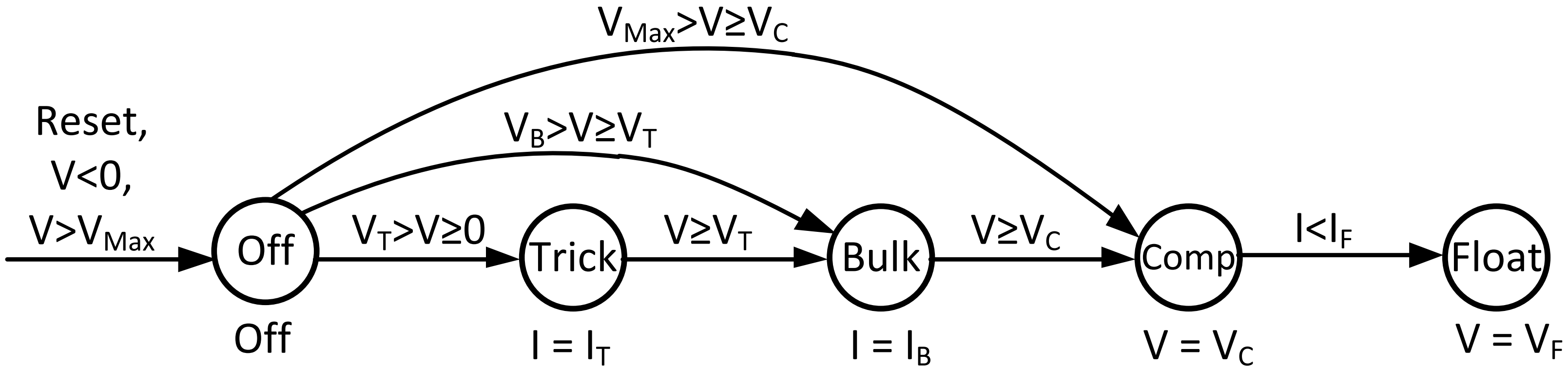
Lead-Acid Charge Cycle



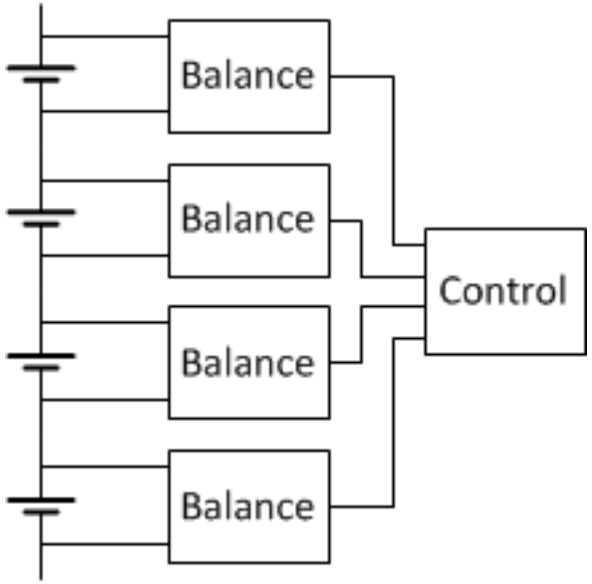
Layered Control

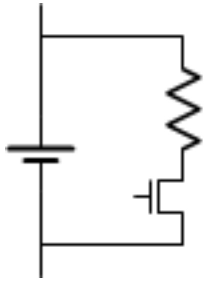


Lead-Acid Charging States



Cell Balancing





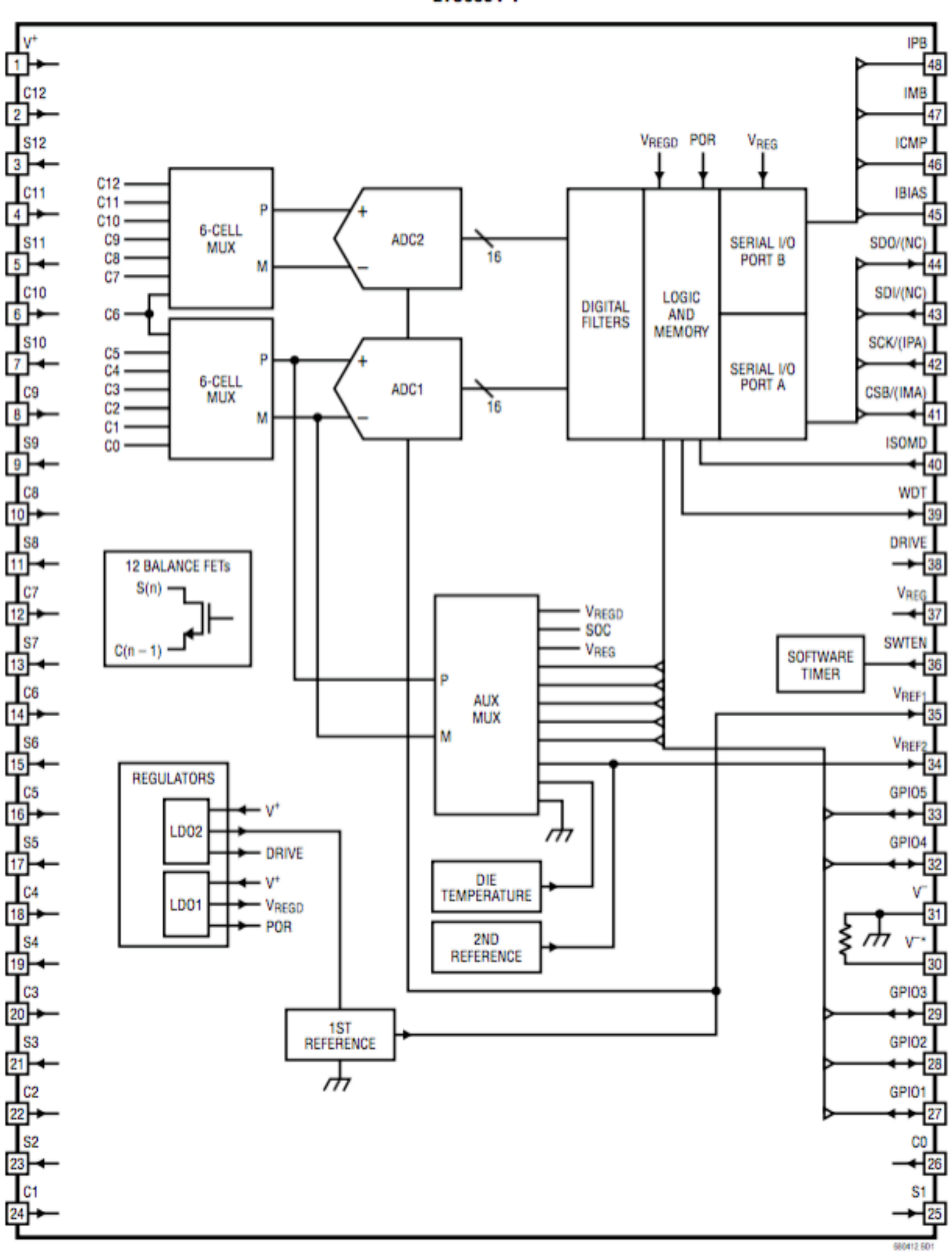
Maximum cell voltage must not be exceeded during charging

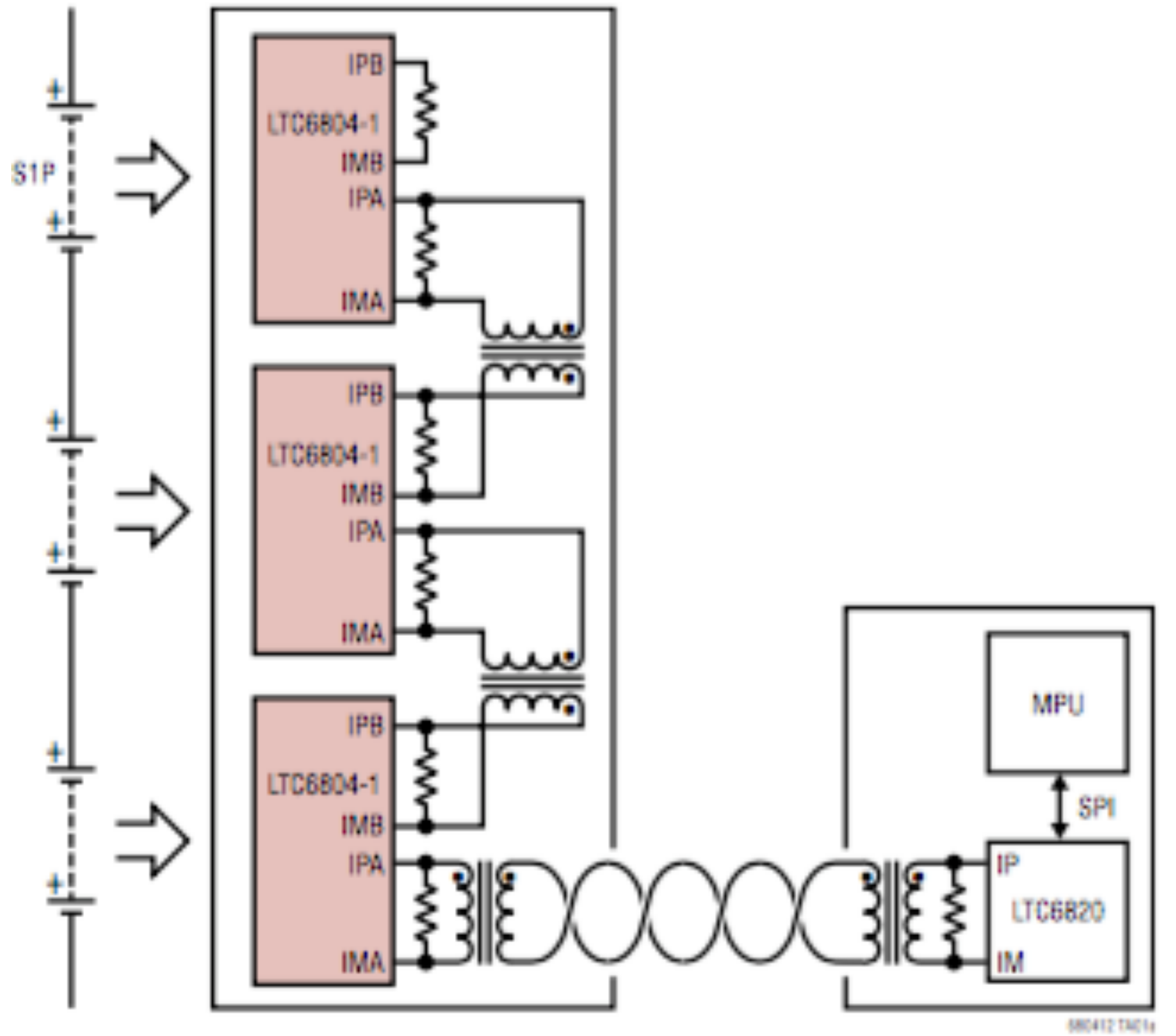
Voltage of each cell must be monitored

Current must be “bled off” of high-voltage cells before they exceed V_{max}

Simple resistive balancer or flyback to recycle energy

Cell Balancing IC LT6804





When Things go Wrong

Tesla Model-S Battery Pack

Telsa Model S Battery Pack
By the Numbers

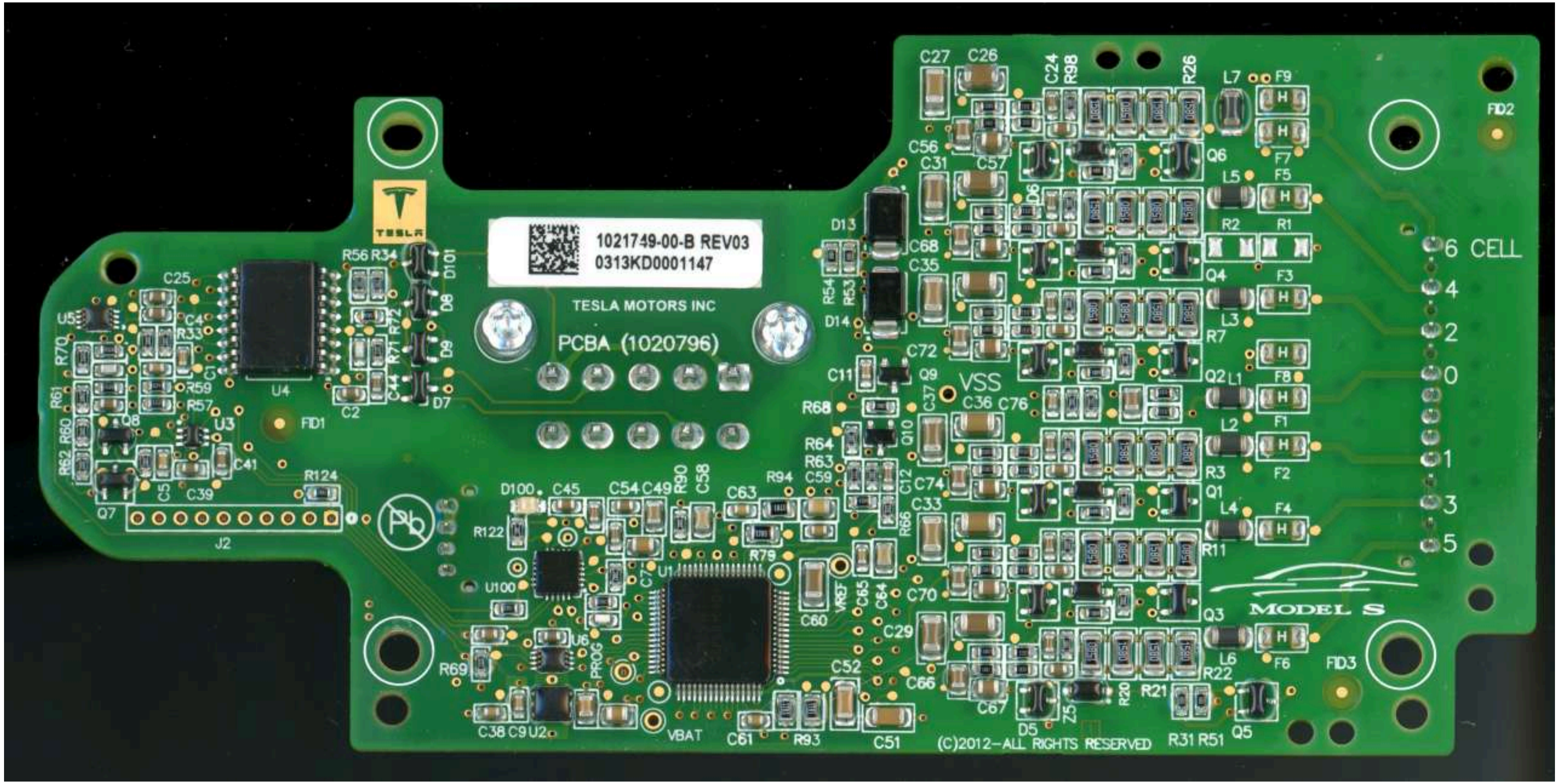
16	Modules – in series
6	Groups per module – in series
7104	Cells (Panasonic 18650A)
74	Cells/Group

Top Off

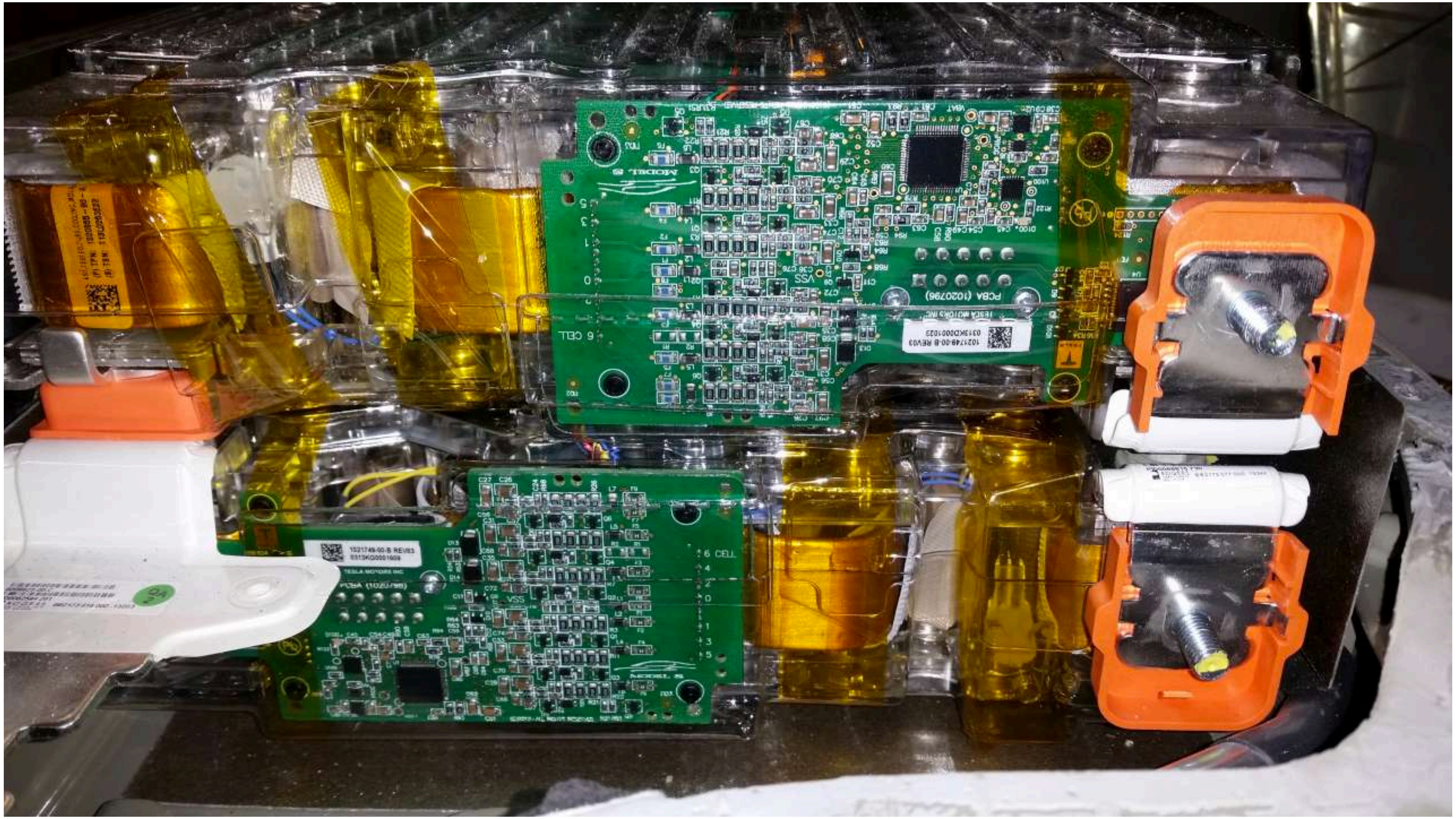
Cell-Level Fusing

Cooling

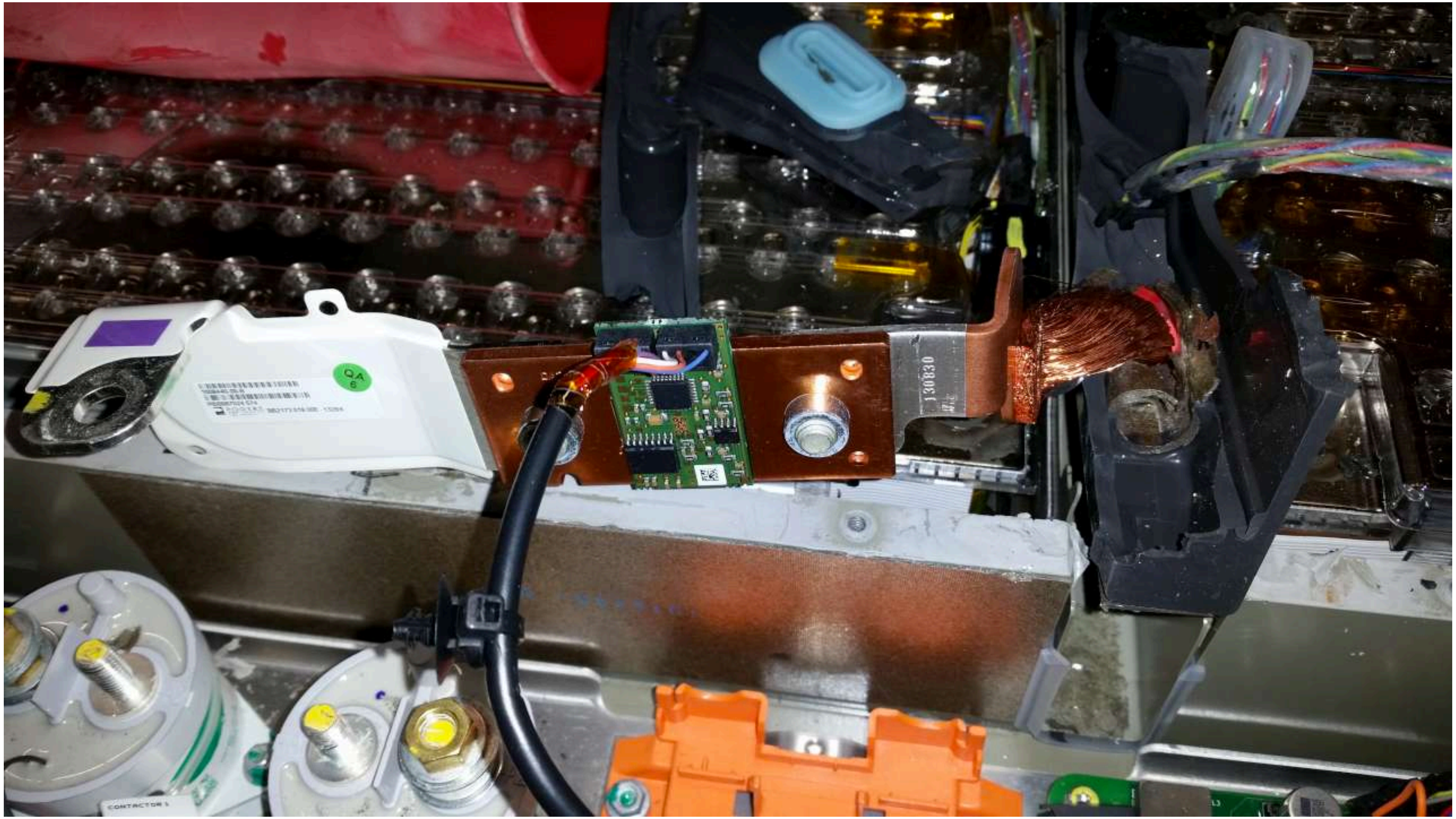
Per Module BMS Board



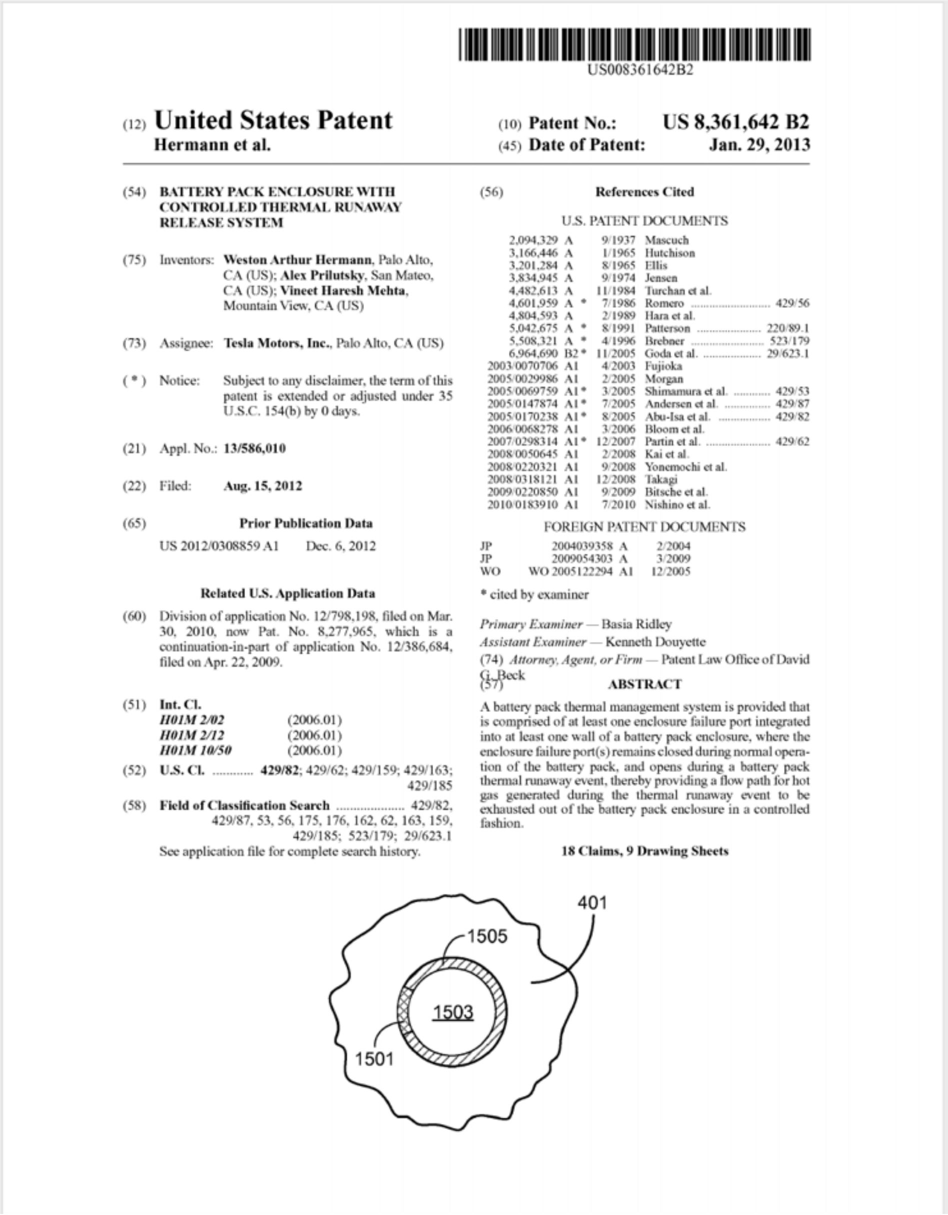
BMS boards in place



Shunt



Lots of Subtleties



US008361642B2

(12) **United States Patent**
Hermann et al.

(10) **Patent No.:** **US 8,361,642 B2**
(45) **Date of Patent:** **Jan. 29, 2013**

(54) **BATTERY PACK ENCLOSURE WITH CONTROLLED THERMAL RUNAWAY RELEASE SYSTEM**

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(73) Assignee: **Tesla Motors, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/586,010**

(22) Filed: **Aug. 15, 2012**

(65) **Prior Publication Data**

US 2012/0308859 A1 Dec. 6, 2012

Related U.S. Application Data

(60) Division of application No. 12/798,198, filed on Mar. 30, 2010, now Pat. No. 8,277,965, which is a continuation-in-part of application No. 12/386,684, filed on Apr. 22, 2009.

(51) **Int. Cl.**

H01M 2/02	(2006.01)
H01M 2/12	(2006.01)
H01M 10/50	(2006.01)

(52) **U.S. Cl.** **429/82**; 429/62; 429/159; 429/163; 429/185

(58) **Field of Classification Search** 429/82, 429/87, 53, 56, 175, 176, 162, 62, 163, 159, 429/185; 523/179; 29/623.1
See application file for complete search history.

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Assistant Examiner — Kenneth Douyette
(74) *Attorney, Agent, or Firm* — Patent Law Office of David G. Beck

(57) **ABSTRACT**

A battery pack thermal management system is provided that is comprised of at least one enclosure failure port integrated into at least one wall of a battery pack enclosure, where the enclosure failure port(s) remains closed during normal operation of the battery pack, and opens during a battery pack thermal runaway event, thereby providing a flow path for hot gas generated during the thermal runaway event to be exhausted out of the battery pack enclosure in a controlled fashion.

18 Claims, 9 Drawing Sheets

Battery Summary

- Batteries store energy in chemical bonds
- Model as dependent voltage source with series R and L
- Terminal voltage is a function of charge state Q
  - Also a function of temperature and charge rate
- Area of charge-discharge curve is loss in battery
- Cells connected in series and parallel to build large batteries (series connection of parallel cells)
- Cells must be balanced to avoid overcharge
- Battery management
  - Charge control
  - Fuel gauge
  - Lifetime extension

YAH

No	Date	Topic	HW out	HW in	Lab out	Lab ck	Lab	HW
1	9/25/17	Intro (basic converters)	1		1		Intro to ST32F3	Periodic Steady State
2	9/27/17	Embedded Prog/Power Elect.						
3	10/2/17	Power Electronics - 1 (switches)	2	1	2	1	AC Energy Meter	Power Devices
4	10/4/17	Power Electronics - 2 (circuits)						
5	10/9/17	Photovoltaics	3	2	3	2	PV MPPT	Motor control Matlab
6	10/11/17	Feedback Control						
7	10/16/17	Electric Motors	4	3	4	3	Motor control - Lab/	Feedback
8	10/18/17	Isolated Converters						
9	10/23/17	Solar Day	5/PP	4	5	4	PS	Isolated Converters
10	10/25/17	Magnetics						
11	10/30/17	Inverters, Grid, PF, and Batteries	6	5/PP	6	5	Magnetics	Magnetics and Inverters
12	11/1/17	Project Discussions						
13	11/6/17	Thermal & EMI		6	P	6	Project	
14	11/8/17	Soft Switching						
15	11/13/17	Quiz Review				C1		
16	11/15/17	Grounding, and Debugging						
Q	11/15/17	Quiz - in the evening						
	11/20/17	Thanksgiving Break				C2		
	11/22/17	Thanksgiving Break						
17	11/27/17	Guest Lecture						
18	11/29/17	Martin Fornage - Enphase				C3		
19	12/4/17	Colin Campbell - Tesla						
20	12/6/17	No Class				C4		
	TBD	Project presentations			P			
	12/15/17	Project webpage due						