TestConX™

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Impact of PWM Resolution in Digital Feedback Loop Precision Power Supplies

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- Power instrument example
  - Digital v/s Analog feedback loop
- Understanding PWM precision impact
- Methods to produce high resolution PWM signals
- Conclusion

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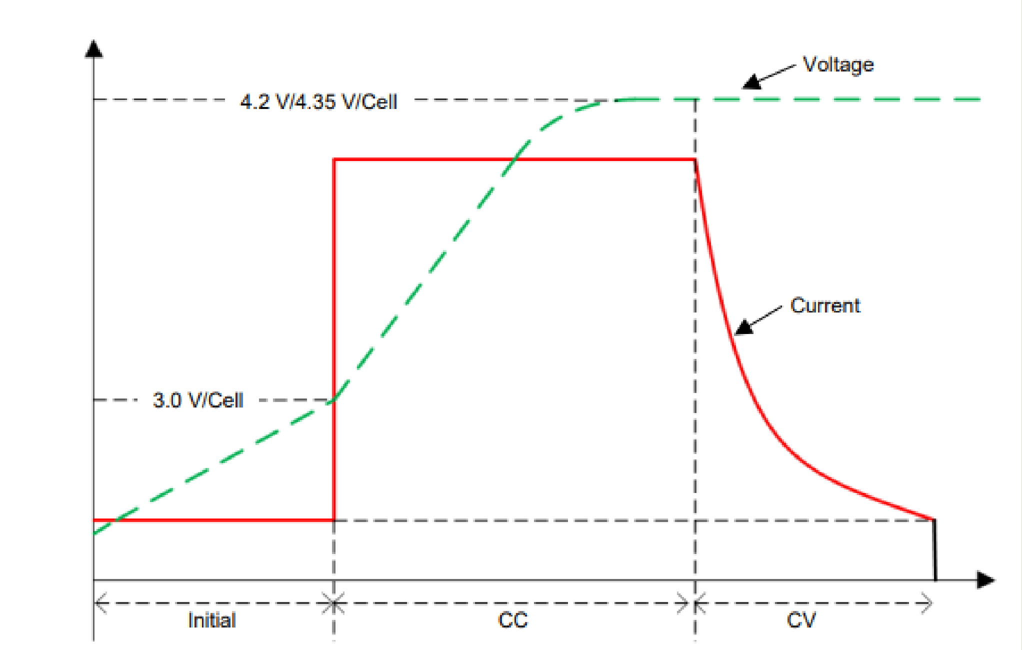
Forming and Testing Lithium batteries require a precise current and voltage output power supply



[1]

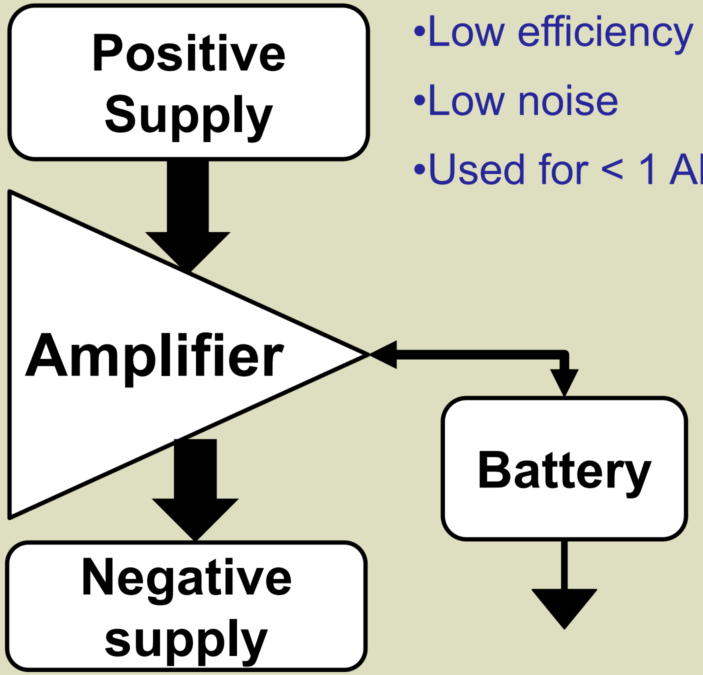
Charging profile of a Li-ion cell

CC: Constant current
CV: Constant voltage

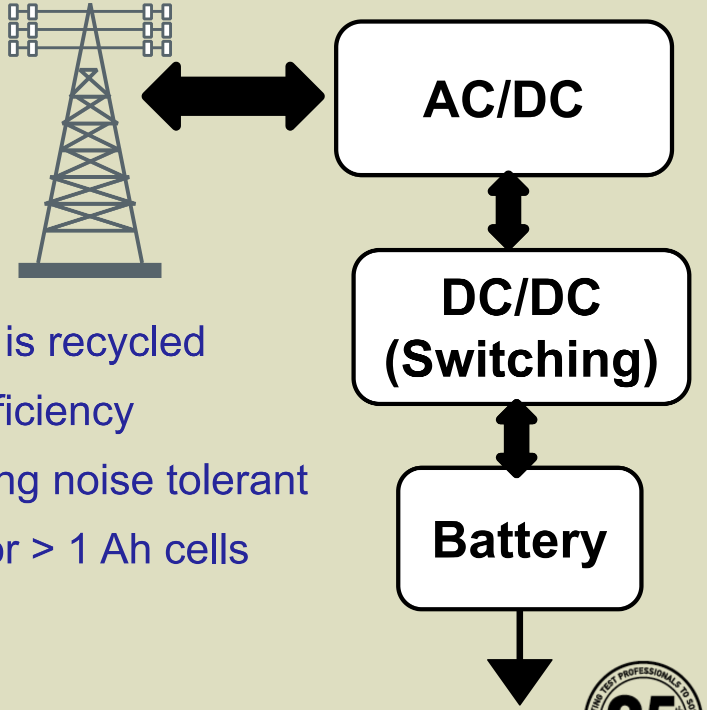
Linear mode DC supply compared to switching mode [2]

Linear DC supply (ATE)

- No energy recycling
- Low efficiency
- Low noise
- Used for < 1 Ah cells

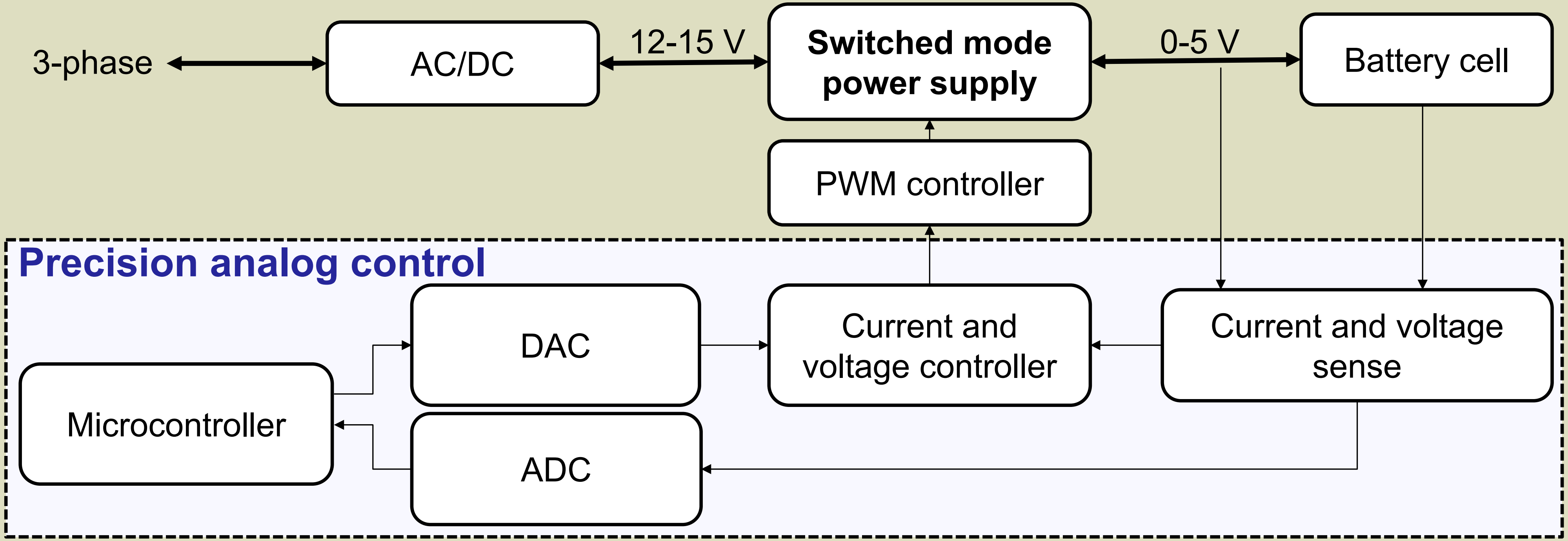


Switched Mode DC supply



- Energy is recycled
- High efficiency
- Switching noise tolerant
- Used for > 1 Ah cells

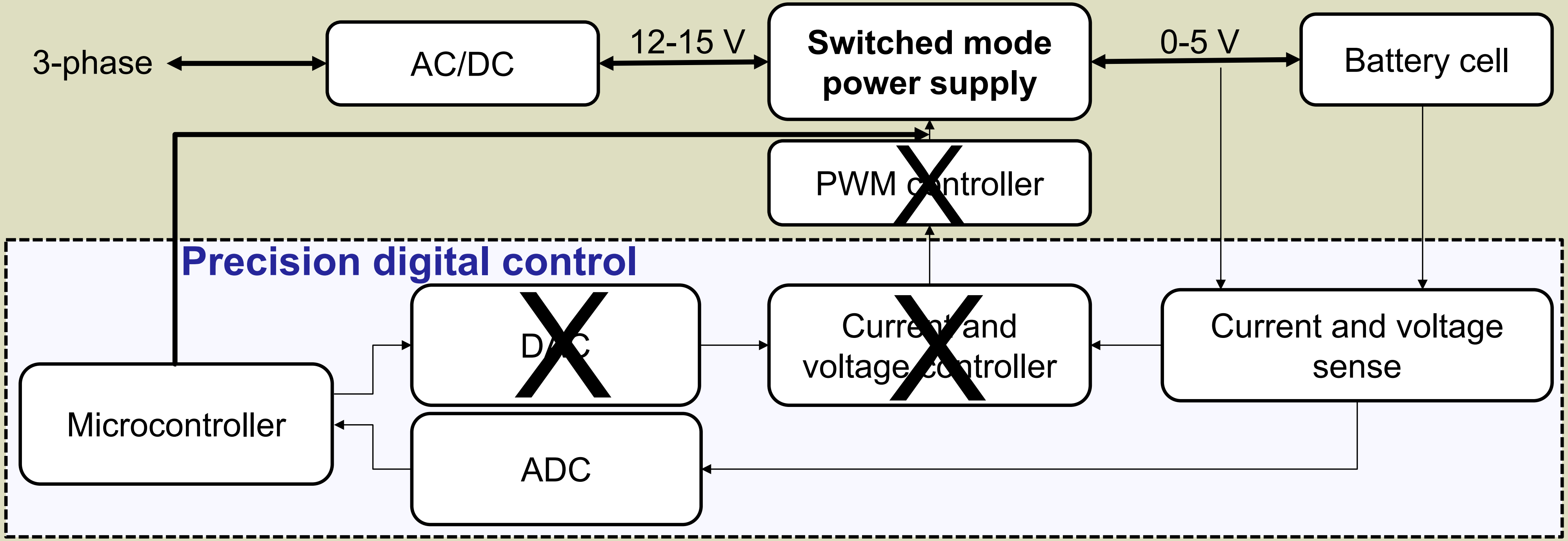
Analog feedback DC power supply [2]



High precision 14-18 bits resolution ADC and DAC are used.

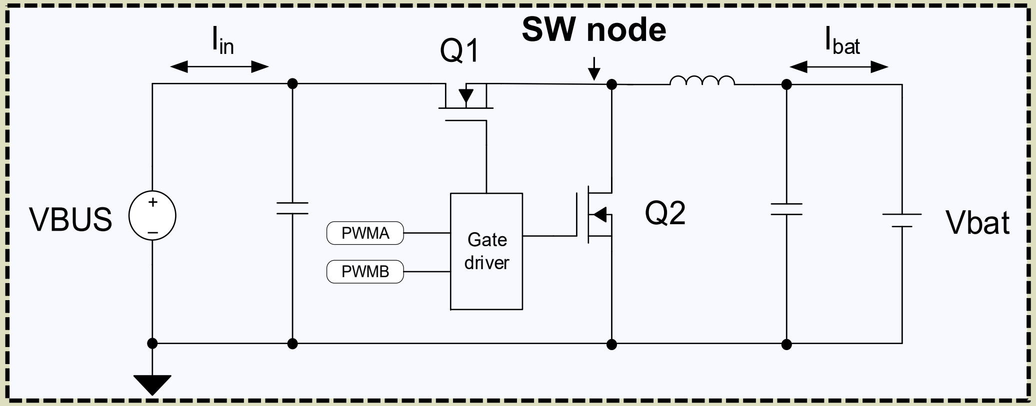
X – Not required

Digital feedback DC power supply [2]

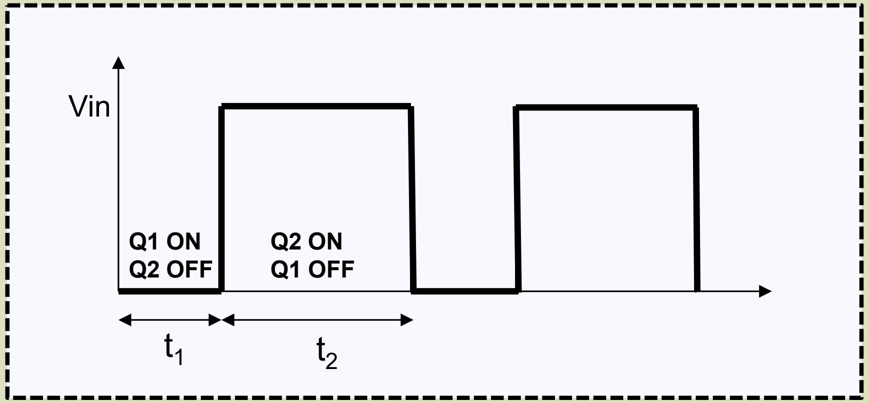


Higher integration and design flexibility with scalable software.

Operating principle of a buck converter



Schematic of a synchronous buck converter



SW node waveform

$$Vout = Vin * \frac{t_1}{t_1+t_2}$$

$\frac{t_1}{t_1+t_2}$ is called as **duty cycle** of the converter

$\frac{1}{t_1+t_2}$ is **switching frequency** of the converter

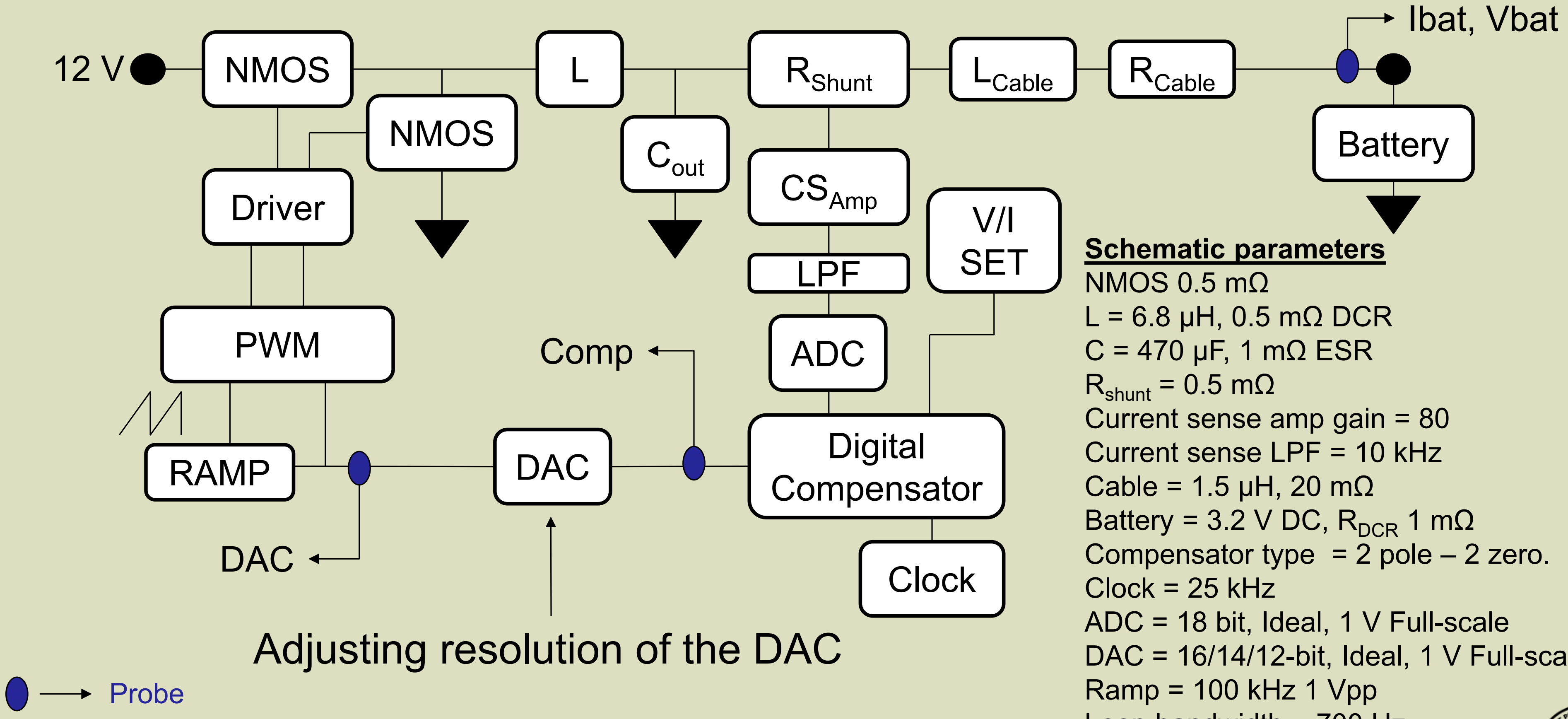
Buck converter can be used to control both charging and discharging [4].

Calculating resolution of PWM signals

Specifications	
Input voltage	12 V
Output voltage	0-5 V
Output current range	-50 A to 50 A
Precision current and voltage control	± 0.01% of full-scale range
Total path resistance (includes inductor, sense resistor, PCB parasitic, cables and internal battery resistance)	**20 mΩ (Cable resistance has most impact)**
Required output voltage resolution for voltage control	5 V × 0.02% = 1 mV
Required PWM resolution for voltage control	12 V / 1 mV = ~13.5 bits
Required output voltage resolution for current control	50 A × 20 mΩ × 0.02% = **200 μV**
Required PWM resolution for current control	12 V / 200 μV = **~16-bit**

16-bit PWM only provides 12-bit precision!

Modeling a Digitally Current Controlled Buck Regulator



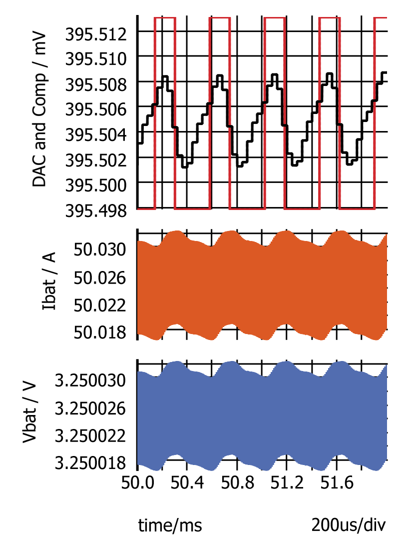
Schematic parameters

NMOS 0.5 mΩ
L = 6.8 μH, 0.5 mΩ DCR
C = 470 μF, 1 mΩ ESR
R_{shunt} = 0.5 mΩ
Current sense amp gain = 80
Current sense LPF = 10 kHz
Cable = 1.5 μH, 20 mΩ
Battery = 3.2 V DC, R_{DCR} 1 mΩ
Compensator type = 2 pole – 2 zero.
Clock = 25 kHz
ADC = 18 bit, Ideal, 1 V Full-scale
DAC = 16/14/12-bit, Ideal, 1 V Full-scale
Ramp = 100 kHz 1 Vpp
Loop bandwidth = 700 Hz

When PWM resolution is not enough!

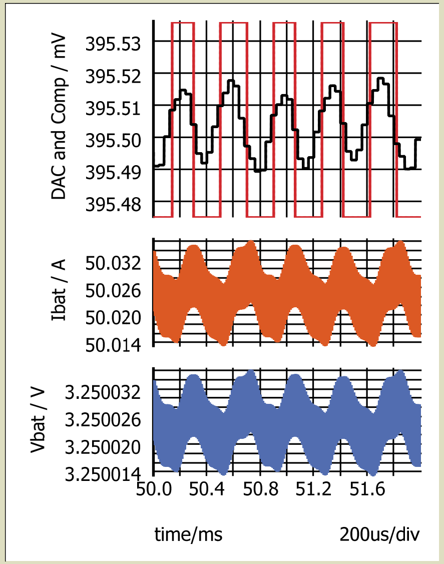
-DAC
-Comp
-Ibat
-Vbat

16-bit PWM



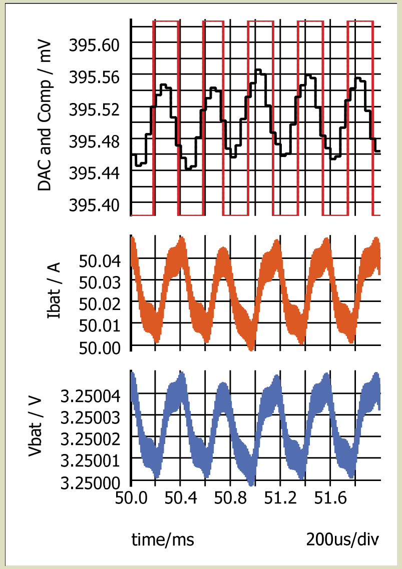
1 LSB of 12 V = 180 µV

14-bit PWM



1 LSB of 12 V = 0.8 mV

12-bit PWM



1 LSB of 12 V = 3 mV

Low frequency oscillation is seen in the loop bandwidth of the converter.

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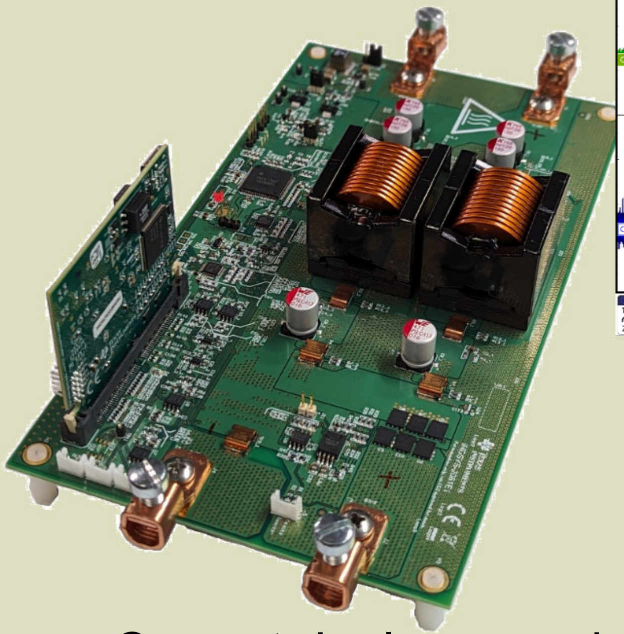
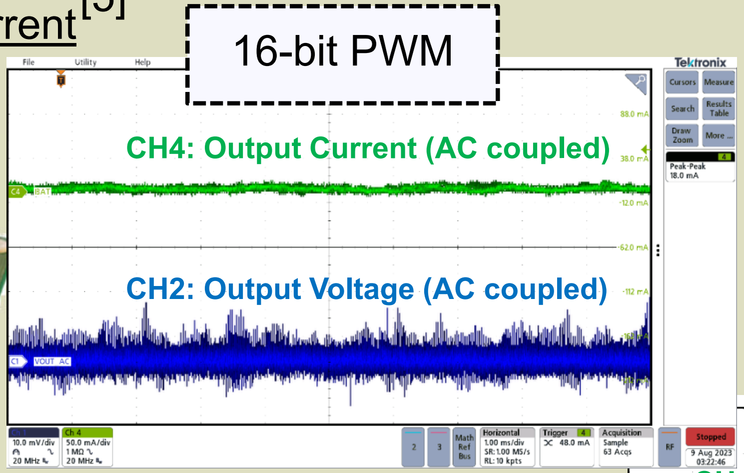
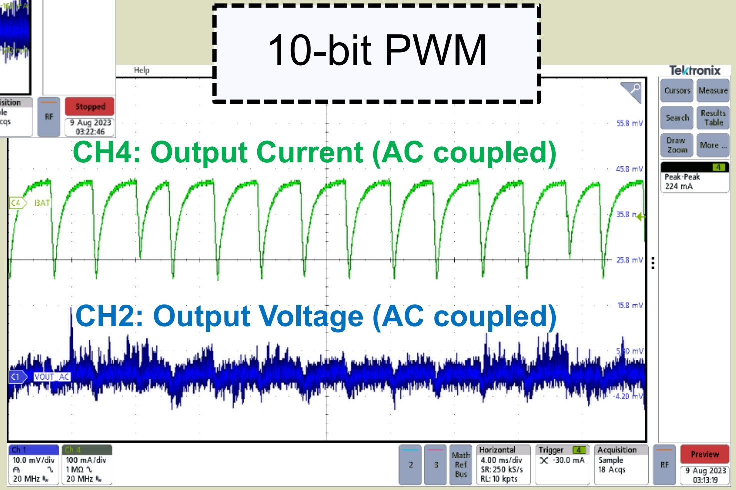
Validating impact of PWM resolution

100-A digitally controlled current output buck converter[5]

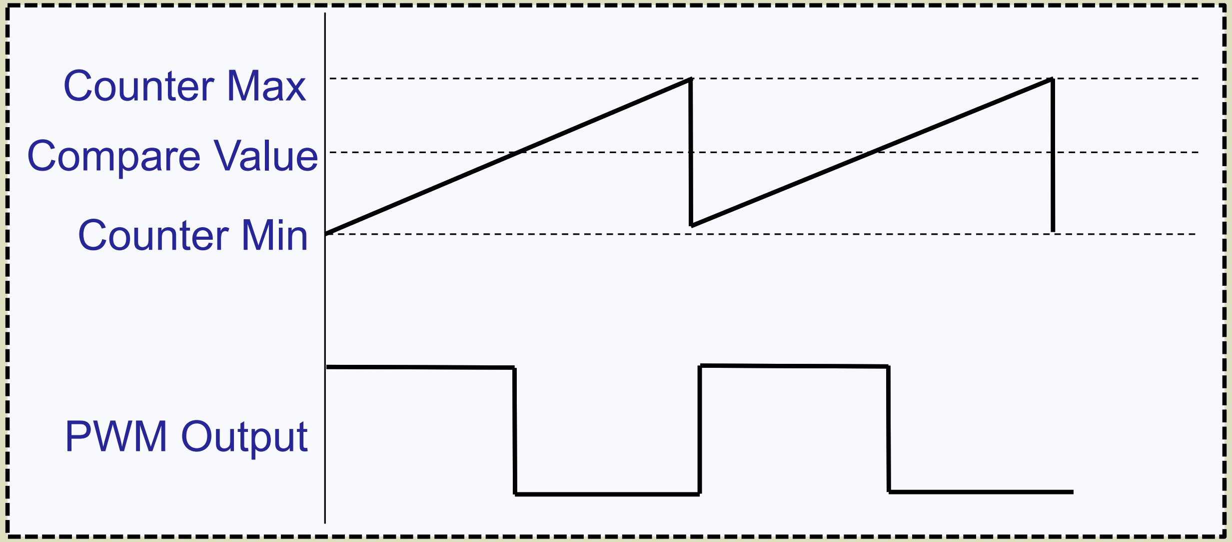






Current ripple exceeds 200 mA for 10-bit PWM.

How PWM signals are produced in MCUs?



PWM frequency = 100 kHz (10 μs)
Digital counter frequency = 100 MHz (10 ns)
Counter steps = 10 μs / 10 ns = 1000 or ~10-bit

PWM resolution directly depends frequency of the counter.

PWM Resolution inversely proportional to switching frequency (F_{SW})

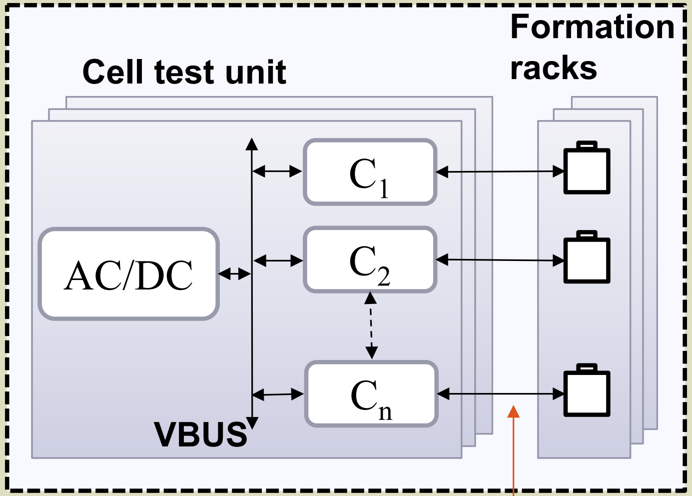
10 ns time resolution → Regular Resolution (PWM)

150 ps time resolution → High Resolution (HRPWM)

PWM Frequency (kHz)	Regular Resolution (PWM) 100 MHz EPWMCLK		High Resolution (HRPWM)	
	Bits	%	Bits	%
20	12.3	0.02	18.1	0.000
50	11	0.05	16.8	0.001
100	10	0.1	15.8	0.002
150	9.4	0.15	15.2	0.003
200	9	0.2	14.8	0.004
250	8.6	0.25	14.4	0.005
500	7.6	0.5	13.4	0.009
1000	6.6	1	12.4	0.018
1500	6.1	1.5	11.9	0.027
2000	5.6	2	11.4	0.036

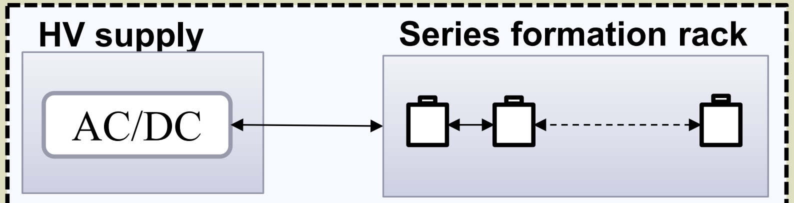
Source: TM320F28003x datasheet

Point-of-load testing requires increase in F_{sw}

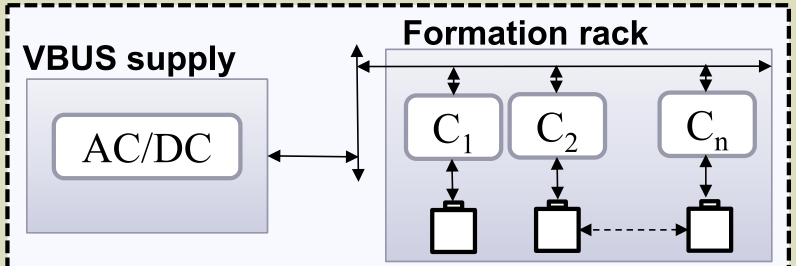


Cable length up to 10 m often reduces power efficiency by about 10%.

Cable optimization



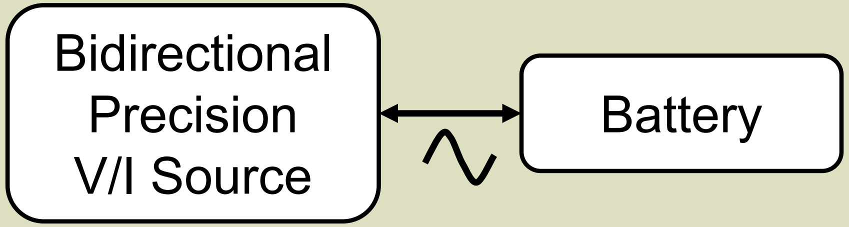
- Temporary series connection
- Challenging to implement CV operation for each cell.

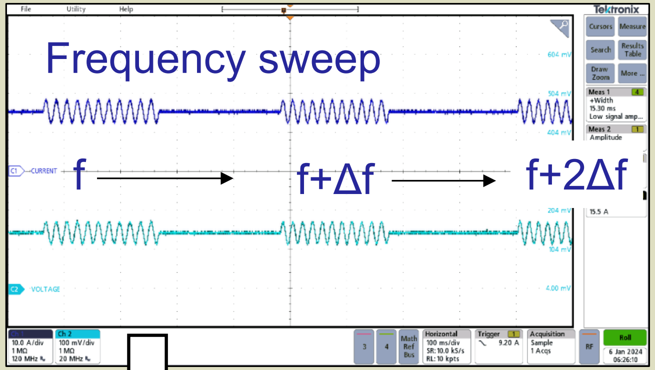


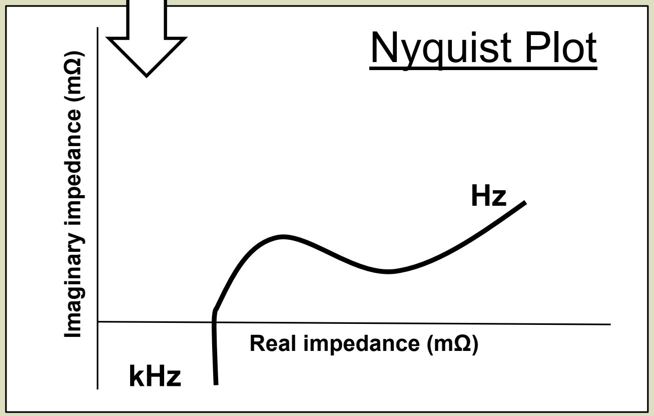
- C_1 is moved closer to the cells.
- Increase switching frequency of C_n converter to reduce magnetics size.

C_n: N[th] test channel, supports CC/CV charge and discharge operation

Increase F_{sw} and loop bandwidth for impedance testing







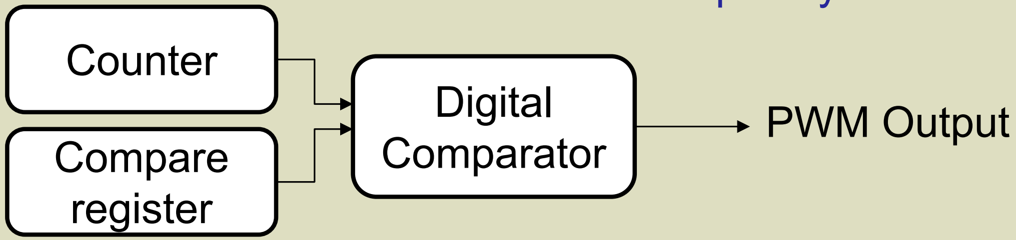
Electrochemical impedance spectroscopy (EIS)

1. Inject sinusoidal current signal
2. Measure battery voltage and current
3. Impedance of cell is $\frac{V\angle\theta_1}{I\angle\theta_2}$
4. Sweep the frequency, and draw Nyquist plot

Comparing methods of PWM generation

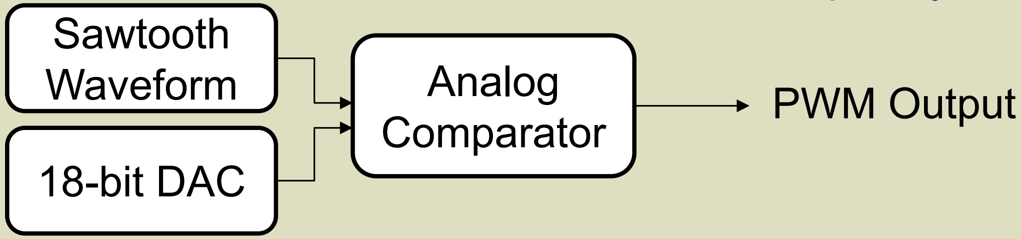
(1) Regular PWM:

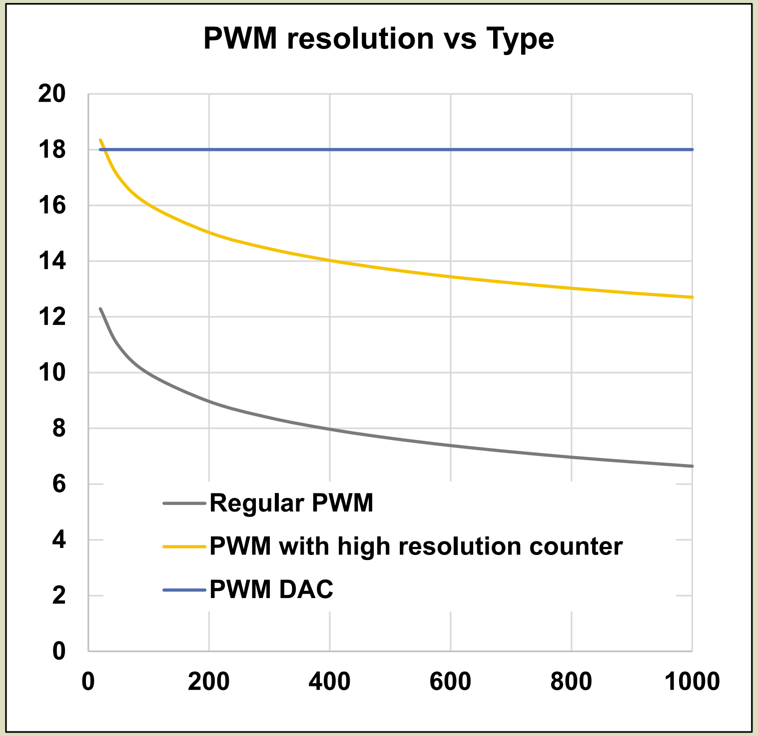
Precision suffers with increase in frequency



(2) High Precision PWM DAC

Precision doesn’t suffer with increase in frequency





Use a PWM DAC to maximize system performance. Dithering is an alternate method to improve PWM precision. Analysis of dithering is beyond the scope of this paper.

What we learnt in this presentation

- PWM resolution directly impacts output ripple of the converter.
- Battery instrumentation requires µV resolution for precise charge and discharge control.
- Increasing switching frequency of the power converters reduces power electronics size, which is needed for point-of-load battery formation and testing.
- Higher switching frequency also enables > 10 kHz closed loop bandwidth which allows battery impedance testing.
- Precision of regular PWM outputs of MCUs falls with increase in switching frequency. Regular PWMs cannot be used with wide-band gap semiconductors that has ability to operate at higher switching frequency while delivering more power.
- Precision analog based PWM is needed for power instruments that use wide bandgap semiconductors.

References

[1] Battery Tester Reference Design for High Current Applications User guide, Texas Instruments, 2018

[2] Li-ion cell formation and test overview, TestConX, 2023

[3] How to design one battery tester for a wide range of sizes, voltages and form factors, Technical article, Texas Instruments, 2020

[4] Selecting a Bidirectional Converter Control Scheme, Texas Instruments, 2017

[5] 100-A, Dual-Phase Digital Control Battery Tester Reference Design, Texas Instruments, 2023