Power Management for Mobile Application

Power Management and Control Techniques for Smartphone Display and Haptic Technology

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The 33rd International Conference on VLSI Design (VLSID 2020)
and The 19th International Conference on Embedded Systems (ES 2020)

Outline

- **Introduction to Research in Power Management at IIT Madras**
- **Introduction to Power Management and DC-DC Converters**
- **Power Management in a Smartphone**
- **Power Management for Display**
- **Mobile Display Technologies**
- **Power Management for LCD**
- **Power Management for AMOLED Display**
- **Board Level Design Guidelines for Display PMIC**
- **Haptics Driver for Mobile Application**

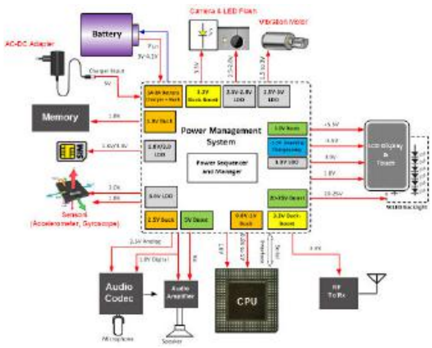
Research in Power Management IC at IITM

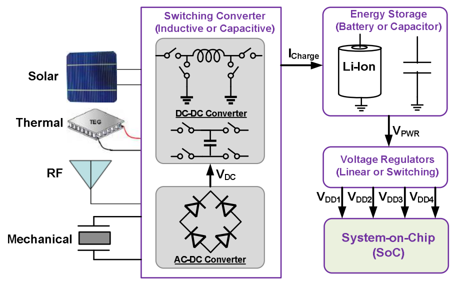
PMIC For Mobile Applications

- Battery Charger and Fuel Gauge
- DC-DC Switching Converters
- Power Management for LED backlight and displays
- Low Drop-Out (LDO) Regulators

PMIC For Energy Harvesting

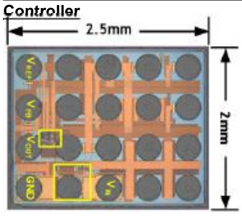
- Energy Harvesting for IoT Application
- Self Powered Devices
- Power Management for Wearables
- Power Management for Biomedical Applications
- Energy Harvesting for Remote Sensing





Previous Works

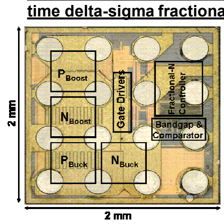
High Frequency DC-DC converter using time-based Controller



- 180nm CMOS
- F_{SW} = 10-25MHz
- 94% Peak Efficiency
- Iq = 20µA @ 10MHz

VLSI Symp., June 2014, Honolulu. and JSSCC

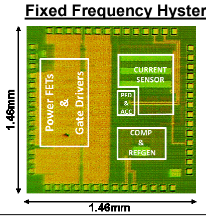
Buck-Boost converter using constant ON/OFF time delta-sigma fractional-N control



- 0.5um CMOS
- F_{SW} = 1-10MHz
- 92% Peak Efficiency

European Solid State Circuits (ESSCIRC), Sept 2011, Finland.

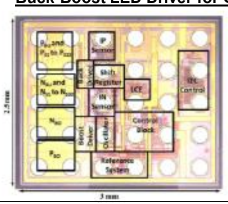
Fixed Frequency Hysteretic Buck Converter



- 130nm CMOS
- F_{SW} = 1MHz
- 93% Peak Efficiency
- Iq = 50µA

VSLI Symp., June 2012, Honolulu.

Buck-Boost LED Driver for Camera Flash



- 0.5um CMOS
- F_{SW} = 2MHz
- 90% Peak Efficiency

International Solid-State Circuits Conference (ISSCC), Feb 2011, San Francisco. and JSSC, Dec 2011.

Recent Work at IITM

Area and Current Efficient Capacitor-Less Low Drop-Out Regulator Using Time-Based Error Amplifier

Proc. Int. Symp. Circuits and Systems, ISCAS, May 2018, Florence, Italy.

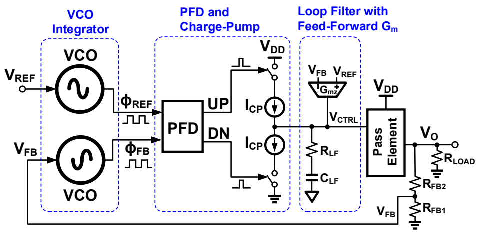


TABLE II. Performance Table And Comparison

Metrics	This Work	ISCAS'17 [3]	ISCAS'17 [4]	CICC'17 [5]
Technology	**65nm**	180nm	180nm	65nm
Vin/Vout	**1.2/ 0.8-1.1**	1.84/1.8	1.2/1	1.2/1
Overshoot/ Undershoot(mV), ΔV_O (Load:10mA/100ns)	**160/70**	50/40	220/150	46/45
Settling Time (µs)	**0.2**	4.6	3.6	1.2
Current, I_Q (µA)	**27.5**	7	3	300
Bandwidth, f_{UGB} (MHz)	**3**	0.1	0.5	8
Max. Load, $I_{L,max}$ (mA)	**10**	50	100	25
Compensation/Load Cap (pF), $C_C/C_{L,max}$	**1.2/100**	10/100	2.5/10	10/240
FOM[1] (ps)	**1.76**	3.89	3.3	7.5

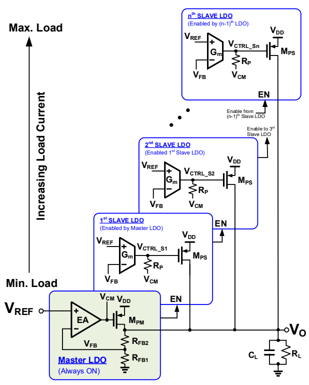
[1]Lower value indicates higher performance.

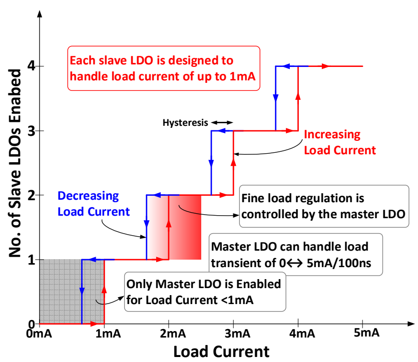
$$FOM = \frac{C_C}{C_{L,max}} \cdot \frac{\Delta V_O}{V_O} \cdot \frac{I_{Q,max}}{f_{UGF}} \cdot \frac{1}{I_{L,max}} \cdot 10^{12}$$

Recent Work at IITM

A Highly Scalable, Time-Based Capless Low-Dropout Regulator Using Master-Slave Domino Control

Proc. Int. Symp. Circuits and Systems, ISCAS, May 2019, Japan.





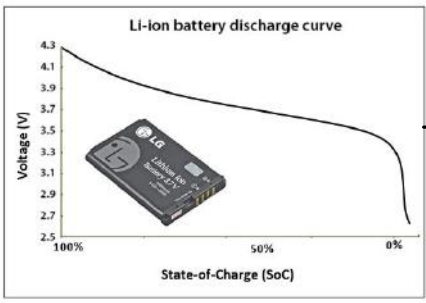
Total I_Q = 11.5uA

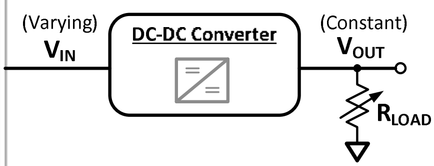
Application of Power Management ICs

Power delivery for these applications is mostly met by DC-DC Converters

DC-DC Power Converter

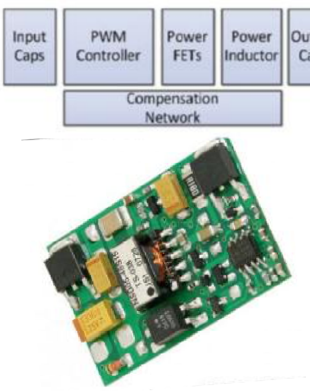
- Converts voltage from one domain to other
- Provides regulated output voltage
  - Under varying conditions (input voltage, output current)



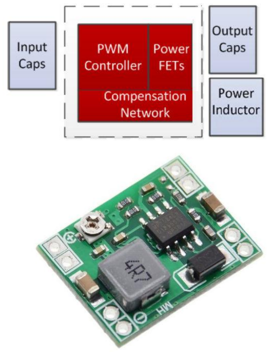


Discrete Vs. Integrated Power Converters

Discrete

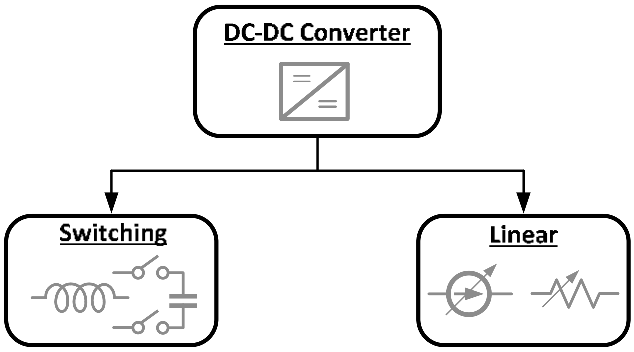


Integrated



VLSI Systems mostly use Integrated DC-DC Converters due to limited board space

DC-DC Converter Types



Inductive or Capacitive

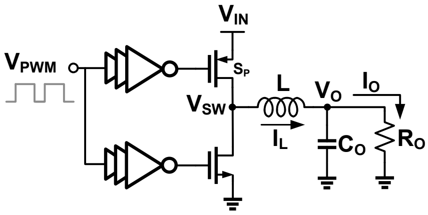
Can generate output voltage less, greater, inverting or equal to input voltage .

Low Drop-Out (LDO) Regulators

Can generate output voltage only less or equal to input voltage.

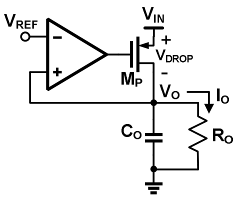
Switching vs Linear Regulator

Switching Regulator



- Regulation achieved by changing on/off time
- Switches are in either linear or cutoff → reduced losses
- High efficiency over wide range of V_O/V_{IN}

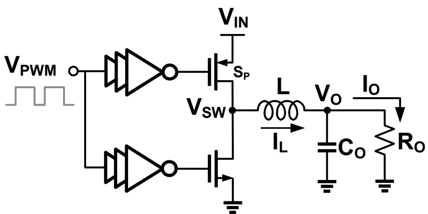
Linear Regulator



- Regulation achieved by dropping voltage
- Switches are in saturation → higher losses
- Poor efficiency when V_O/V_{IN} ratio is low

Switching vs Linear Regulator

Switching Regulator



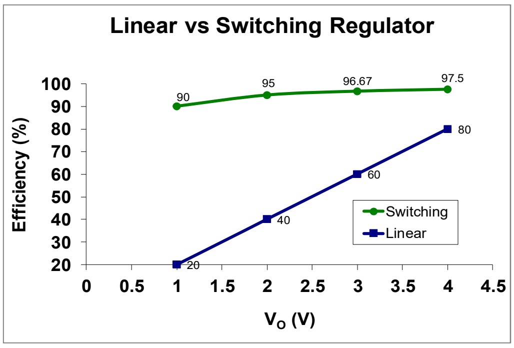
- Regulation achieved by changing on/off time
- Switches are in either linear or cutoff → reduced losses
- High efficiency over wide range of V_O/V_{IN}

More than 90% of power requirement is met by Switching Converters

Switching Vs Linear Regulator

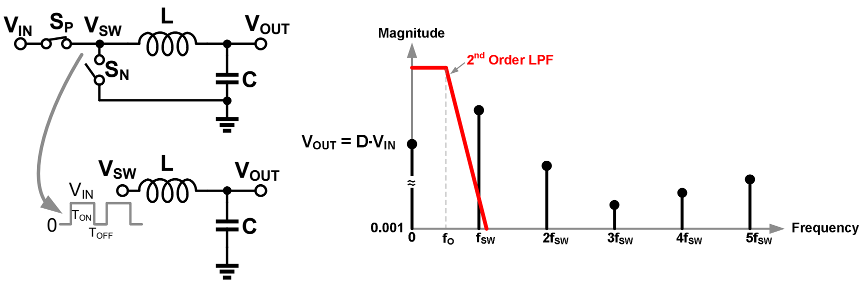
- For Vin = 5V, Vo = 1V and I_{Load} = 1A
  - 80% power loss in the Linear regulator as compared to 10% in switching regulator
- For Vin = 5V, Vo = 4V and I_{Load} = 1A
  - 20% power loss in linear regulator as compared to 2.5% in switching regulator

$$Efficiency\,(\eta) = \frac{Output\ Power}{Input\ Power}$$



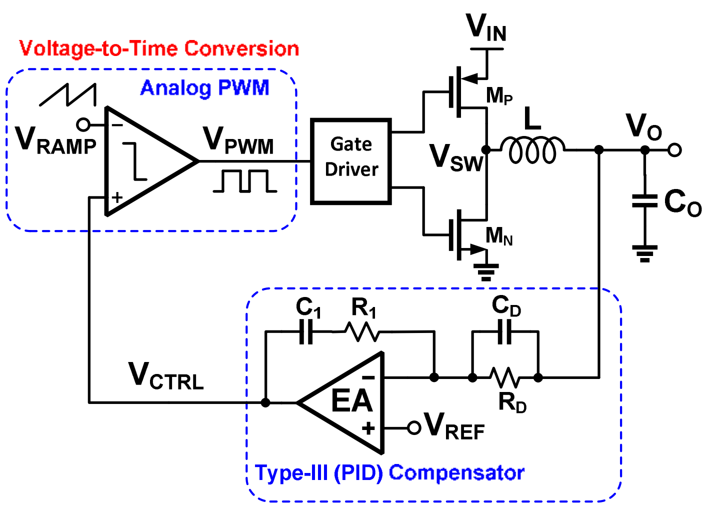
Basic Operation of Switching DC-DC Converter

- DC output voltage generated by filtering pulse width modulated waveform
- V_{OUT} is regulated by controlling the pulse width or Duty Cycle, D

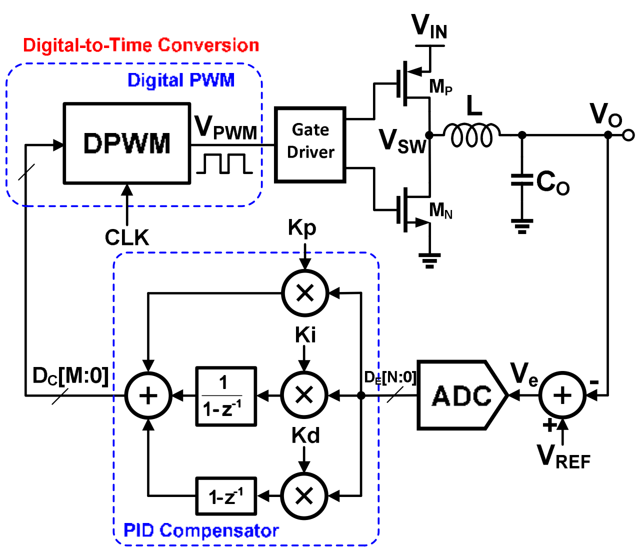


D = Duty Cycle = T_{ON}/T_{SW}

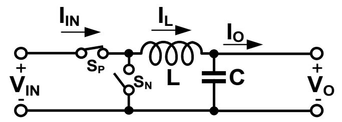
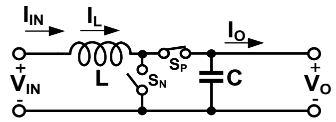
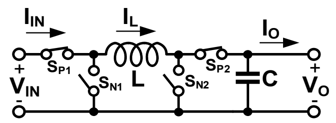
Closed Loop Control - Analog



Closed Loop Control - Digital

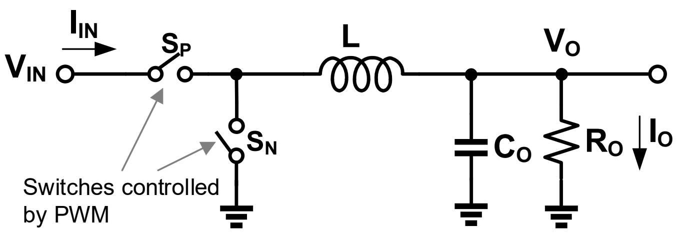


Switching Converter Types

BUCK		$V_O = DV_{IN}$ $I_L = I_O$ $I_{IN} = DI_O$	$V_O < V_{IN}$
BOOST		$V_O = \frac{1}{1-D} V_{IN}$ $I_L = \frac{I_O}{1-D}$ $I_{IN} = I_L$	$V_O > V_{IN}$
BUCK BOOST		$V_O = \frac{D}{1-D} V_{IN}$ $I_L = \frac{I_O}{1-D}$ $I_{IN} = I_O$	$V_O \geq V_{IN}$ $V_O \leq V_{IN}$

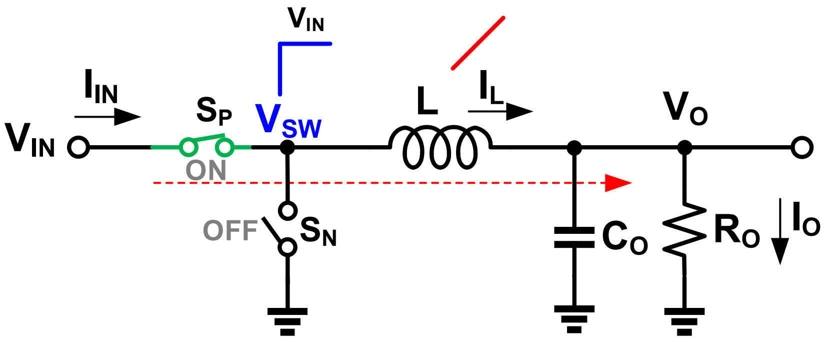
Buck Converter

- **Buck (step-down) converter is used when output voltage is less than input voltage**
- **Uses two switches, S_P & S_N controlled by pulse width modulation (PWM) signal. These switches are usually implemented with MOSFETs**
- **Inductor and capacitor acts as lossless low pass filter and converter PWM into a DC output voltage, V_O**



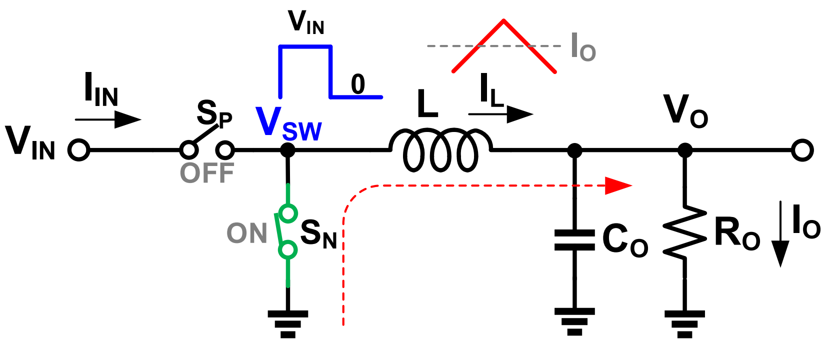
Operation of a Buck Converter

PWM = High

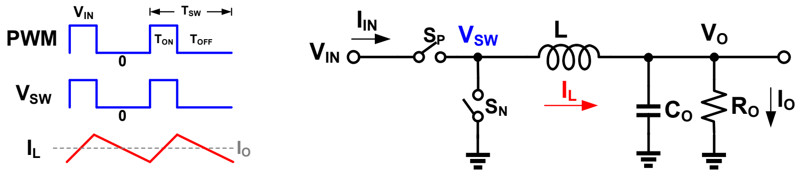


Operation of a Buck Converter

PWM = Low



Operation of a Buck Converter



- For lossless inductor, average voltage across the inductor is zero

  $V_{SW}\text{ (avg)} - V_O = 0$

  $V_{SW}\text{ (avg)} = D \cdot V_{IN}$; D = duty cycle of PWM signal = T_{ON}/T_{SW}

  $\rightarrow \boxed{V_O = D \cdot V_{IN}}$

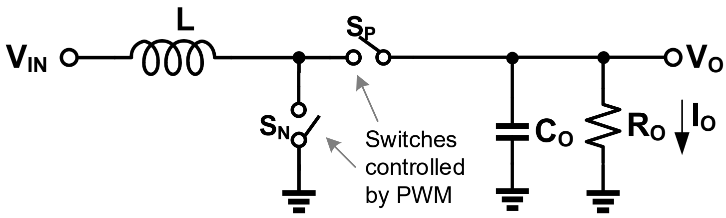
- Under no loss,

  $P_{IN} = P_{OUT}$ or $V_{IN} \cdot I_{IN} = V_O \cdot I_O$

  $\rightarrow \boxed{I_{IN} = D \cdot I_O}$ and inductor current, $\boxed{I_L = I_O}$

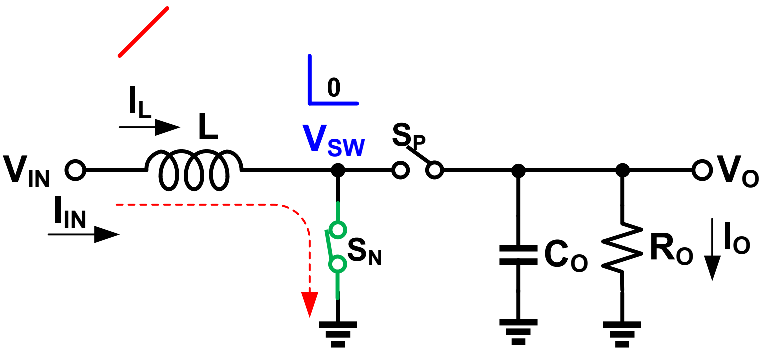
Boost Converter

- Boost (step-up) converter is flipped version of buck converter and used when output voltage is more than input voltage
- Uses two switches, S_P & S_N controlled by pulse width modulation (PWM) signal.



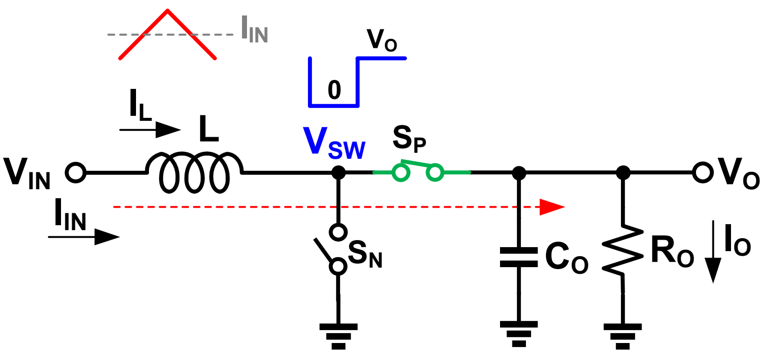
Operation of a Boost Converter

PWM = High

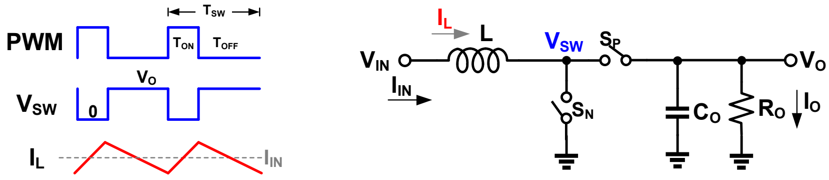


Operation of a Boost Converter

PWM = Low



Operation of a Boost Converter



- For lossless inductor, average voltage across the inductor is zero

  $V_{IN} - V_{SW}\text{ (avg)} = 0$

  $V_{SW}\text{ (avg)} = (1\text{-}D)\cdot V_O$; D = duty cycle of PWM signal = T_{ON}/T_{SW}

  $\rightarrow \boxed{V_O = V_{IN}/(1\text{-}D)}$

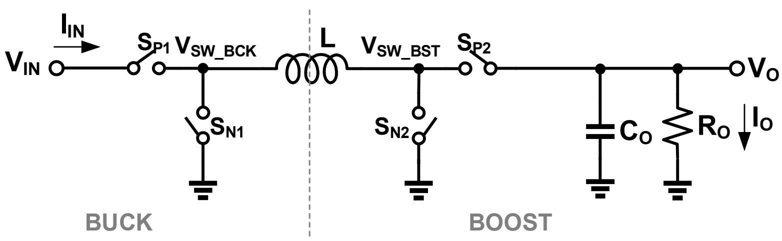
- Under no loss,

  $P_{IN} = P_{OUT}$ or $V_{IN}\cdot I_{IN} = V_O\cdot I_O$

  $\rightarrow \boxed{I_{IN} = I_O/(1\text{-}D)}$ and inductor current, $\boxed{I_L = I_{IN}}$

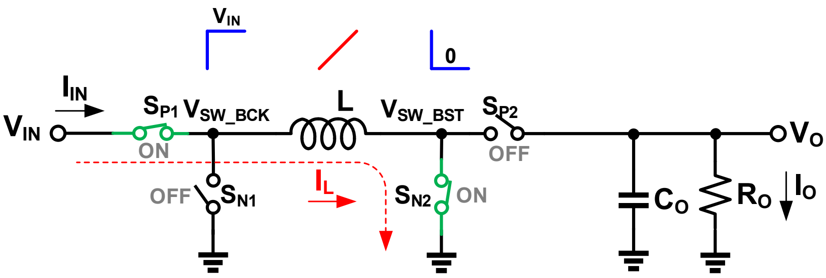
Buck-Boost Converter

- Buck-Boost converter combines both buck and boost.
- Buck-Boost converter is used when output voltage is either less, equal or more than input voltage
- Uses four switches, S_{P1}, S_{N1} and S_{P2}, S_{N2} controlled by pulse width modulation (PWM) signal.



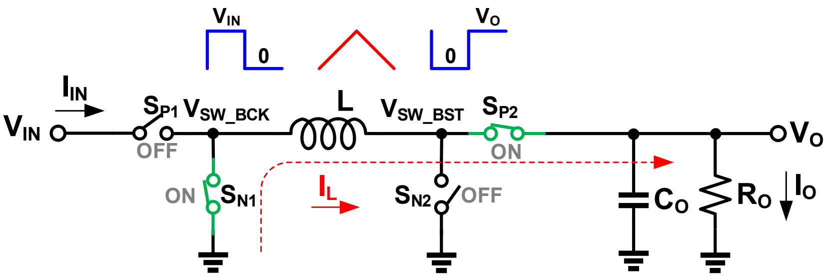
Operation of a Buck-Boost Converter

PWM = High

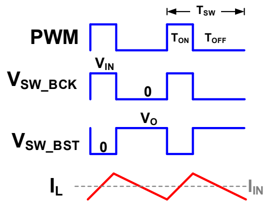


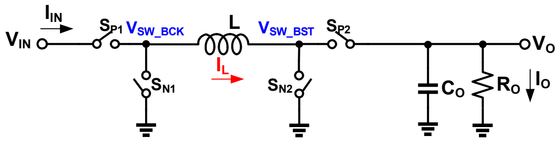
Operation of a Buck-Boost Converter

PWM = Low



Operation of a Buck-Boost Converter





- For lossless inductor, average voltage across the inductor is zero

  V_{SW_BCK} (avg) – V_{SW_BST} (avg) = 0

  $D \cdot V_{IN} = (1-D) \cdot V_O$

  → $\boxed{V_O = \frac{D}{1-D} \cdot V_{IN}}$

  D < 0.5 → $V_O < V_{IN}$: Buck

  D = 0.5 → $V_O = V_{IN}$

  D > 0.5 → $V_O > V_{IN}$: Boost

- Under no loss,

  $P_{IN} = P_{OUT}$ or $V_{IN} \cdot I_{IN} = V_O \cdot I_O$

  → $\boxed{I_{IN} = \frac{D}{1-D} \cdot I_O}$

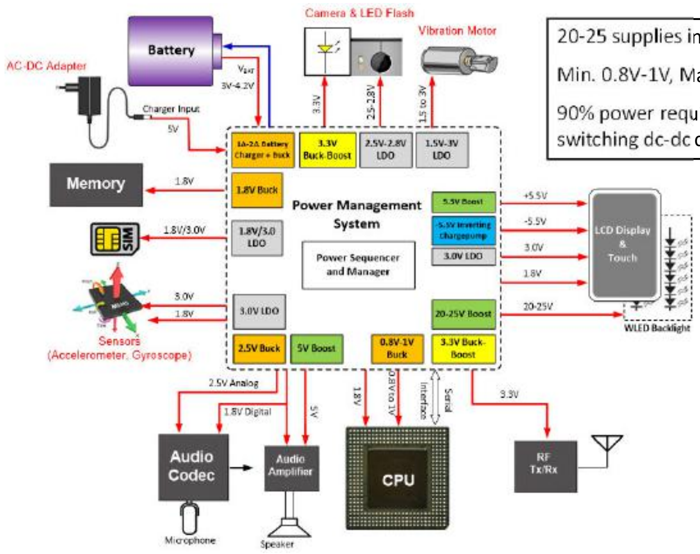
  Also, $I_{IN} = D \cdot I_L$

  Substituting $I_{IN} = \frac{D}{1-D} \cdot I_O$

  → inductor current,

  $\boxed{I_L = \frac{1}{1-D} \cdot I_O}$

Power Management in a Smartphone

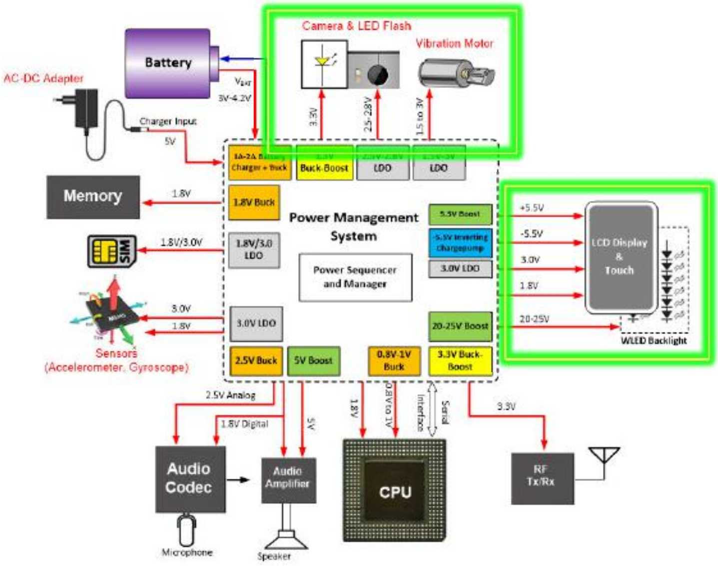


20-25 supplies in a Smartphone

Min. 0.8V-1V, Max. 20V-25V

90% power requirement is met by switching dc-dc converters

Power Management in a Smartphone



History of Display Technologies

1897 – Birth of CRT (Cathode Ray Tube)

1925 - CRT TV was invented and used until early 2000s with advancements in technologies like color TV, flat screen etc.

1964 - Invention of LCD. Used in modern LCD watch and calculators in 1972.

1980s – Color LCD displays and Organic LED (OLED) displays were invented

Early 2000: LCD technology started outperforming CRT in terms of both quality as wells as power consumption and played critical role in smartphones revolution and tablets later

History of Display Technologies

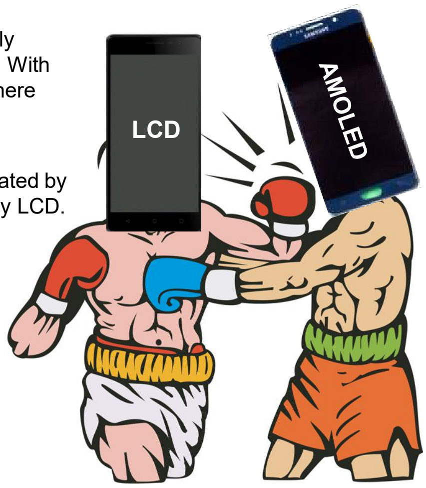
2007: iPhone, first commercially successful smartphone that is exclusively touchscreen was launched.

2010: Samsung Galaxy S series with AMOLED display launched

LCD Vs. AMOLED

Present: LCD and AMOLED are the two widely used displays in smartphones and tablet PCs. With advancements in both display technologies, there has been neck to neck competition.

High end smartphone market is mostly dominated by AMOLED and mid and low tier is dominated by LCD.



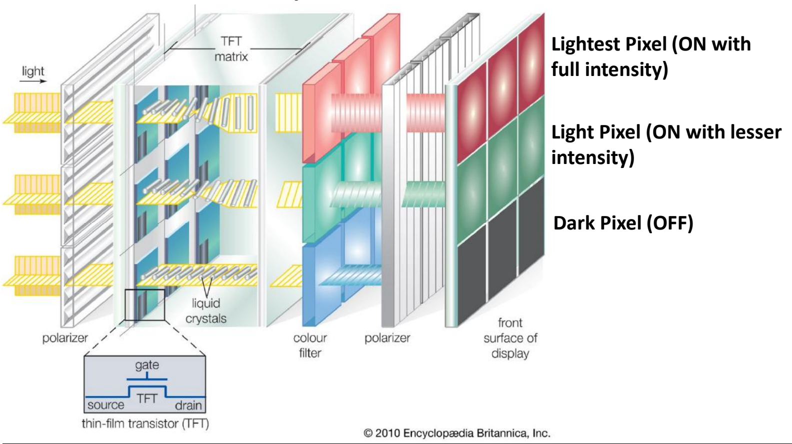
LCD Vs. AMOLED Structure

- Uses multiple layers which limit the minimum achievable thickness (~1-1.5mm)
- Requires backlight

- Uses fewer layers hence thickness is quite low (paper thin)
- No backlighting is needed

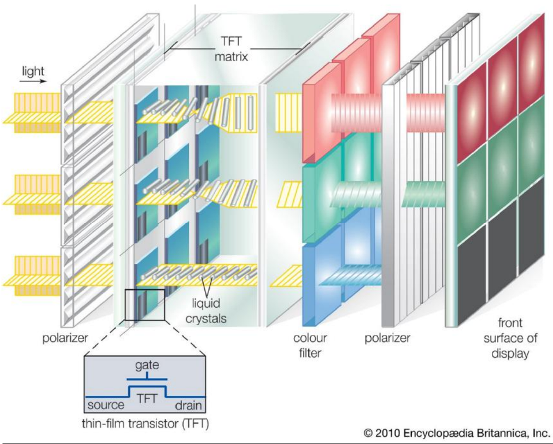
How LCD Works

- Crystal alignment is changed when voltage is applied between two electrodes (through TFT)
- Voltage applied across LCD electrodes determines how much light will be passed and controls the intensity.

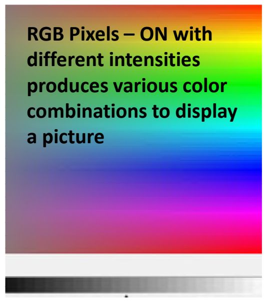


LCD Color Depth

- 8-bit intensity of each color (R, G and B) provides 16 million (2^8x2^8x2^8) color combinations.



Display Color Depth

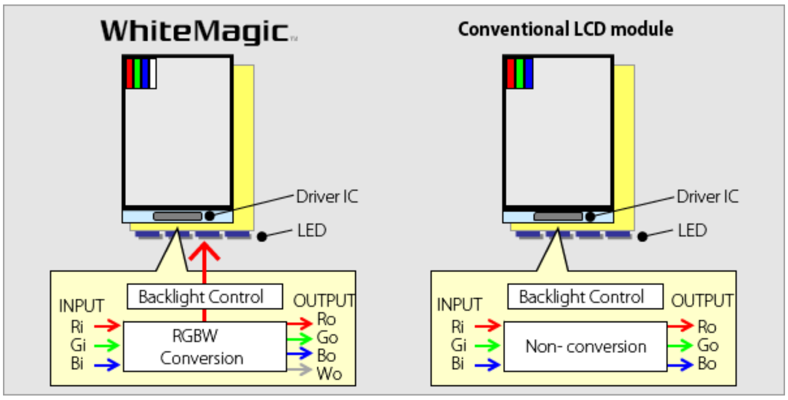


RGB Pixels – OFF (Black)

RGB Pixels – ON (White)

RGBW LCD Display

- JDI (Japan Display Inc) WhiteMagic LCD technology adds while sub-pixel along with RGB (Also called RBGW)



Source: Japan Display Inc.

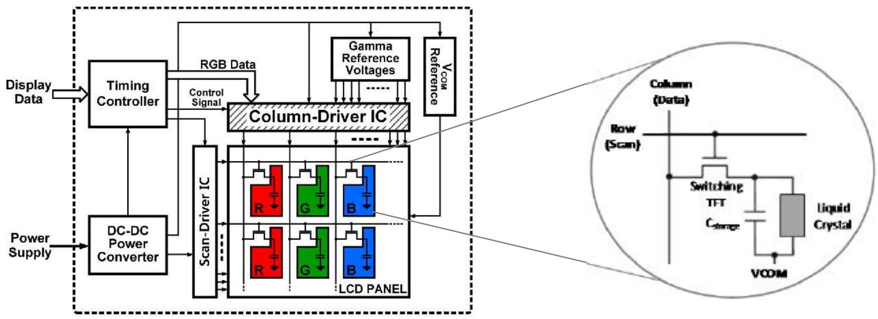
Power Reduction with RGBW LCD Display

- White pixel is transparent and passes the full white backlight making the pixel brighter
- For the same brightness, RGBW achieves ~40% power reduction without degrading the image quality

Source: Japan Display Inc.

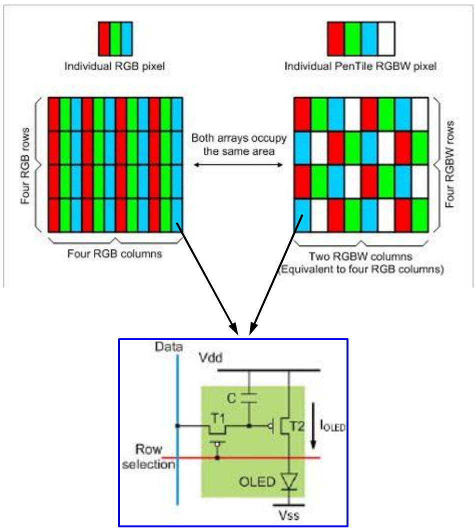
LCD Pixel Driver

- LCD requires multiple supplies to drive a pixel.
- Some of the supplies are generated on display panel (inside DDIC) and some are generated outside the panel (on phone board)



How AMOLED Works

- Each pixel is LED and three LEDs (R, G and B) forms one sub-pixel.
- Fourth LED (White) can also be added in a sub-pixel for better brightness
- Current in each OLED pixel is controlled to control the brightness and form color combinations
- Since each OLED is self lit, it doesn't require any backlight

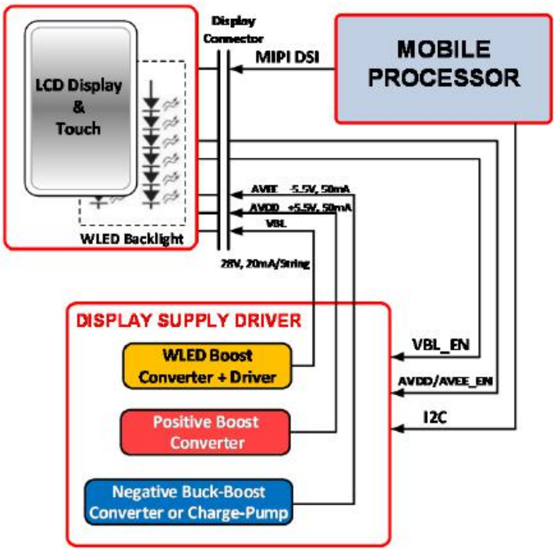


Power Management for LCD

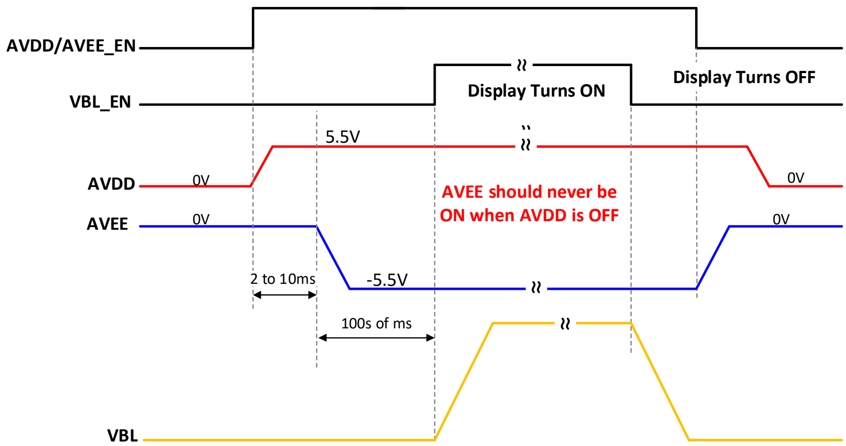
Power Supplies for Mobile Display (LCD)

Power Supply	Description	Value (Typ)	Supply Generation
VDDI	Digital Power Supply	1.8V	External (system VDD)
VDDA	Power Supply for Analog Systems	3.3V	Inside panel DDIC
VGH	TFT Row/Gate drive positive (ON) supply	15V	Inside panel DDIC
VGL	TFT Row/Gate drive negative supply	-10V	Inside panel DDIC
VCOM	LCD common electrode voltage	-2V – +2V	Inside panel DDIC
AVDD		5.5V	External (dedicated power IC)
AVEE		-5.5V	External (dedicated power IC)
VBL	Backlight supply	28V (for 8s2p) 14V (for 4s4p)	External (dedicated power IC)

LCD Power Supply Regulators



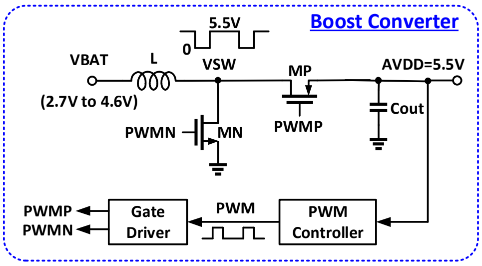
LCD Power-Up/Power Down Sequencing



Generating +/-5.5V

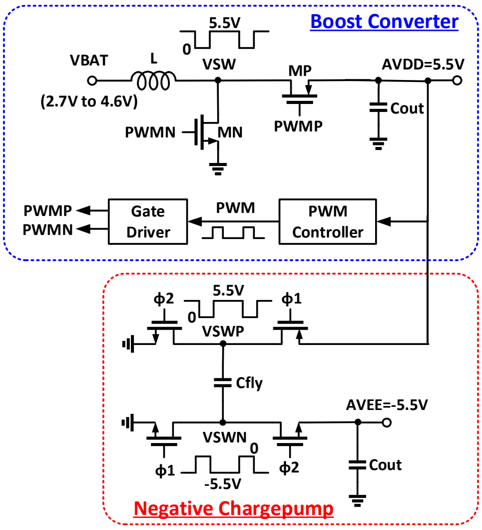
- **+5.5V can be generated from an inductive boost**

$$AVDD = \frac{1}{1-D} \cdot VBAT$$



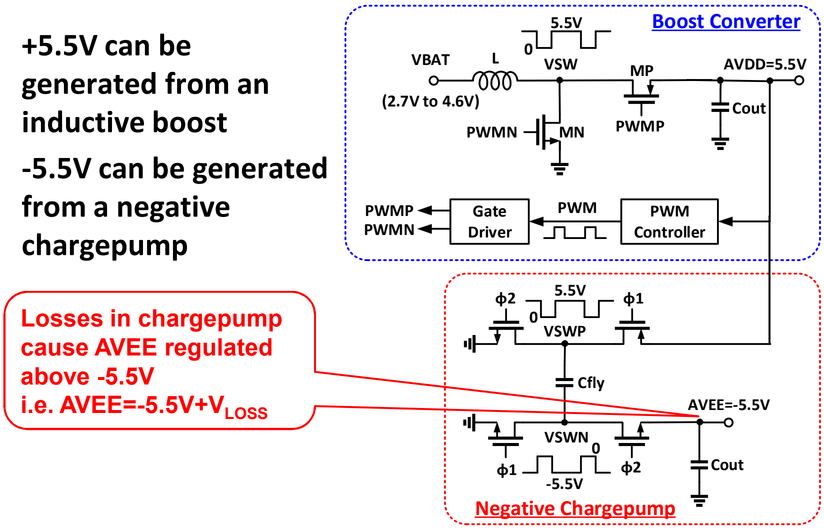
Generating +/-5.5V

- +5.5V can be generated from an inductive boost
- -5.5V can be generated from a negative chargepump

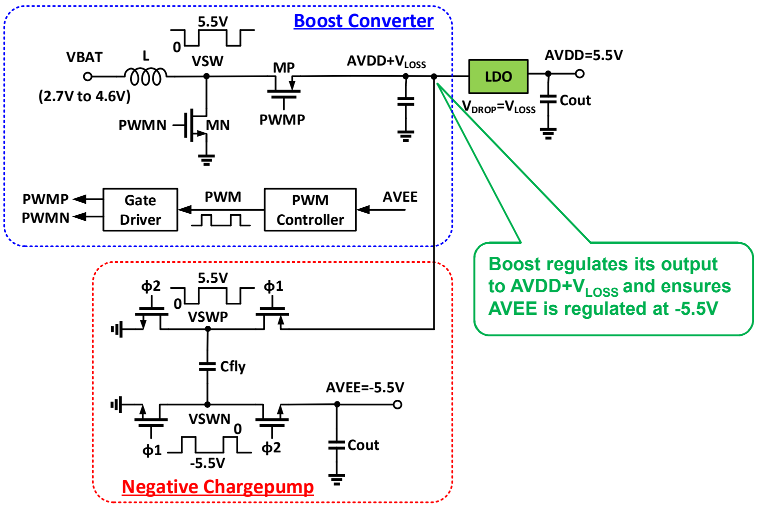


Generating +/-5.5V

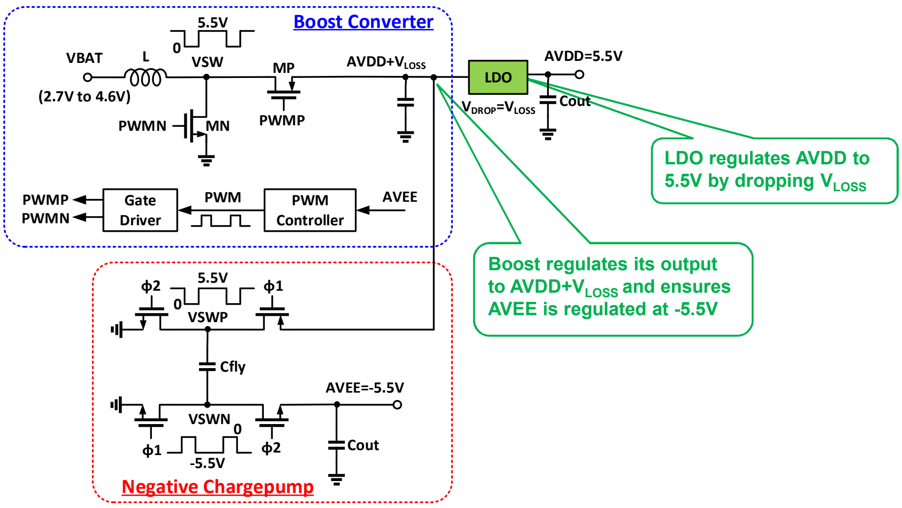
- +5.5V can be generated from an inductive boost
- -5.5V can be generated from a negative chargepump



Compensating for Chargepump V_{LOSS}

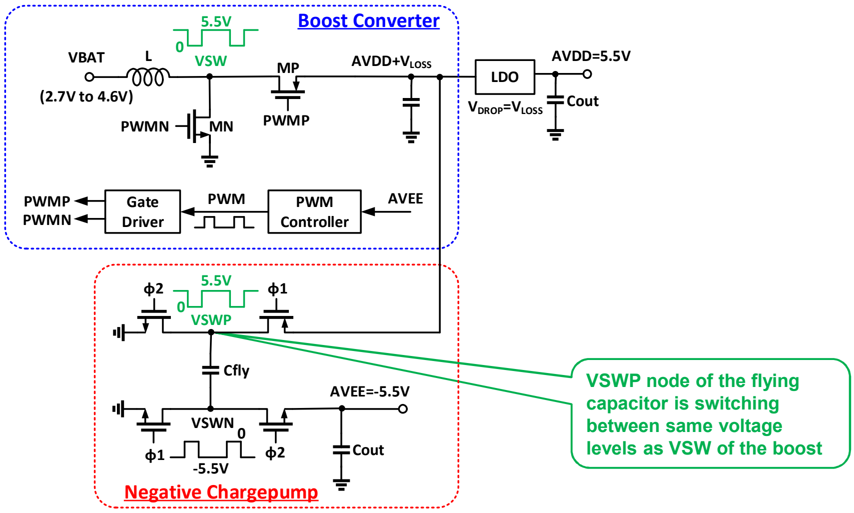


Compensating for Chargepump V_{LOSS}

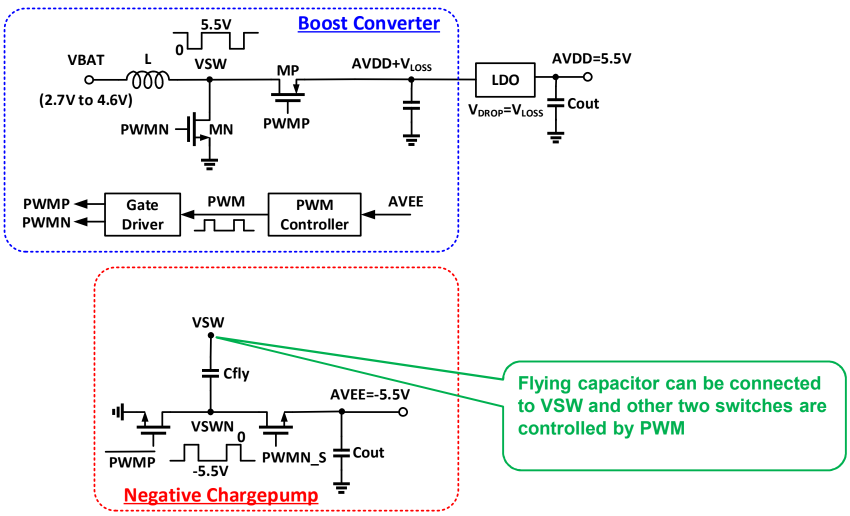


Ref: TI's tps65132 datasheet

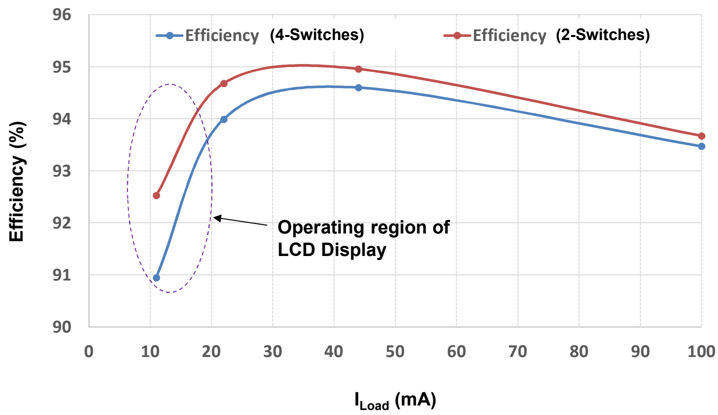
Switch reduction from Chargepump



Switch reduction from Chargepump



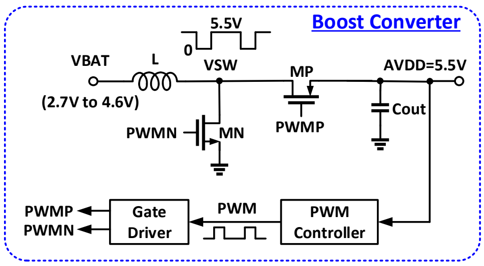
Efficiency Improvement with Switch reduction



Generating +/-5.5V

- **+5.5V can be generated from an inductive boost**

$$AVDD = \frac{1}{1\text{-}D} \cdot VBAT$$



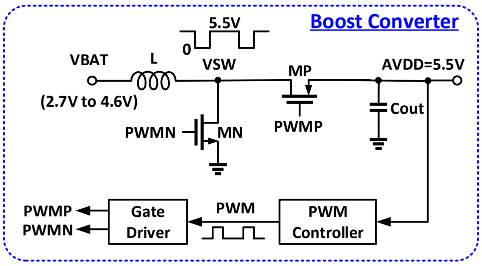
Generating +/-5.5V

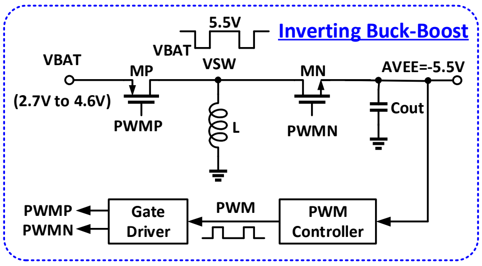
- **+5.5V can be generated from an inductive boost**

$$AVDD = \frac{1}{1-D} \cdot VBAT$$

- **-5.5V can be generated from an inductive buck-boost**

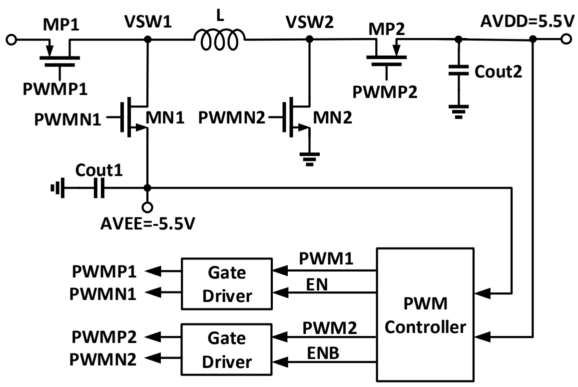
$$AVEE = -\frac{D}{1-D} \cdot VBAT$$





Single Inductor Dual Output (SIDO) Converter

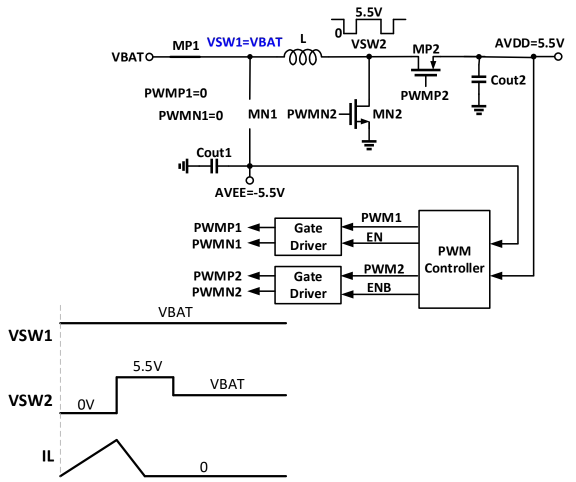
- **Uses single inductor to generate both AVDD and AVEE**
- **PWM is time multiplexed between Boost and Inverting Buck-Boost**
- **Mostly used in DCM or CCM-DCM boundary to avoid cross regulation**



SIDO Operation

Boost Mode

MP1=ON, MP2=OFF & MP2, MN2 → PWM

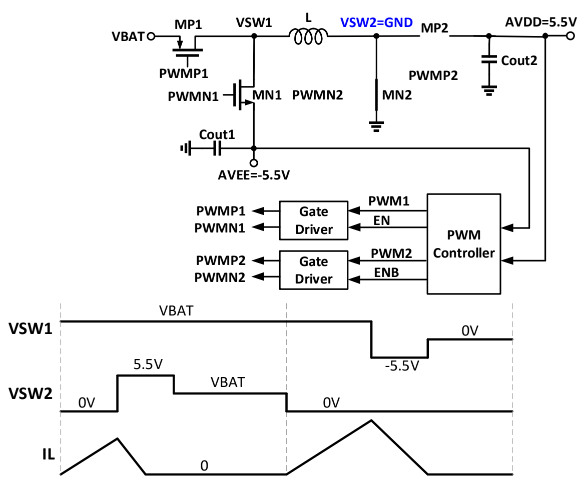


Boost Mode

SIDO Operation

IBB Mode

MP1=ON, MP2=OFF & MP2, MN2 → PWM



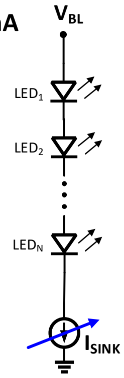
Boost Mode **IBB Mode**

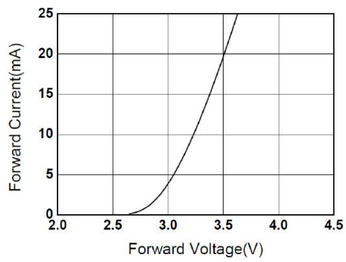
LCD Backlight

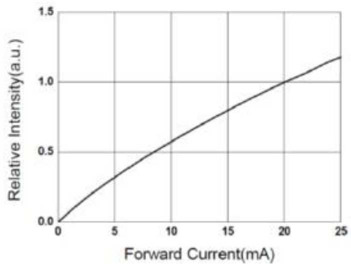
- LCD backlight is provided by multiple white LED connected in series
- Power supply VBL can be supplied externally or generated inside the LED driver
- Full scale is LED current is ~20mA

$V_{BL}=N\cdot V_F+V_{SENSE}$

LED brightness α I_{LED}

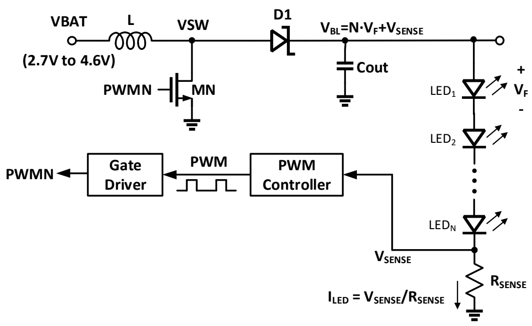






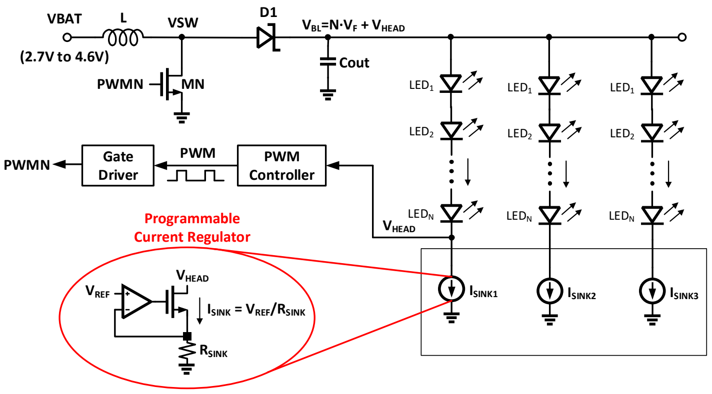
LCD Backlight Power Supply + Driver

- LCD backlight is supplied by LED drivers driven with a constant current
- Multiple LEDs are usually connected in series thus requiring much higher voltage (~28V for 8 LEDs)
- Simplest way is drive LEDs is boost converter with external current sense resistor
- Works only for single string



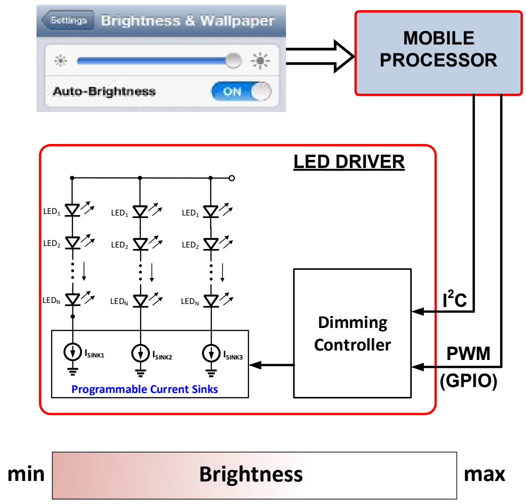
LED Driver for Parallel Strings

- Usually LCD panels for smartphones require 16-24 LEDs (8s2p or 8s3p) hence requiring independent current sinks for each string
- V_{HEAD} is regulated to minimum voltage required to keep current sinks in saturation region



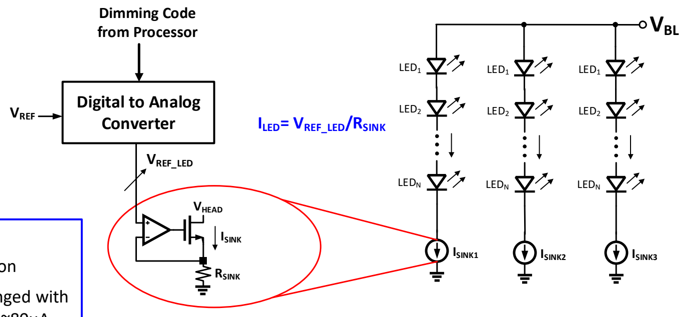
Controlling Backlight Brightness (Dimming)

- Two ways to control the brightness
  - PWM or Digital Dimming
  - Analog Dimming



Analog Dimming

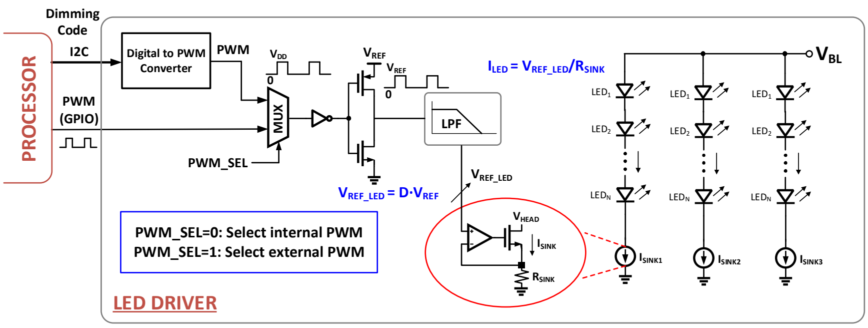
- Analog dimming is achieved by converting the digital dimming code to an analog reference voltage through D/A converter
- Alternatively R_{SINK} can also be programmed
- For smooth dimming, usually 7-8 bit of D/A resolution is used



Full scale I_{LED}= 20mA
With 8-bit D/A conversion
LED current can be changed with step size = 20mA/256 = ~80µA

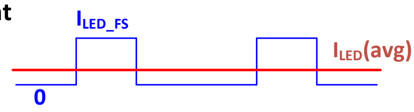
Analog Dimming using PWM

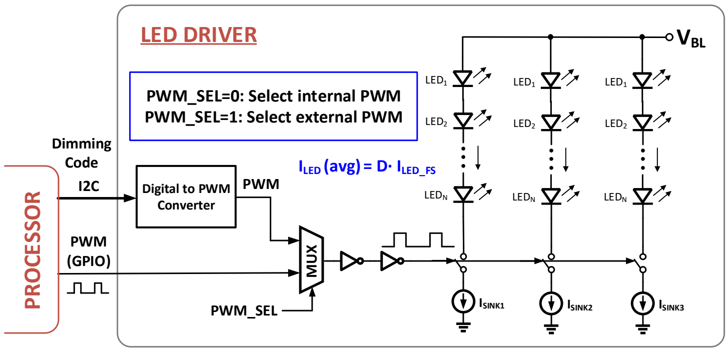
- V_{REF} is modulated with PWM duty cycle and low pass filtered to get V_{REF_LED}
- Doesn't require D/A converter
  - Area efficient
  - Reduces design complexity



Digital or direct PWM Dimming

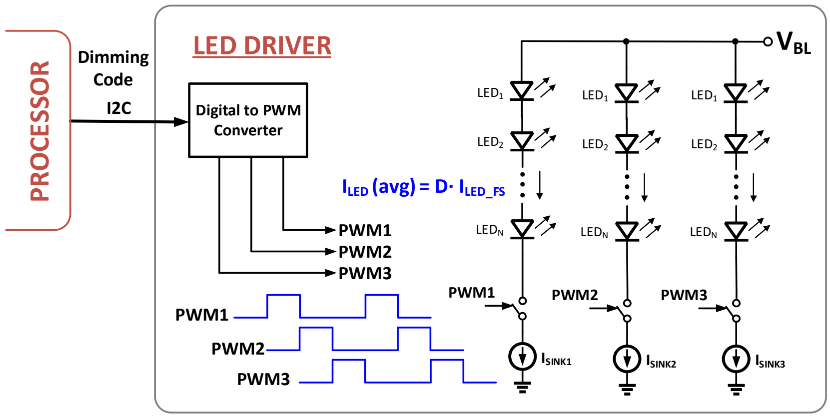
- Full scale LED current (I_{LED_FS}) is directly modulated with PWM duty cycle at frequency high enough (≥ 1 kHz) to be filtered by the human eyes
- EMI concerns due to switching current
  - Peak current = $3 \cdot I_{LED\_FS}$





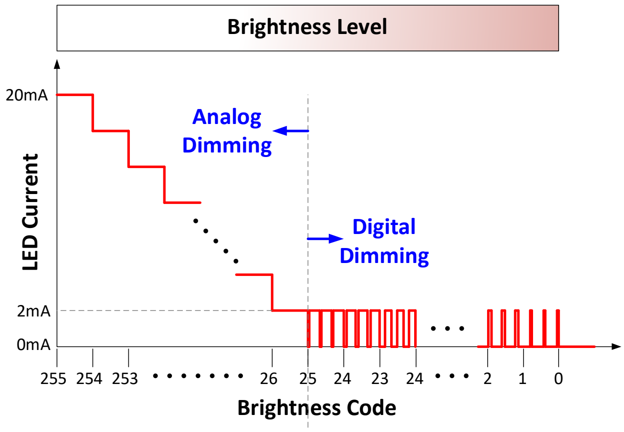
Staggered PWM Dimming

- EMI can be mitigated by switching each LED string at different times
- Suitable mainly with internal PWM as external PWM requires 3 GPIOs



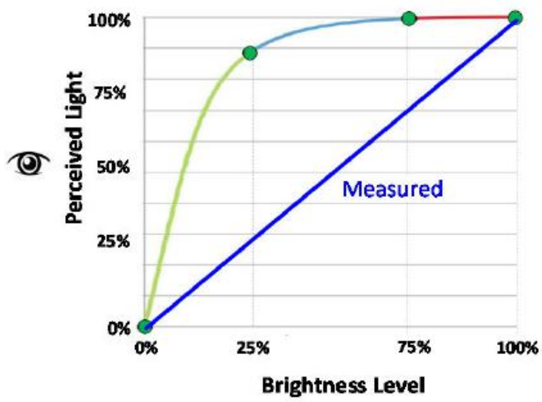
Hybrid Dimming

- Hybrid dimming combines both analog and digital to address the concern of:
  - Flicker in analog dimming due to noise at very low brightness
  - EMI in digital dimming due to high switching current



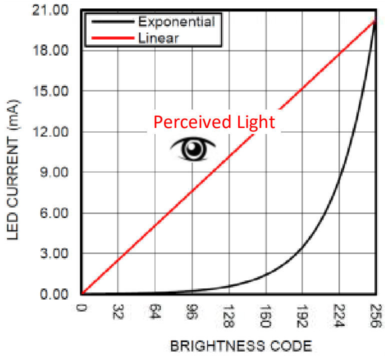
Human Perception of Brightness Level

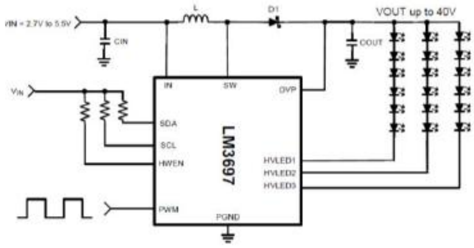
- Human eyes perceive light in logarithmic manner
- With linear brightness control, eyes observe very little change in brightness above 50% while steeper change in light observed at low brightness



Exponential Mapping of Brightness Code

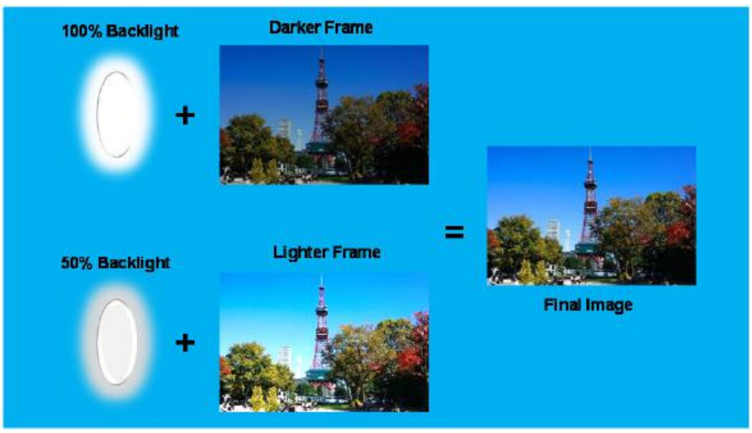
- Instead of controlling the brightness in linear manner, codes are mapped to exponentially which appears linear to human eyes



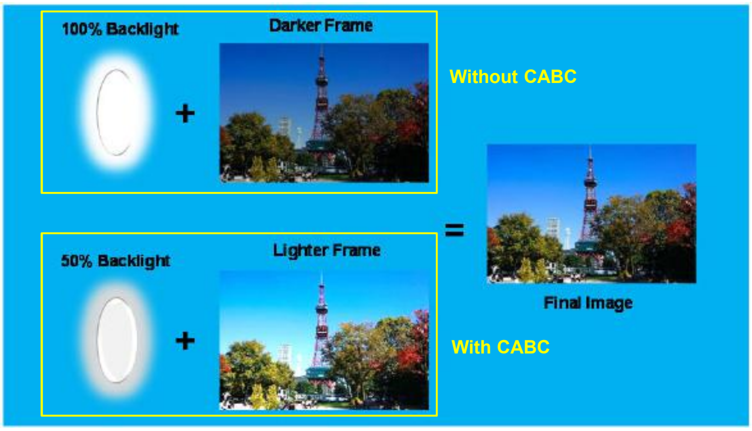


Source: Texas Instruments

Content Adaptive Brightness Control

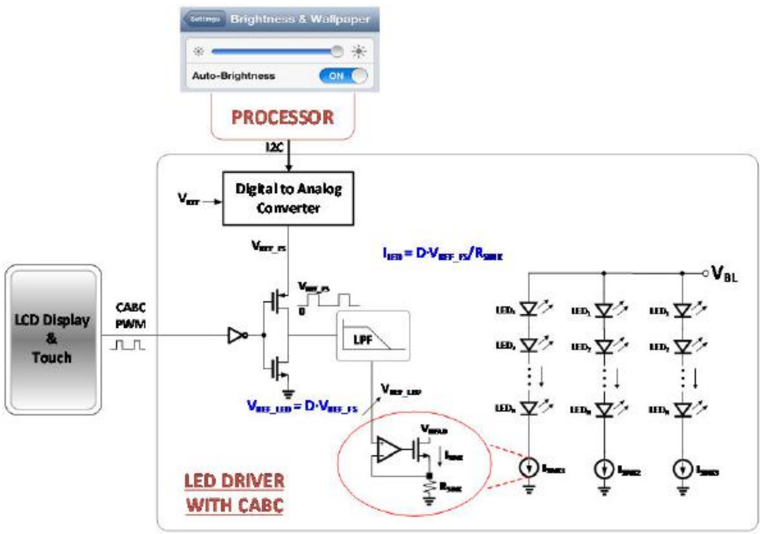


Content Adaptive Brightness Control



CABC adaptively changes backlight depending upon the image intensity

LED Driver with CABC



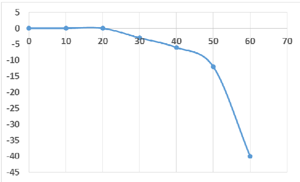
Flicker in Display Panels

- **Flicker is caused by period change in display brightness level at frequency below the human visual perception (usually below 100 Hz)**

Flicker Perception of Human Eye

Frequency (Hz)	Factor dB	Ratio
0	0	1.000
10	0	1.000
20	0	1.000
30	- 3	0.708
40	- 6	0.501
50	- 12	0.251
60	- 40	0.010

Sensitivity



Frequency

Flicker in Display Panels

- **Flicker is caused by period change in display brightness level at frequency below the human visual perception (usually below 100 Hz)**

Flicker Perception of Human Eye

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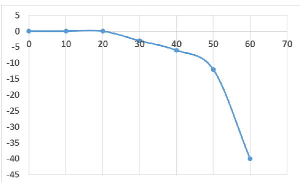
Sensitivity



Frequency

Flicker @10Hz

Flicker @60Hz

Sources of Flicker

1. Unstable power supply
2. Un-matched gamma in Positive and Negative frame
3. Low refresh rate
4. Un-optimized Vcom level

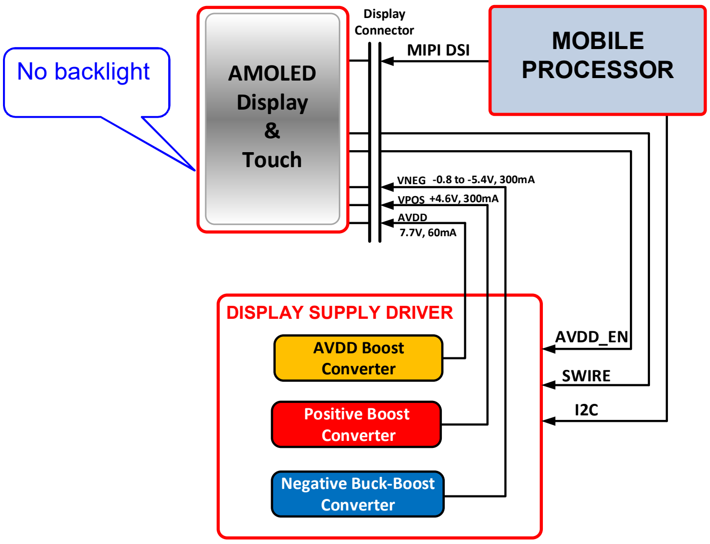
2,3 & 4 are non-power management related

Flicker in LCD

- Flicker in LCD is mainly caused by unstable backlight which is driven by LED drivers
- Instability in LED current could be caused by low frequency ripple in output voltage due to low frequency load and line transient

Power Management for AMOLED Displays

AMOLED Power Supplies



Power Supplies for AMOLED Display

Power Supply	Description	Value (Typ)	Supply Generation
VDDI	Digital Power Supply	1.8V	External (system VDD)
VDDA	Power Supply for Analog Systems	3.3V	Inside panel DDIC
VPOS	Positive Supply	4.6V	External (dedicated power IC)
VNEG	Negative Supply	-1.4V to -5.4V	External (dedicated power IC)
AVDD	High Voltage Analog for TFT	7.7V	External (dedicated power IC)

- **VPOS is fixed and has tight accuracy and ripple requirement**
- **VNEG is programmable and accuracy requirement is not as tight as VPOS**

Why Fixed VPOS?

- **When TFT is ON gate voltage is sampled and held on Cs**
- **When TFT is OFF, any low frequency noise at VPOS will modulate I_{LED} (through M_{P2}) and cause flicker**
- **Low frequency noise may be caused by GSM burst during call (burst frequency = 217Hz) or 120Hz noise from wall adapter when charger is plugged in**

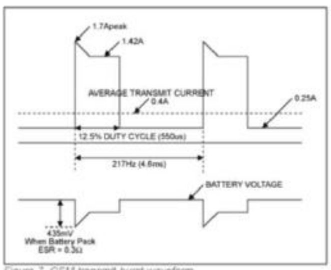
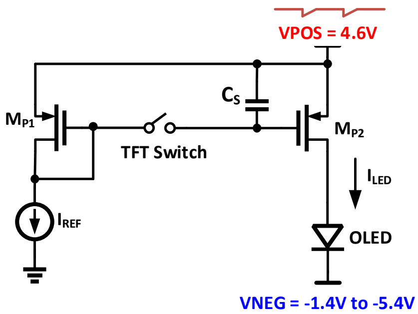


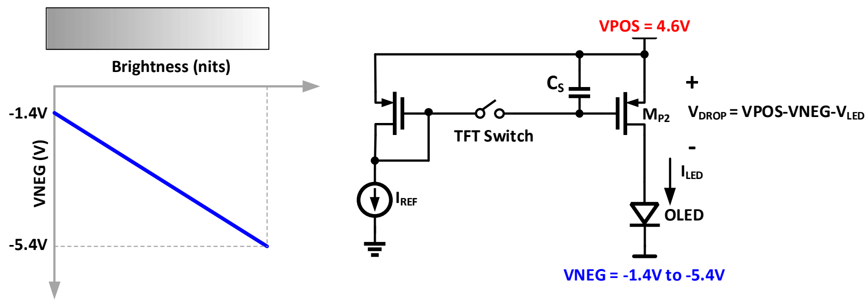
Figure 7. GSM transmit burst waveform.

Source: Maxim



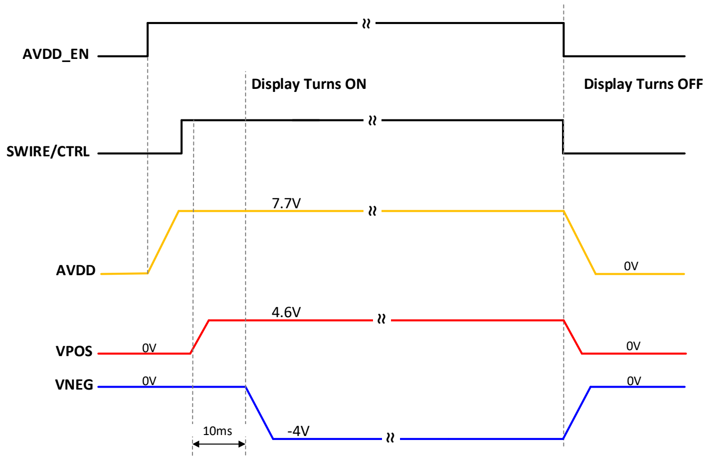
Why Variable VNEG?

- LED current is varied based on required brightness
- Since forward voltage of LED is reduced at lower current, extra voltage between VPOS and VNEG is dropped across current source MP2 hence decreasing the efficiency
- VNEG is adjusted to reduce the drop-out across MP2 when brightness is changed

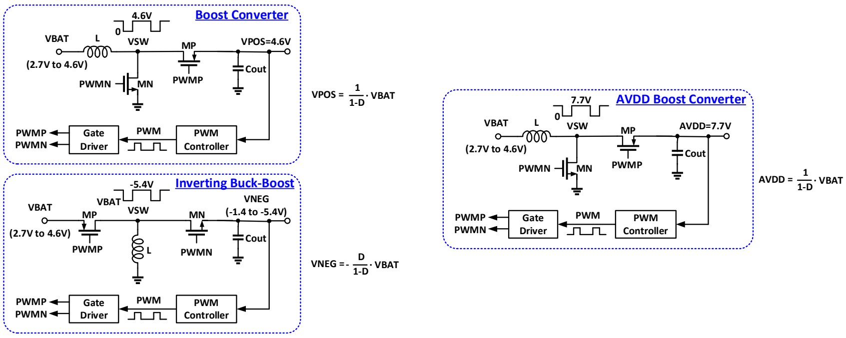


AMOLED Power UP/DOWN Sequencing

- AVDD is enabled first then VPOS.
- VNEG is enabled after VPOS (~10ms delay)



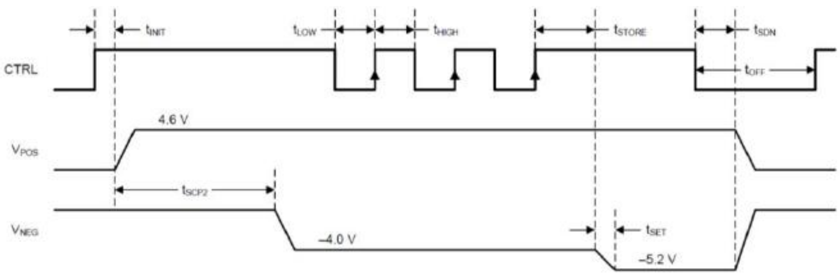
Generating Three Supplies for AMOLED



VNEG Programming Using SWIRE

- VPOS is usually fixed at 4.6V
- VNEG is varied based on brightness:

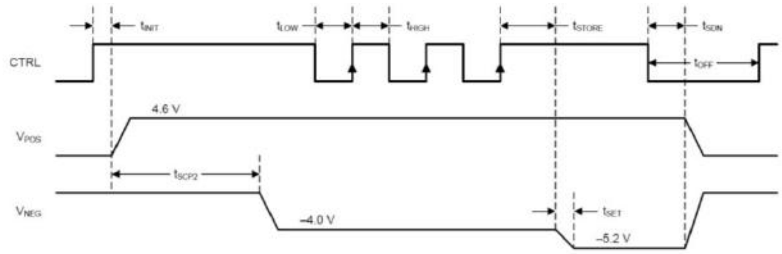
	min	typ	max
t_{INIT}		300μs	400μs
t_{SCP2}		10ms	
t_{LOW}	2μs	10μs	25μ
t_{HIGH}	2μs	10μs	25μ
t_{STORE}	30μs		80μs
t_{SDN}	30μs		80μs
t_{OFF}	200μs		



Source: Texas Instruments

VNEG Programming

- By default, VNEG turns ON with -4V when SWIRE goes High then programmed by sending pulse.
- VNEG is pre-defined at 1 pulse (positive edge) and then reduces by 100mV after every SWIRE pulse (~10uS).
- VNEG@1-pulse = 5.4V, VNEG@N-pulses = -(5.4 – (N-1)*100mV).



Source: Texas Instruments

VNEG Programming Table

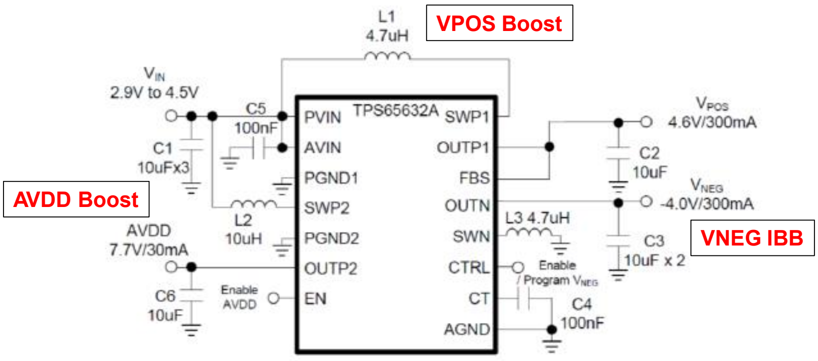
VNEG= -(5.4 – (N-1)*100mV)

Bit / Rising Edges	V_{NEG}	DAC Value	Bit / Rising Edges	V_{NEG}	DAC Value
0 / no pulse	–4.0 V	000000	21	–3.4 V	010101
1	–5.4 V	000001	22	–3.3 V	010110
2	–5.3 V	000010	23	–3.2 V	010111
3	–5.2 V	000011	24	–3.1 V	011000
4	–5.1 V	000100	25	–3.0 V	011001
5	–5.0 V	000101	26	–2.9 V	011010
6	–4.9 V	000110	27	–2.8 V	011011
7	–4.8 V	000111	28	–2.7 V	011100
8	–4.7 V	001000	29	–2.6 V	011101
9	–4.6 V	001001	30	–2.5 V	011110
10	–4.5 V	001010	31	–2.4 V	011111
11	–4.4 V	001011	32	–2.3 V	100000
12	–4.3 V	001100	33	–2.2 V	100001
13	–4.2 V	001101	34	–2.1 V	100010
14	–4.1 V	001110	35	–2.0 V	100011
15	–4.0 V	001111	36	–1.9 V	100100
16	–3.9 V	010000	37	–1.8 V	100101
17	–3.8 V	010001	38	–1.7 V	100110
18	–3.7 V	010010	39	–1.6 V	100111
19	–3.6 V	010011	40	–1.5 V	101000
20	–3.5 V	010100	41	–1.4 V	101001

Source: Texas Instruments

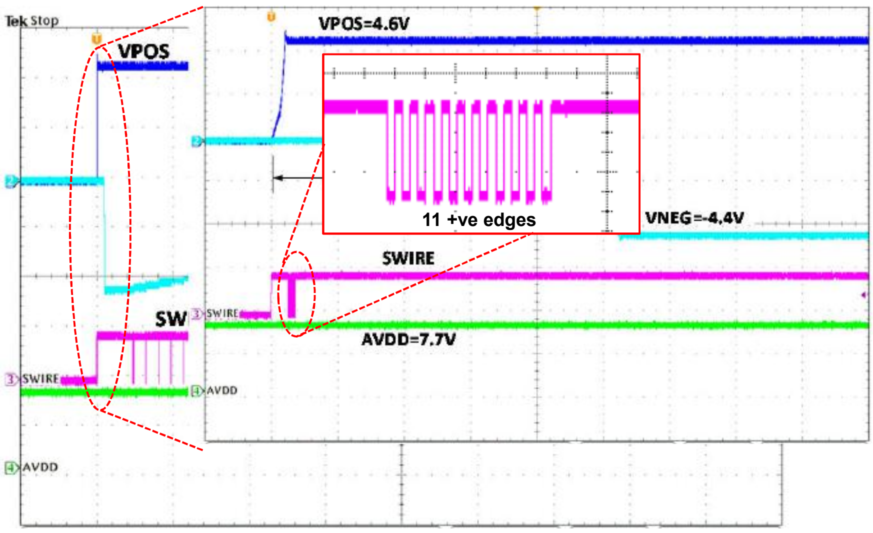
TI AMOLED Display Power Supply – TPS65632

- Uses boost converter for VPOS (4.6V) and inverting buck-boost for VNEG (programmable through CTRL/SWIRE)

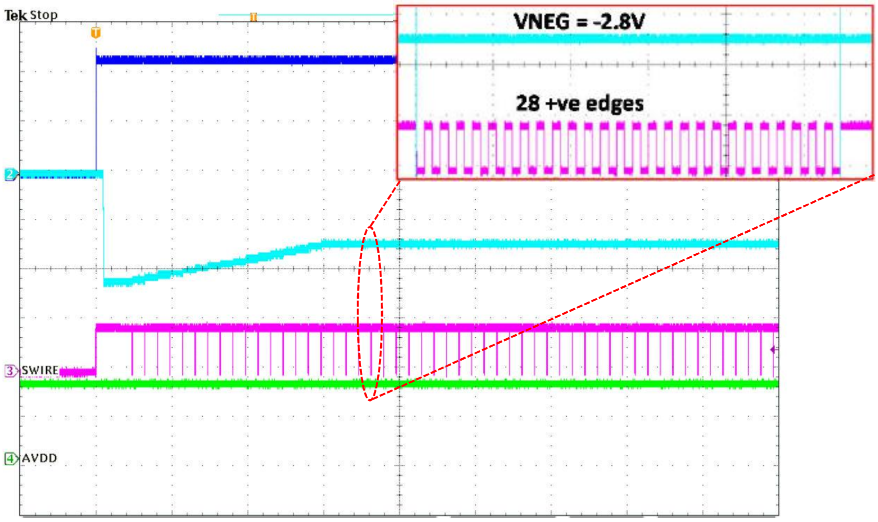


Source: Texas Instruments

Display Power-Up

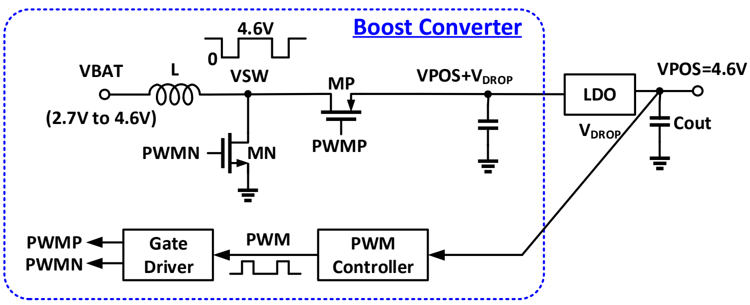


Display Power-Up



Issue with AMOLED Boost Converter

- Battery voltage when fully charged could be as high as 4.6V
- Boost can be regulated to higher voltage and extra voltage can be dropped in LDO to regulate VPOS to 4.6V



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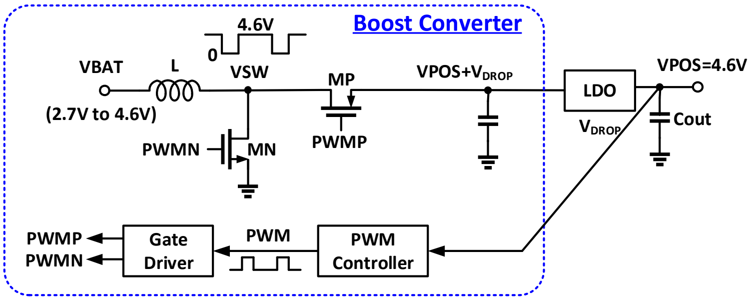
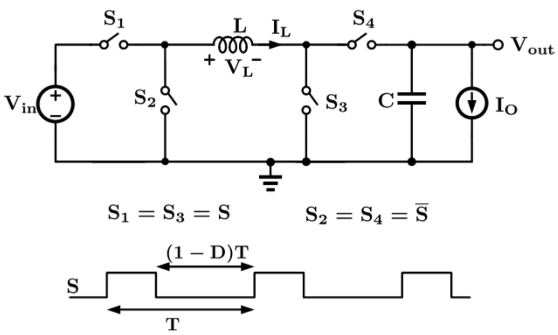


Loss in efficiency due to V_{DROP}

Using Buck-Boost Converter

- Buck-Boost works for entire range input voltage

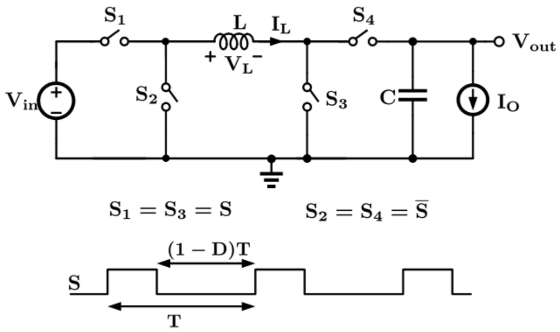


$$V_{out} = \frac{D}{1-D} V_{in} \quad (1)$$

$$I_L = \frac{1}{1-D} I_o \quad (2)$$

Vout can be regulated at:
<Vin : D < 0.5
> Vin: D > 0.5
≈ Vin: D ≈ 0.5

Issue with Conventional BB converter

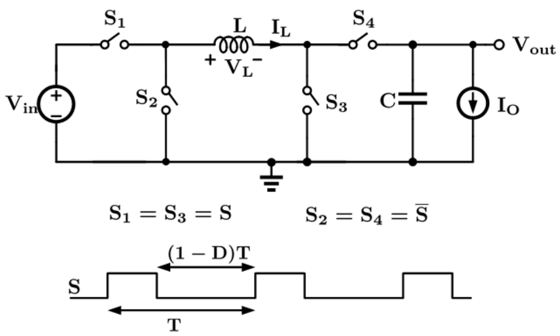


$$V_{out} = \frac{D}{1-D} V_{in} \quad (1)$$

$$I_L = \frac{1}{1-D} I_o \quad (2)$$

- Single Duty cycle, D, controls all the switches
- Switching losses are higher due to simultaneous operation of 4 switches
- Conduction losses are higher due to larger Inductor current (nearly 2x when Vin ≈ Vout.

Issue with Conventional BB converter

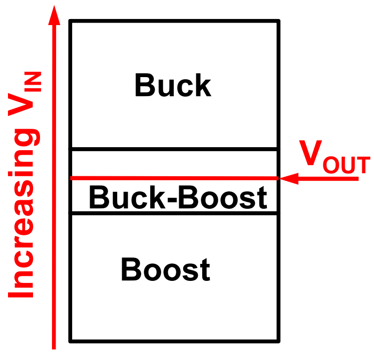


$$V_{out} = \frac{D}{1-D} V_{in} \quad (1)$$

$$I_L = \frac{1}{1-D} I_o \quad (2)$$

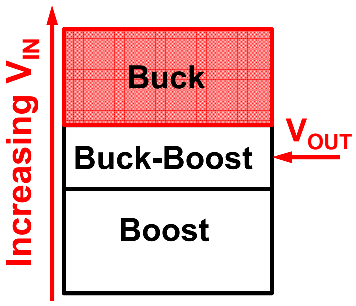
Can we do it in a better way?

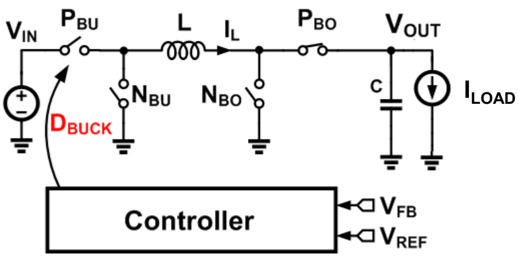
Tri-Mode Operation of BB Converter



- $V_{IN} > V_{OUT}$: **Buck Mode**
- $V_{IN} < V_{OUT}$: **Boost Mode**
- $V_{IN} \sim V_{OUT}$: **Buck-Boost Mode**

Tri-Mode: Buck

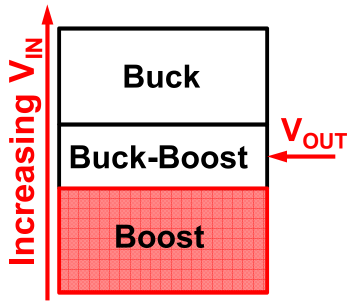


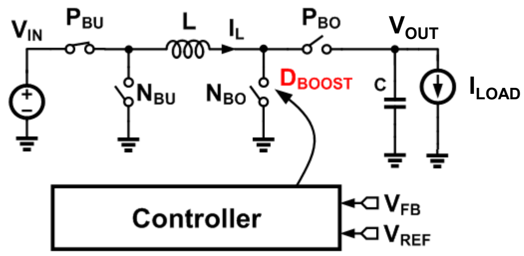


- **P_{BO} always ON**
- **D_{BUCK} controls buck switches**

$$\boxed{V_{OUT} \approx (D_{BUCK})V_{IN}} \quad \boxed{I_L = I_{LOAD}}$$

Tri-Mode: Boost

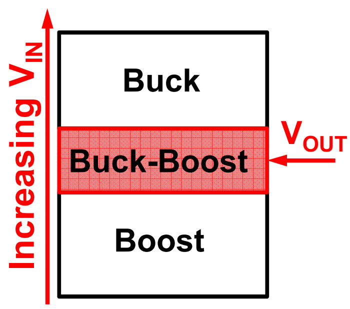


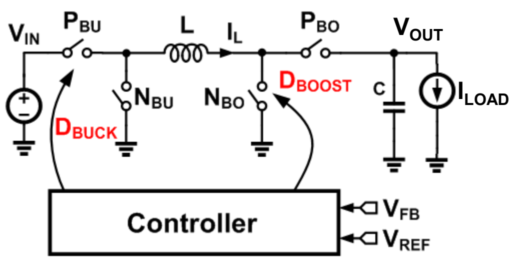


- P_{BU} always ON
- D_{BOOST} controls boost switches

$$V_{OUT} \approx \frac{V_{IN}}{(1-D_{BOOST})} \qquad I_L = \frac{I_{LOAD}}{(1-D_{BOOST})}$$

Tri-Mode: Buck-Boost

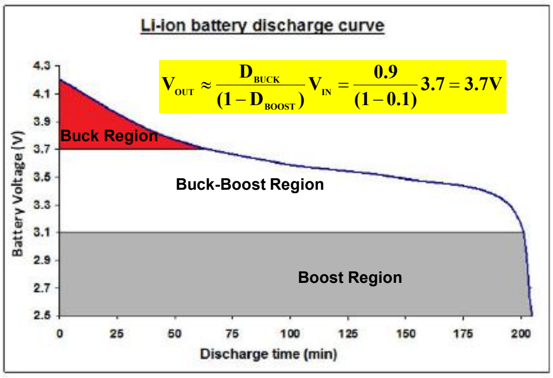




- D_{BUCK} controls buck switches
- D_{BOOST} controls boost switches

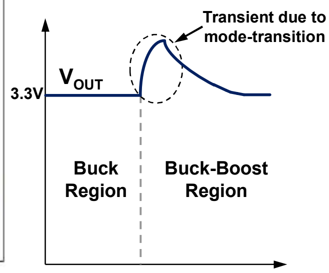
$$V_{OUT} \approx \frac{D_{BUCK}}{(1-D_{BOOST})} V_{IN} \qquad I_L = \frac{I_{LOAD}}{1-D_{BOOST}}$$

Issue with Tri-Mode Buck-Boost



$\text{Buck Mode}: D_{BOOST} = 0$

$\text{Boost Mode}: D_{BUCK} = 1$



- Mode transition causes large voltage transient
- Boundary condition must be satisfied
  - Varies with load current and losses

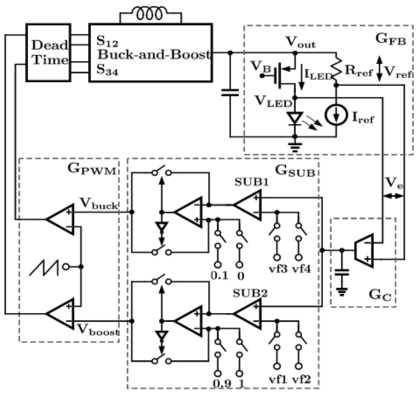
Boundary Condition

$V_{OUT}(\text{buck}) = V_{OUT}(\text{buck-boost})$

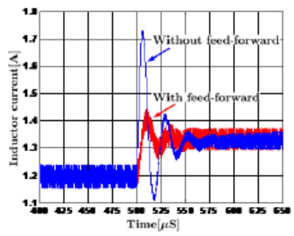
$\rightarrow D_{BUCK\_max} = \frac{D_{BUCK}}{1-D_{BOOST\_min}}$

$\rightarrow D_{BUCK} = D_{BUCK\_max} \cdot (1-D_{BOOST\_min})$

Solution for Mode Transitions



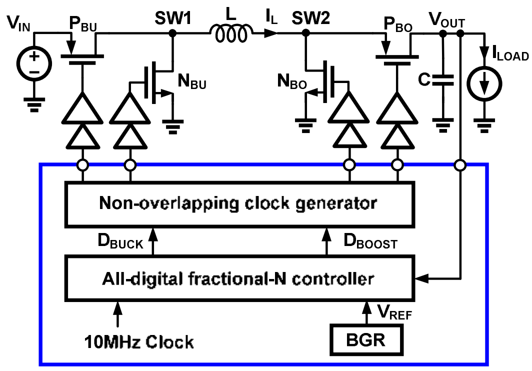
- Appropriate Feed-forward voltage vf1 - 4 is subtracted to instantaneously change the duty cycles during mode transition.
- Analog Implementation makes is susceptible to PVT and requires external compensation capacitor



S. Bang, D. Swank, A. Rao, W. McIntyre, Q. Khan and P. K. Hanumolu, A 1.2A 2MHz tri-mode Buck-Boost LED driver with feed-forward duty cycle correction, *2010 IEEE Custom Integrated Circuits Conference (CICC)*, pp. 1-4, Sept. 2010.

Digitally Controlled Buck-Boost

- Uses constant ON/OFF technique
- Enables High Switching Frequency Operation
- All digital implementation eliminates the need of external compensation capacitor



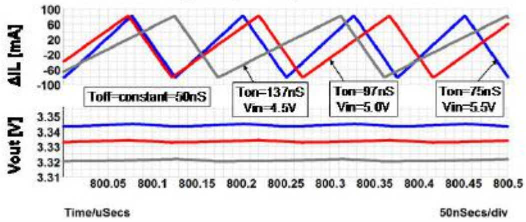
Q. Khan, S. Rao, D. Swank, A. Rao, W. McIntyre, S. Bang, P.K. Hanumolu, "A 3.3V 500mA Digital Buck-Boost Converter with 92% Peak Efficiency Using Constant ON/OFF Time Delta-Sigma Fractional-N Control," *37th European Solid-State Circuits Conference (ESSCIRC)*, 12-16 Sept. 2011, Helsinki, Finland.

Constant ON/OFF Time Operation

$$\text{Inductor ripple current, } \Delta I_L = \frac{V_{IN} - V_{OUT}}{L} T_{ON} \qquad (1)$$

$$T_{ON} = D \cdot T \qquad T_{OFF} = (1 - D) \cdot T$$

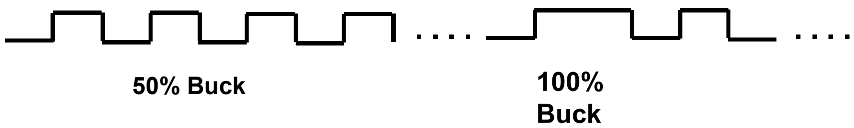
- Max ripple occurs at D=0.5 (Ton = Toff)
  - The converter can be operated at high switching frequency when D=0.5
- From eq. 1, D increases with Vin
  - Fixing OFF time and making ON time function of Vin does not affect the inductor ripple
  - Causes variable switching frequency



Fractional-N Control

Buck Mode:

N cycles of 50% Buck : 1 cycle of 100% Buck

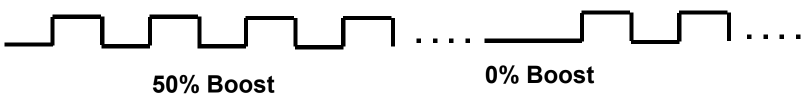


Buck-Boost Mode:

1 cycle of 50% Buck : 1 cycle of 50% Boost

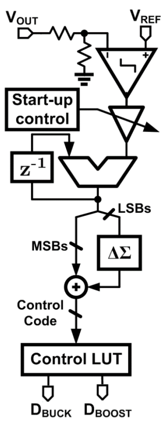
Boost Mode:

N cycle of 50% Boost : 1 cycle of 0% Boost



Fractional-N Control Logic

- **Predefined states are stored in the lookup table providing the coarse voltages**
- **Uses 18-bit acc for integrating the error (4 MSBs, 7 LSBs, 7 dropped bits.**
- **Any intermediate states are resolved by ΔΣ Modulator**



	Operating States	Control Code	Fraction N:1
			50%Buck:100%Buck
Buck Mode	ST1	0001	5:1
	ST2	0010	4:1
	ST3	0011	3:1
	ST4	0100	2:1
	ST5	0101	1:1
			50%Buck:50%Boost
Buck-Boost Mode	ST6	0110	1:1
			50%Boost:0%Boost
Boost Mode	ST7	0111	1:1
	ST8	1000	2:1
	ST9	1001	3:1
	ST10	1010	4:1
	ST11	1011	5:1

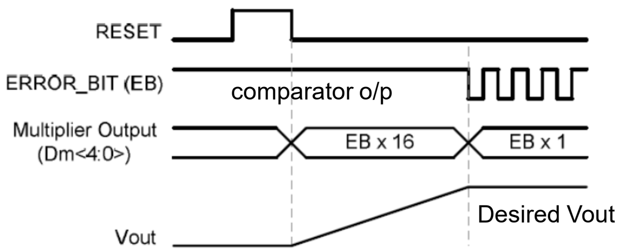
5.5V — Decreasing V_{IN} — **2.7V**

Start-up Control

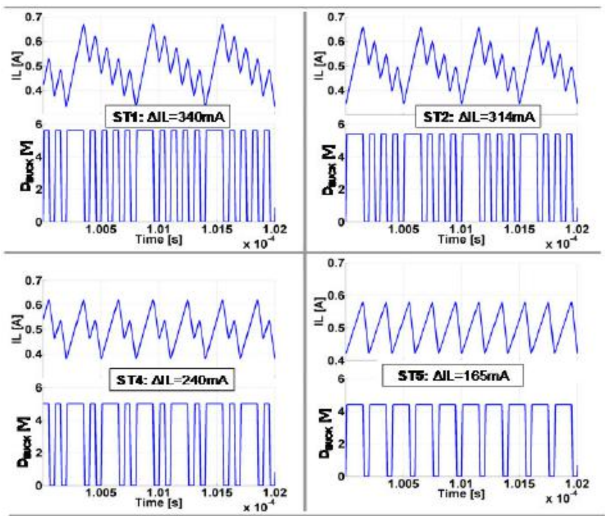
- **Startup time is the function of no. of bits dropped in the accumulator and converter resolution**

- **No. of ACC bits dropped = 7**
  → The startup time may be more than 10ms

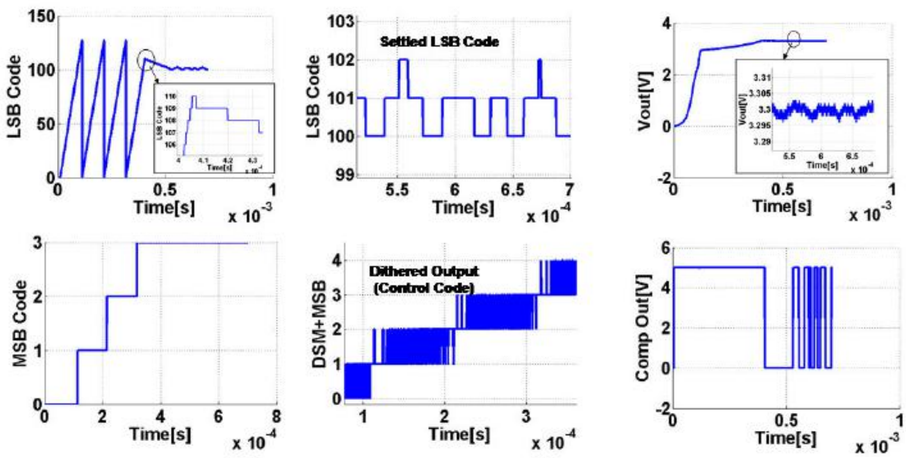
- **Speeded up by dropping only 3 bits in accumulator and switch to 7 bits once the output settles**



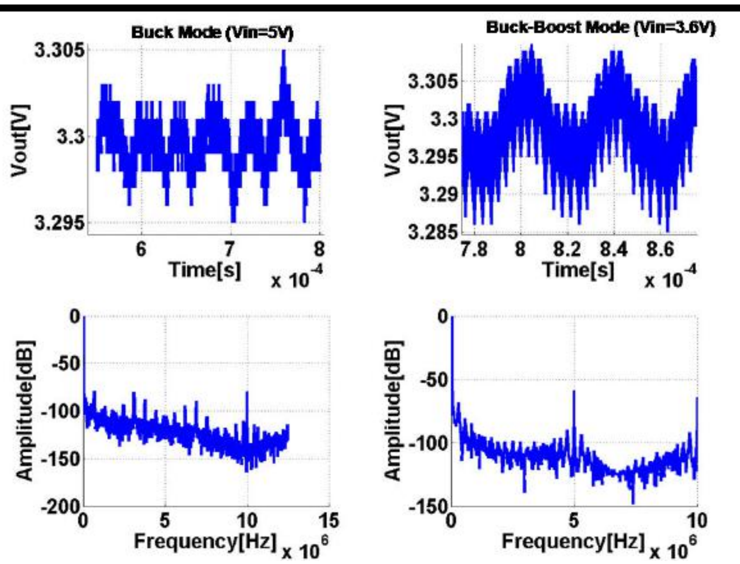
Inductor Current Profile



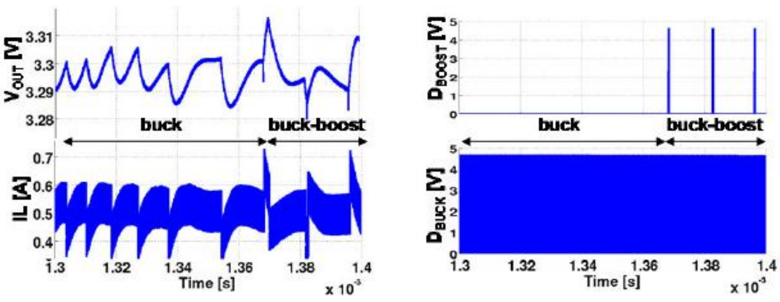
Controller Response



Output Voltage Ripple

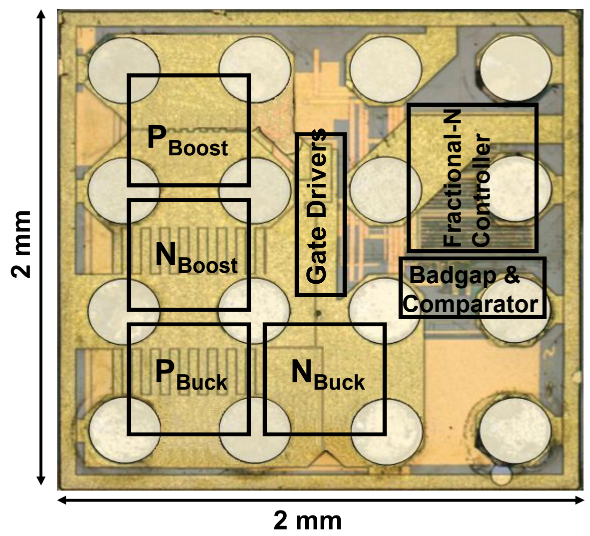


Mode Transition



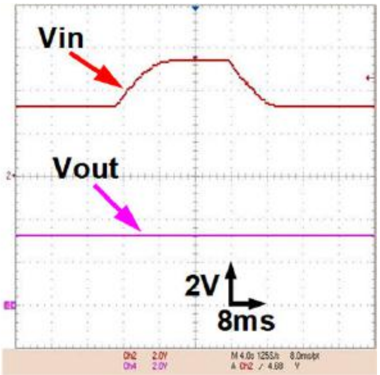
Performance Table and Die Photo

Technology	0.5um CMOS
L	1uH
C	10uF
ESR in C	10mΩ
ESR in L	50mΩ - 100mΩ
Vout	3.3V
Vin	3.3V to 5.5V
Load Current	500mA
Efficiency	85% - 92%
Area Digital Total	 0.24 mm² 4 mm²
Power FETs	On-chip

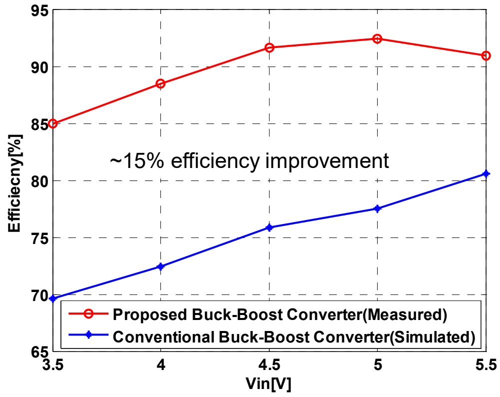


Measurement Results

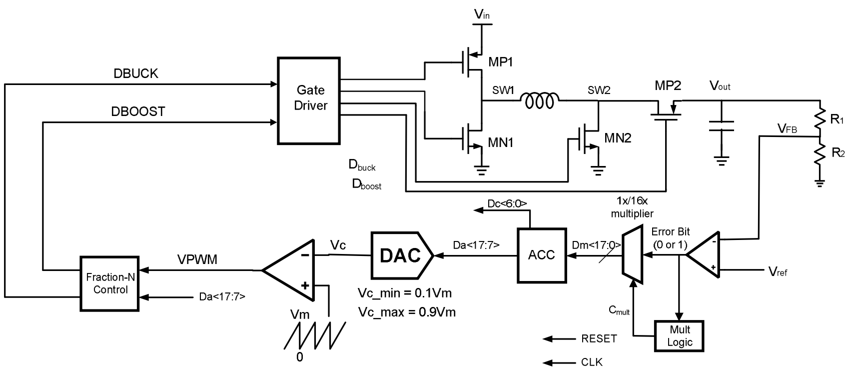
Vin & Vout



Efficiency



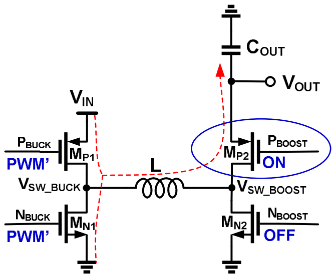
Hybrid Analog-Digital PWM Fractional-N Control

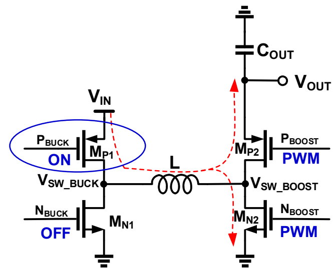


Buck Mode	Buck-Boost Mode	Boost Mode
DBOOST = 1 DBUCK = VPWM	90%Buck:100%Buck 90%Buck:10%Boost 10%Boost:0%Boost	DBOOST = VPWM DBUCK = 1

Losses in Tri-Mode Buck-Boost

- Buck Mode with equivalent loss model
  - Additional conduction loss due to M_{P2}
- Boost Mode with equivalent loss model
  - Additional loss due to M_{P1}
  - Loss increases due to boosted current Iout/(1-D)





Losses in Tri-Mode Buck-Boost

- Buck Mode with equivalent loss model
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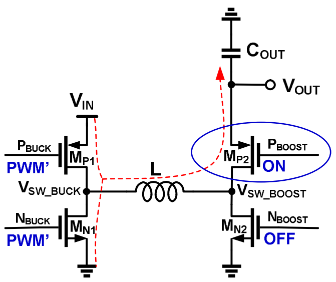
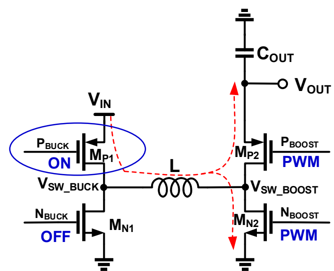
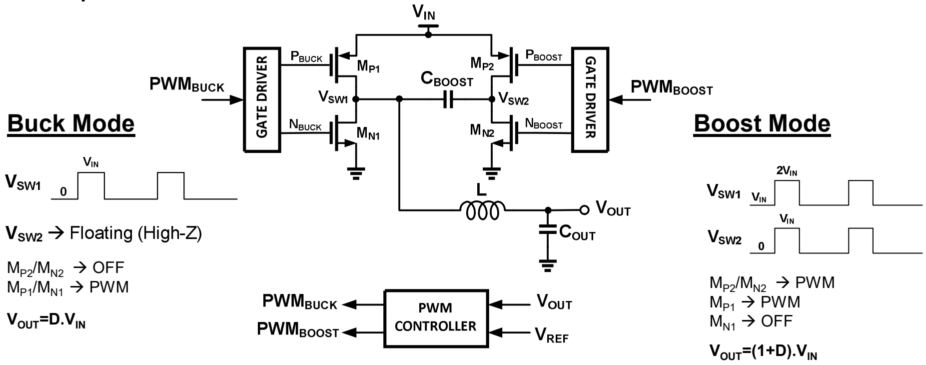




Can we improve?

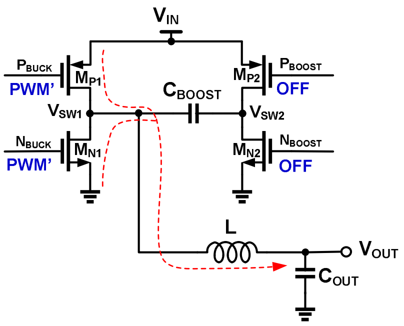
Hybrid Buck-Boost

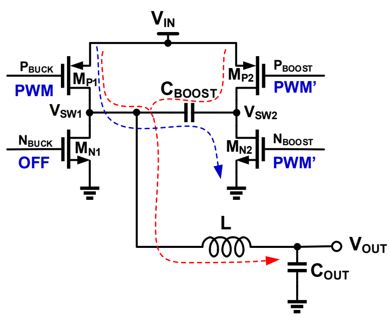
- Uses Hybrid Switched Capacitor and Inductor where Capacitive stage is used to boost the voltage at 2x and Inductive stage is used for regulation
- Since Switched Capacitor is isolated from Inductor current path, it incurs less conduction losses
- Inductive buck stage has no right half plane zero hence provides better transient response



Hybrid Buck-Boost(Contd.)

- Buck Mode with equitant loss model
  - No additional conduction loss due to MP2
- Boost Mode with equivalent loss model
  - Reduces loss as inductor current remains same as load current





Conventional Vs. Hybrid BB (Buck Mode)

Conventional

- **Additional conduction loss due to MP2**
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100\text{m}\Omega$, $I_{OUT} = 1\text{A}$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DS\_ON2} + R_{DCR})$

  = 300mW

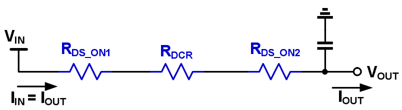
Hybrid

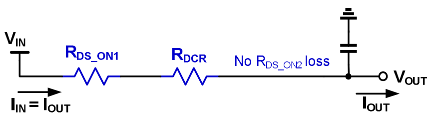
- **No additional conduction loss due to MP2**
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100\text{m}\Omega$, $I_{OUT} = 1\text{A}$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DCR})$

  = 200mW → 100mW saving in loss





Conventional Vs. Hybrid BB (Boost Mode)

Conventional

- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100\text{m}\Omega$, $I_{OUT} = 1\text{A}$. $V_{OUT} = 1.5\text{x}V_{IN}$

  Total conduction loss will be:

  $P_{LOSS} = \{I_{OUT}/(1\text{-}D)\}^2(R_{DS\_ON1} + R_{DS\_ON2} + R_{DCR})$

  = 675mW

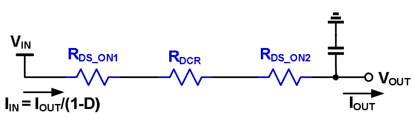
Hybrid

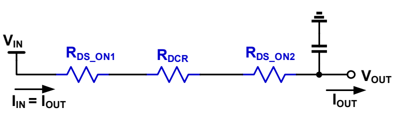
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100\text{m}\Omega$, $I_{OUT} = 1\text{A}$, $V_{OUT} = 1.5\text{x}V_{IN}$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DCR} + R_{DS\_ON2})$

  = 300mW → 375mW saving in loss



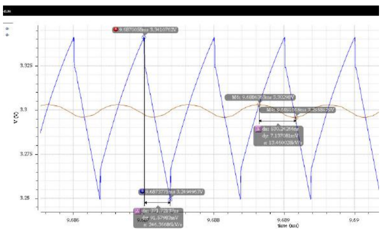


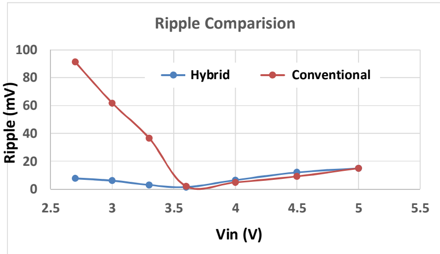
Simulation Results – Ripple Comparison

Boost Mode
Vin = 2.7V, Vout = 3.3V, Iout=1A
Fsw = 1MHz, L = 2.2uH, Cout = 4.7uF

Hybrid→ 7mV Vs. Conventional → 91mV

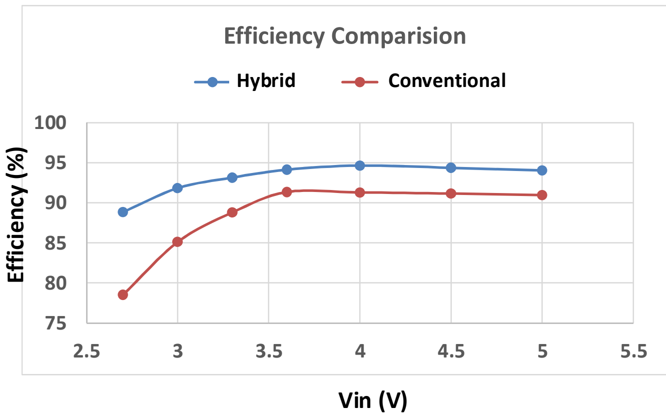
More than 10x reduction in output ripple voltage → Highly suitable for noise sensitive applications





Efficiency Comparison

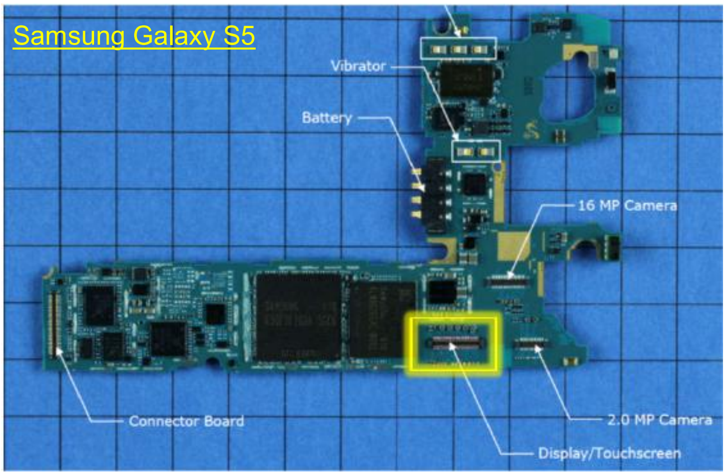
- **Hybrid solution provides ~10% improvement in efficiency in Boost mode and ~3% improvement in Buck mode**



Board Level Design Guidelines

Placement of Display Supply Driver

PCB top view

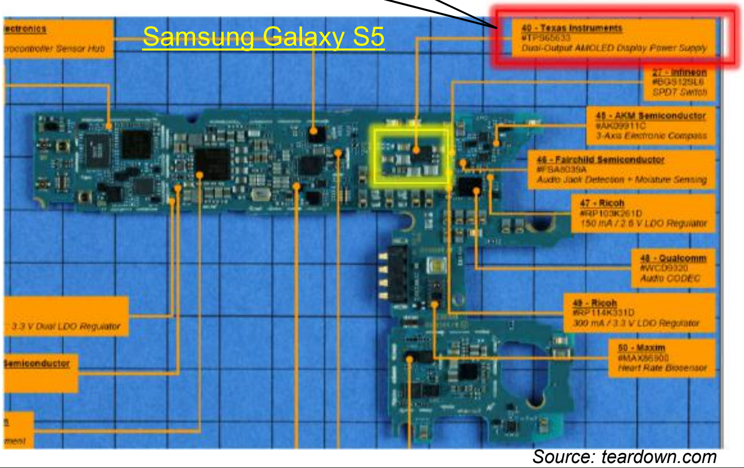


Source: teardown.com

Placement of Display Supply Driver

TI's TPS65633 AMOLED Supply placed right under the display connector

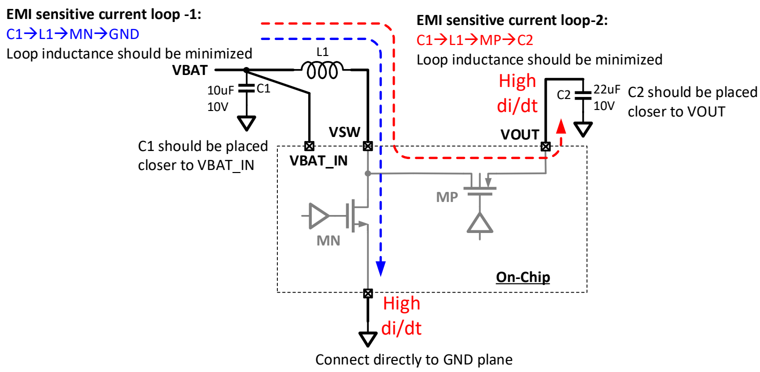
PCB bottom view



Source: teardown.com

EMI Guidelines

- **Parasitic Inductance of all traces carrying high switching current (high di/dt) should be minimized**
- **Capacitors on all voltage switching pins (high dv/dt) should placed closer to the pin**



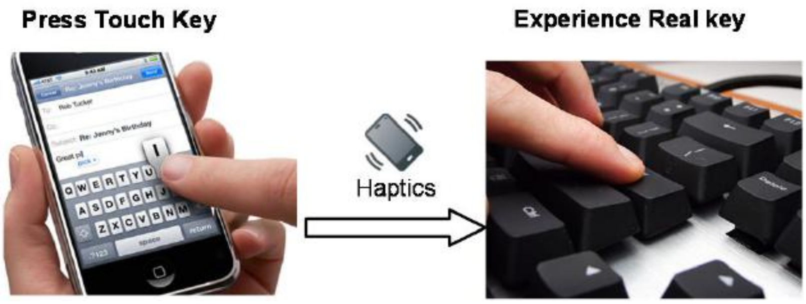
Summary

- Power management techniques for LCD and AMOLED panels were presented
- System level techniques such as RGBW and CABC offer significant power savings
- Hybrid dimming of backlight can be used to reduce the risk of flicker due to noise
- Hybrid Buck-Boost converter for AMOLED positive supply offers better performance compared to conventional boost or buck-boost
- Proper placement of power supply driver and passive components mitigates the effect of EMI

Haptic Driver for Mobile Application

What is Haptics?

- *Haptic* is a sense of touch which provides a feedback through vibration to simulate an event or action.
- Gives user a more enhanced computing experience by simulating 3 dimensional effect on touch screen



Haptic Applications – Medical

- Robotic surgery for remotely located patients
- Surgical training

Haptic Applications – Gaming Consoles

- **Enhanced gaming experience**

Haptic Applications – Automotive

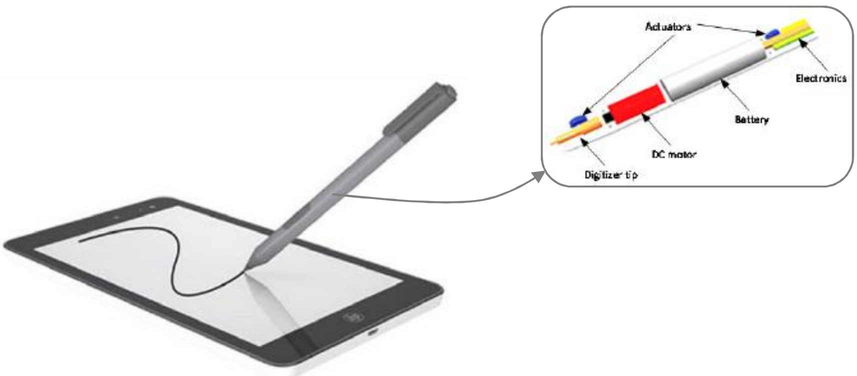
- **Safety alters and dashboard control for ADAS**

Haptic Applications – Tablets and PCs

- Touchscreens
- Touchpads and keyboards

Haptic Applications – Stylus

- Vibration is created to provide the feeling of writing on a real paper



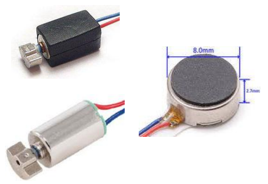
Haptic Applications – Smartphones and Wearables

- Touchscreens
- Touchpads
- Vibration Alerts

Types of Haptic Actuators

- Three most commonly used actuators for haptic

ERM – Eccentric Rotating Mass

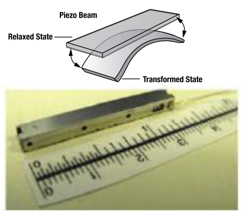


Brushed or brushless DC motor
Comes in various shapes
Operating voltage: up to 1V-3.6V
Slow response time : 50m-100ms
Variable vibration frequency: 1-300 Hz
Drive Signal : DC

LRA – Linear Resonant Actuator

Resonant vibrator
Rectangular and circular shapes
Operating voltage : 2Vrms
Faster response time : 20-30ms
Fixed vibration frequency: 150-200 Hz
Drive Signal : AC

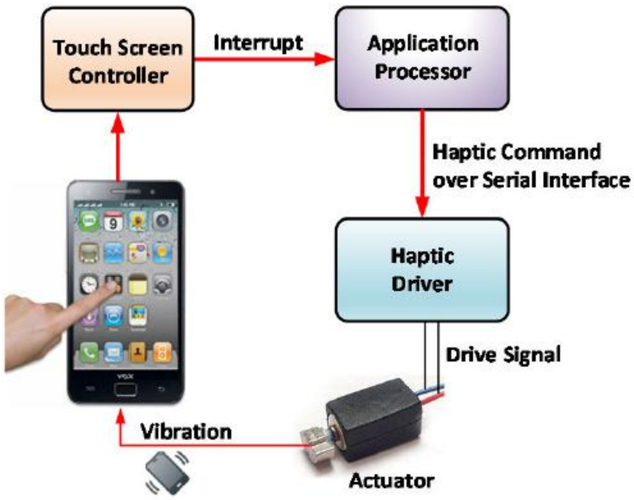
Piezo



Piezo beam
Rectangular shape, large size
Operating voltage : 50-200V
Fastest response time : < 1ms
Fixed vibration frequency: 150-200 Hz
Mostly used in tablets and not suitable for mobiles phones due to large for factor

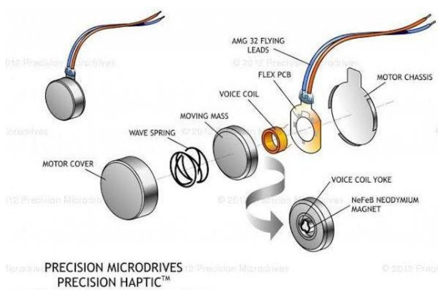
Sources: Texas Instruments, Precision Microdrives, EEtimes

How Haptic System Works

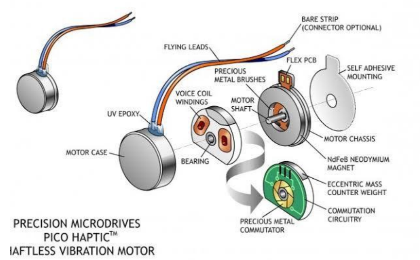


Inside ERM and LRA

LRA



ERM

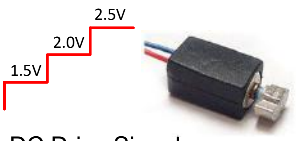


Sources: Precision Microdrives

Driving ERM and LRA

ERM (Eccentric Rotating Mass)

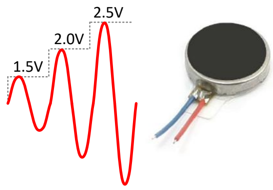
- Based on dc motor with off centered mass
- Uses DC voltage drive
- Operating voltage up to 3.6V dc
- Vibration strength is proportional to dc voltage
- Slow start/stop (50ms-100ms)
- Overdrive is used to start faster and reverse braking is used to stop it faster



DC Drive Signal

LRA (Linear Resonant Actuator

- Based on fixed voice coil and moving magnet
- Uses AC drive signal and operate at fixed resonance frequency (~200Hz).
- Operating voltage up to 2.0V rms
- Vibration strength is proportional to AC signal amplitude
- Fast start (15-20ms) but slow stop (~100-200ms) due to spring action
- Reverse braking is used to stop it faster



AC Drive Signal

ERM consumes ~2x more power compared to LRA

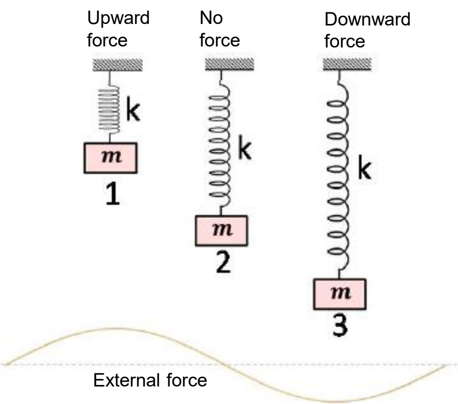
How Does It Work

- A hanging spring with one end fixed and other end attached to a moving mass will resonate if an external force is applied.
- The resonance frequency is given by:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

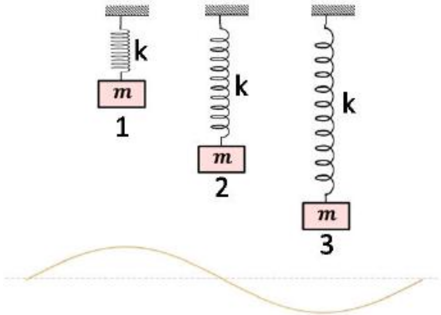
Where k=spring constant, m=mass

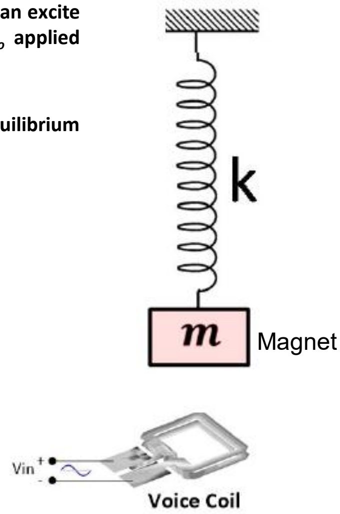
- Since spring is a high-Q resonant system, it generates maximum force when driven at it's natural frequency, f_o.
- A driving force with frequency ≠ f_o will tend to oppose the reactive force generated by spring due to phase shift and reduces the vibration amplitude.



Generating External Force

- If the moving mass is replaced with a magnet then a voice coil, which acts as electromagnet, placed close the magnet can excite the spring if an electrical AC signal with frequency=f_o applied across the voice coil.
- Mass of the magnet is selected such that spring is in equilibrium when no electrical signal is applied across the voice coil.

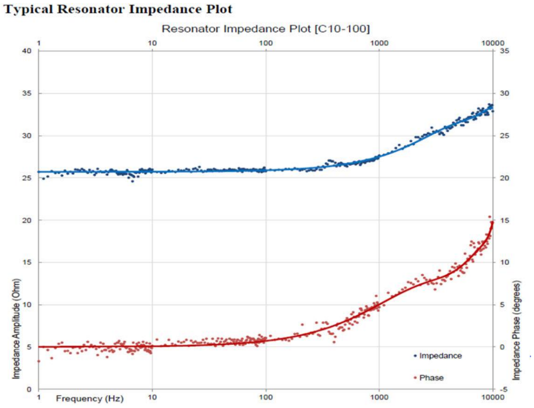




LRA Electrical Model

- LRA manufactures datasheet usually show input impedance plot which doesn't model the resonance
- Since electrical coupling of LRA is through voice coil which has only R and L so it's only a LPF

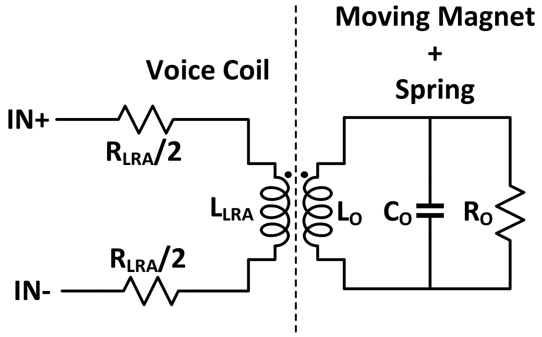
Typical Resonator Impedance Plot



Sources: Precision Microdrives

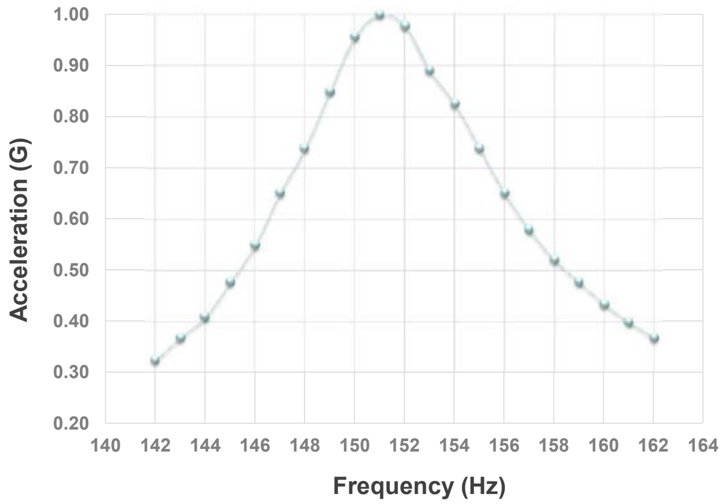
Improved Electrical Model of LRA

- There is only magnetic between voice coil and resonating spring.
- The electrical model can be approximated as series L-R (voice coil) with magnetically coupled LC tank (spring + magnet).



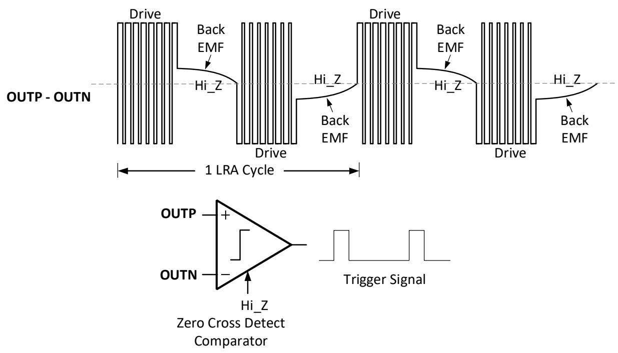
Q. Khan et al, Circuits and Methods for Driving Resonant Actuators, US 9,344,022 B2, May 17, 2016.

Frequency Response of LRA



Detecting LRA Resonance Frequency using Back EMF

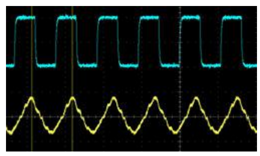
- LRA is driven for partial cycle and left in high-z mode to read the back EMF
- During high-z phase, ZXD comparator generates next trigger edge when back EMF at OUTP and OUTN cross



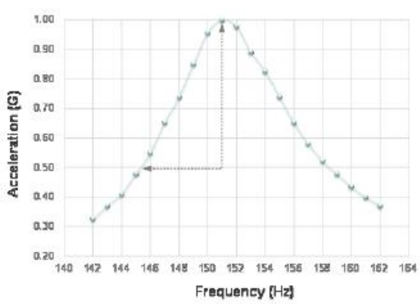
Q. Khan et al, Circuits and Methods for Driving Resonant Actuators, US 9,344,022 B2, May 17, 2016.

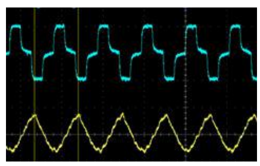
Auto Resonance for LRA

- LRA is a high Q system, a small drift in the resonance frequency may cause significant drop in the vibration strength.
- Auto resonance detection to correct any drifts in the frequency and ensures optimum driver strength across varying operating conditions.



Without Auto resonance
Power consumption = 200mW/g

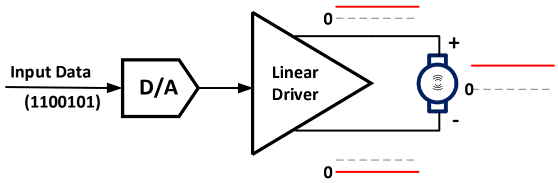




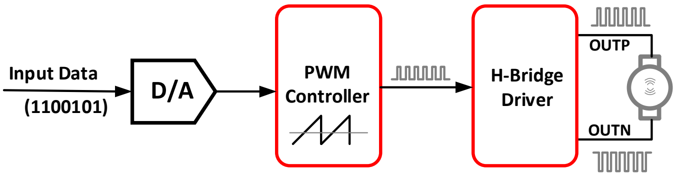
Without Auto resonance
Power consumption = 100mW/g

Drive Methods

- Fully differential driver is used to support both DC (for ERM) and AC (for LRA) as well as active braking (reverse drive)



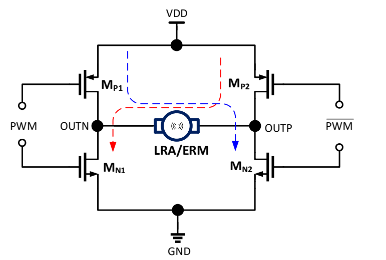
Linear Drive

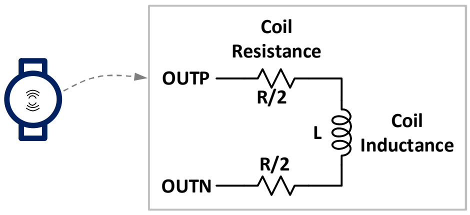


PWM Drive

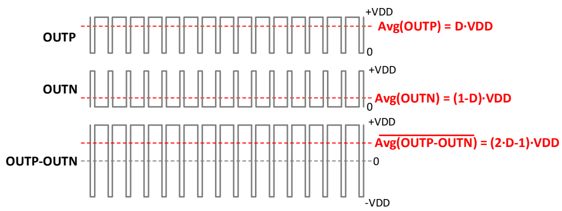
Differential PWM Drive

- H-Bridge driver is used
- High value of actuator inductance (100uH-1mH) converts





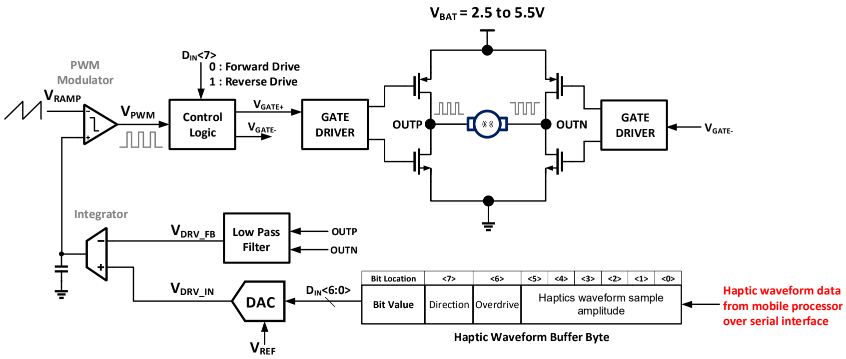
Actuator model



D > 0.5 : Positive or Forward Drive
D = 0.5 : No Drive
D < 0.5 : Negative or Reverse Drive

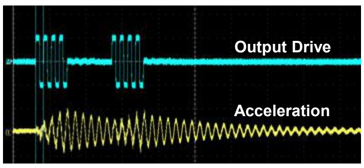
Closed Loop Control

- Closed loop control is needed to compensate for variation in input supply voltage (V_{BAT}) and IR drop across MOSFET switches

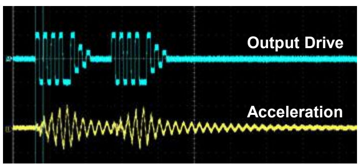


Active Braking

- Since LRAs can't stop quickly due to resonance, users can hardly differentiate between quick key press
- Driving LRA in reverse direction (active braking) helps in stopping it faster



Without Active Braking



With Active Braking

Types of Patterns

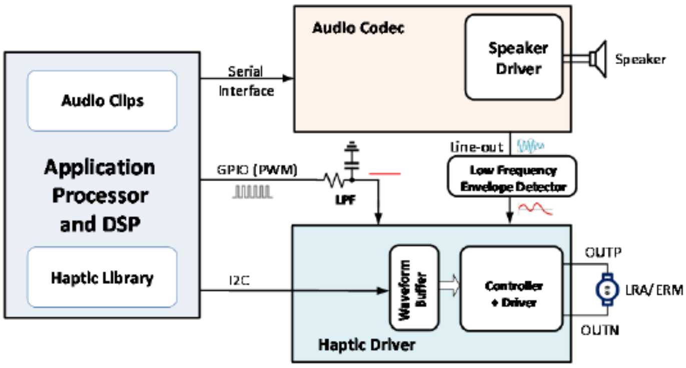
- Short Patterns
  - Used in typing for generating press/bump
  - Message alert
- Long Patterns
  - Scrolling
  - Call alerts
- Complex Patterns
  - Typing with synchronized press/bump and click sound
  - Synchronized ringtone with vibration
  - Setting different vibration patterns for different callers
  - Full audio-visual gaming with haptics added as another dimension

Haptics-Audio Interfacing

- Can play the sound pattern through haptics for enhanced gaming and computing experience
- Ringtones or audio clips can be used as vibration pattern in silent mode

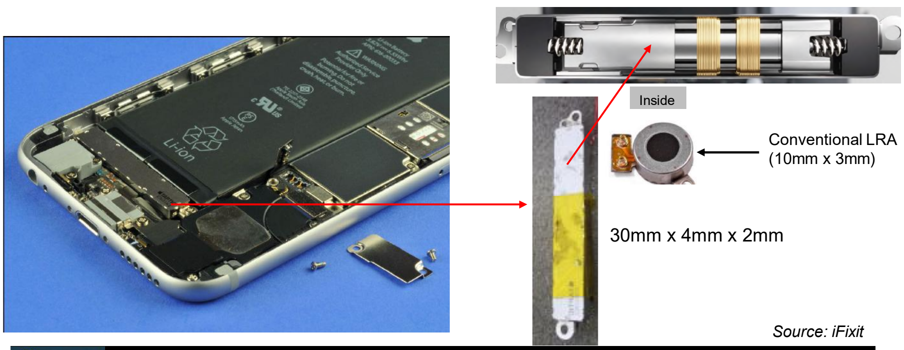
Playing Waveforms

- Haptic waveforms can be played from three sources
  - Serial interface by buffering the data in waveform buffer
  - External PWM sent over general purpose IO (GPIO)
  - Audio Line-out from codec



Iphone Haptics Module

- The Haptics driver inside iphone 6S is called Taptic engine, integrated with TS module
- Larger in size (comparable to piezo) and supports much higher voltage (10-12V)
- Lower Q so doesn't require auto resonance detection



Source: iFixit

Thank You

Power Management for Mobile Application

Power Management and Control Techniques for Smartphone Display and Haptic Technology

Qadeer A. Khan

Integrated Circuits and Systems Group
Department of Electrical Engineering
Indian Institute of Technology Madras, Chennai

The 33rd International Conference on VLSI Design (VLSID 2020) and The 19th International Conference on Embedded Systems (ES 2020)

Outline

- Introduction to Research in Power Management at IIT Madras
- Introduction to Power Management and DC-DC Converters
- Power Management in a Smartphone
- Power Management for Display
- Mobile Display Technologies
- Power Management for LCD
- Power Management for AMOLED Display
- Board Level Design Guidelines for Display PMIC
- Haptics Driver for Mobile Application

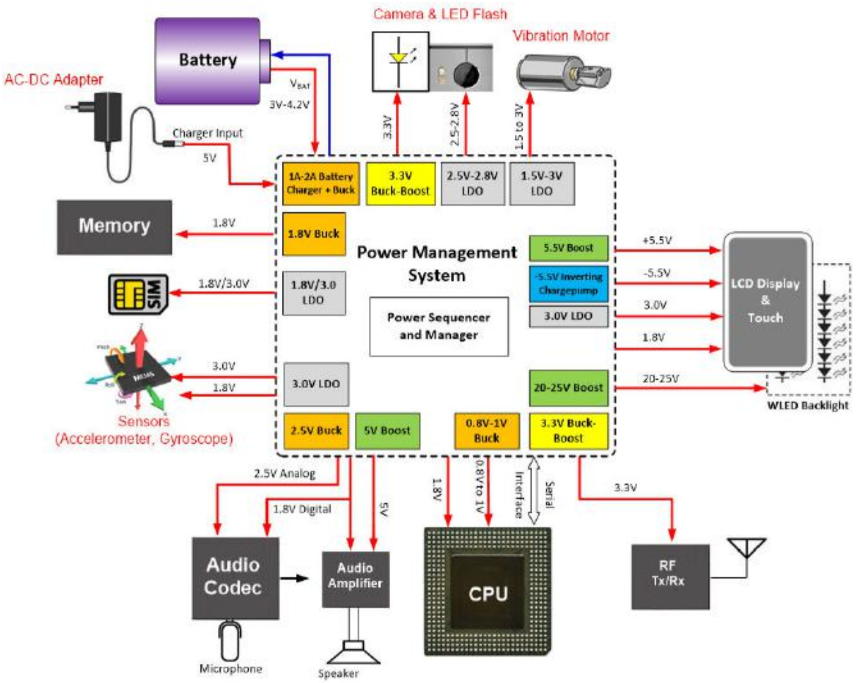
Research in Power Management IC at IITM

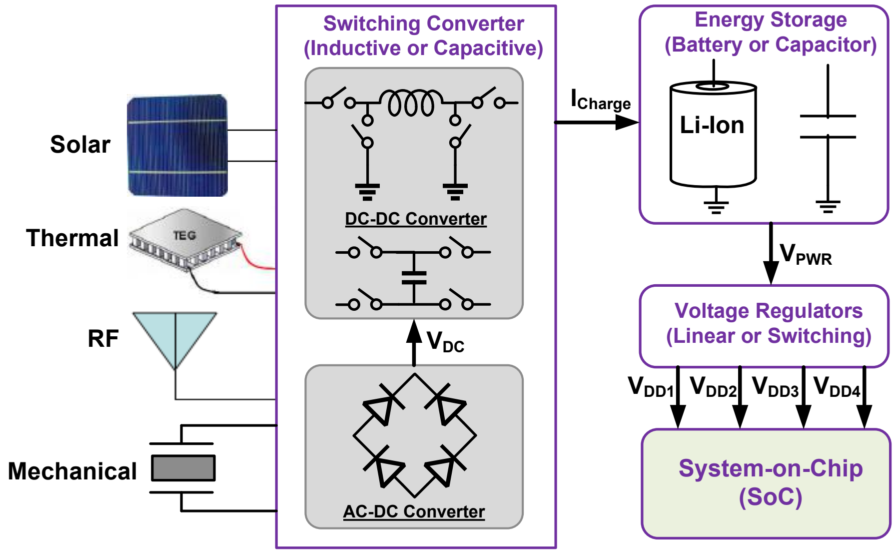
PMIC For Mobile Applications

- Battery Charger and Fuel Gauge
- DC-DC Switching Converters
- Power Management for LED backlight and displays
- Low Drop-Out (LDO) Regulators

PMIC For Energy Harvesting

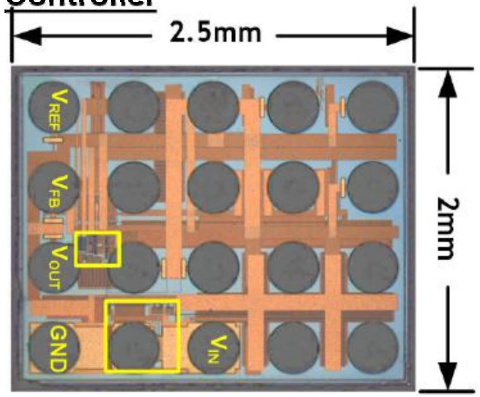
- Energy Harvesting for IoT Application
- Self Powered Devices
- Power Management for Wearables
- Power Management for Biomedical Applications
- Energy Harvesting for Remote Sensing





Previous Works

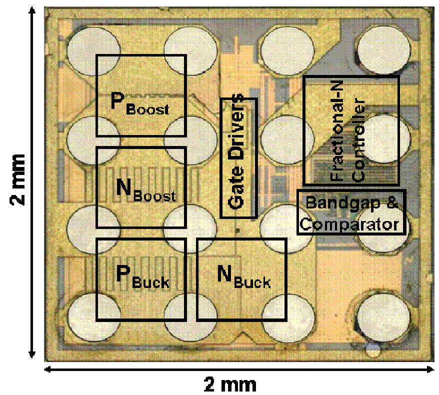
High Frequency DC-DC converter using time-based Controller



- 180nm CMOS
- F_{SW} = 10-25MHz
- 94% Peak Efficiency
- Iq = 20µA @ 10MHz

VLSI Symp., June 2014, Honolulu. and JSSCC

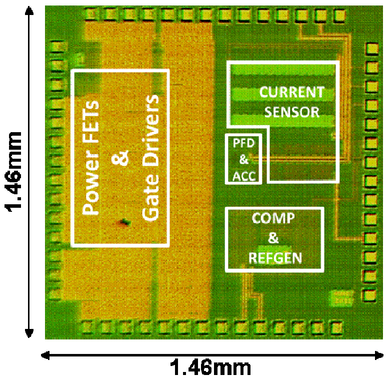
Buck-Boost converter using constant ON/OFF time delta-sigma fractional-N control



- 0.5um CMOS
- F_{SW} = 1-10MHz
- 92% Peak Efficiency

European Solid State Circuits (ESSCIRC), Sept 2011, Finland.

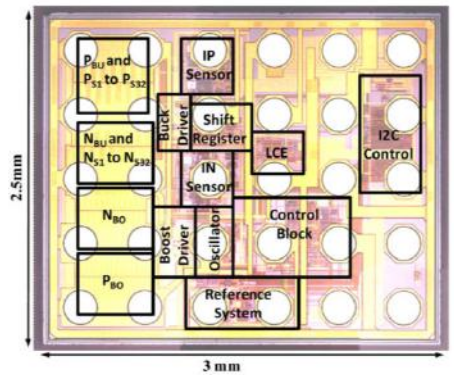
Fixed Frequency Hysteretic Buck Converter



- 130nm CMOS
- F_{SW} = 1MHz
- 93% Peak Efficiency
- Iq = 50µA

VSLI Symp., June 2012, Honolulu.

Buck-Boost LED Driver for Camera Flash



- 0.5um CMOS
- F_{SW} = 2MHz
- 90% Peak Efficiency

International Solid-State Circuits Conference (ISSCC), Feb 2011, San Francisco. and JSSC, Dec 2011.

Recent Work at IITM

Area and Current Efficient Capacitor-Less Low Drop-Out Regulator Using Time-Based Error Amplifier

Proc. Int. Symp. Circuits and Systems, ISCAS, May 2018, Florence, Italy.

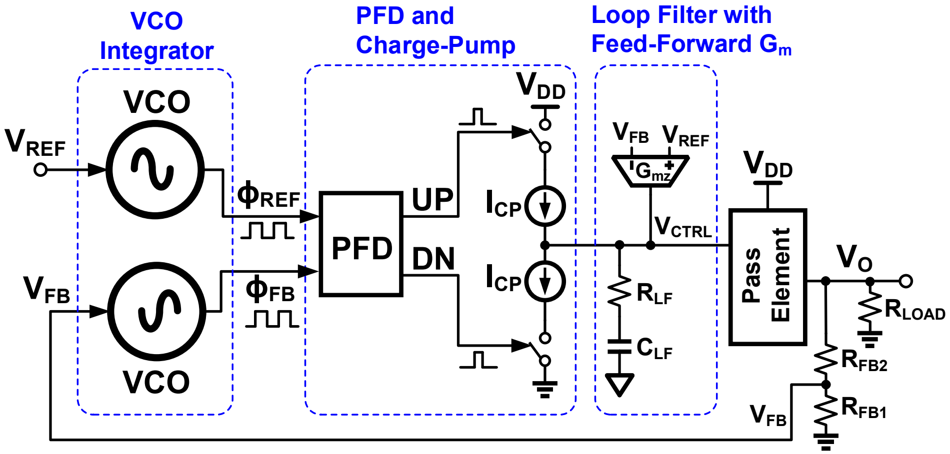


TABLE II. PERFORMANCE TABLE AND COMPARISON

Metrics	This Work	ISCAS'17 [3]	ISCAS'17 [4]	CICC'17 [5]
Technology	**65nm**	180nm	180nm	65nm
Vin/Vout	**1.2/ 0.8-1.1**	1.84/1.8	1.2/1	1.2/1
Overshoot/ Undershoot(mV), ΔV_O (Load:10mA/100ns)	**160/70**	50/40	220/150	46/45
Settling Time (µs)	**0.2**	4.6	3.6	1.2
Current, I_Q (µA)	**27.5**	7	3	300
Bandwidth, f_{UGB} (MHz)	**3**	0.1	0.5	8
Max. Load, $I_{L\,max}$ (mA)	**10**	50	100	25
Compensation/Load Cap (pF), $C_C/C_{L\,max}$	**1.2/100**	10/100	2.5/10	10/240
FOM[1] (ps)	**1.76**	3.89	3.3	7.5

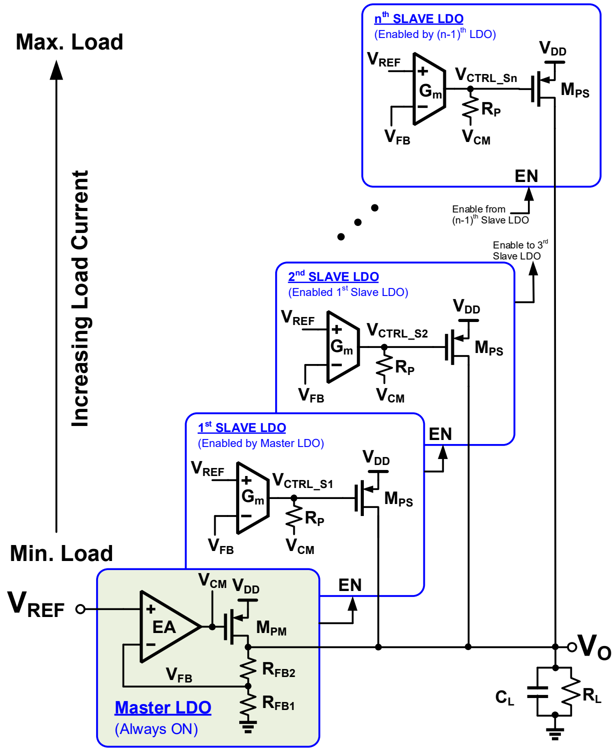
[1]Lower value indicates higher performance.

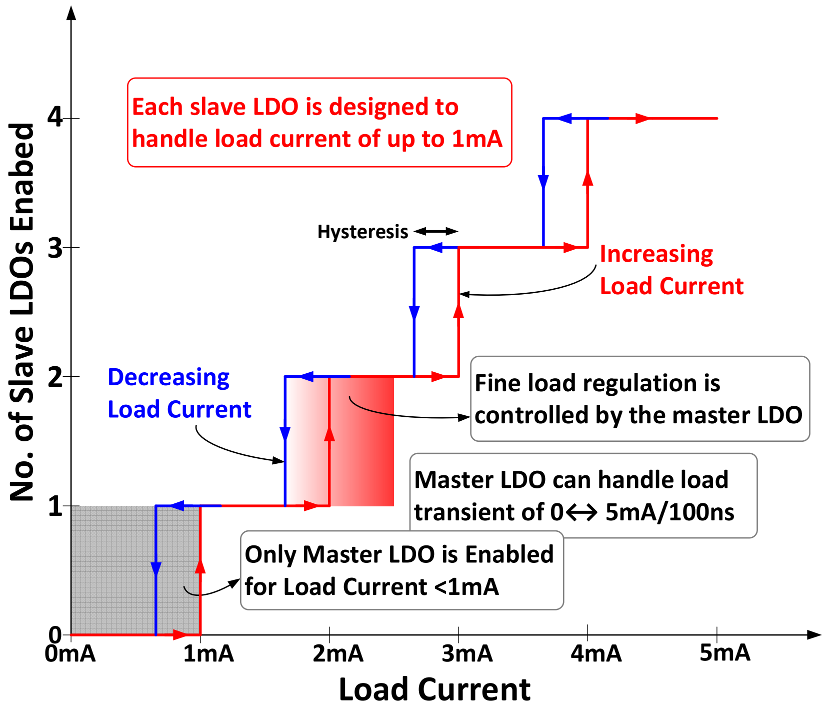
$$FOM = \frac{C_C}{C_{L\,max}} \cdot \frac{\Delta V_O}{V_O} \cdot \frac{I_{Q\,max}}{f_{UGF}} \cdot \frac{1}{I_{L\,max}} \cdot 10^{12}$$

Recent Work at IITM

A Highly Scalable, Time-Based Capless Low-Dropout Regulator Using Master-Slave Domino Control

Proc. Int. Symp. Circuits and Systems, ISCAS, May 2019, Japan.

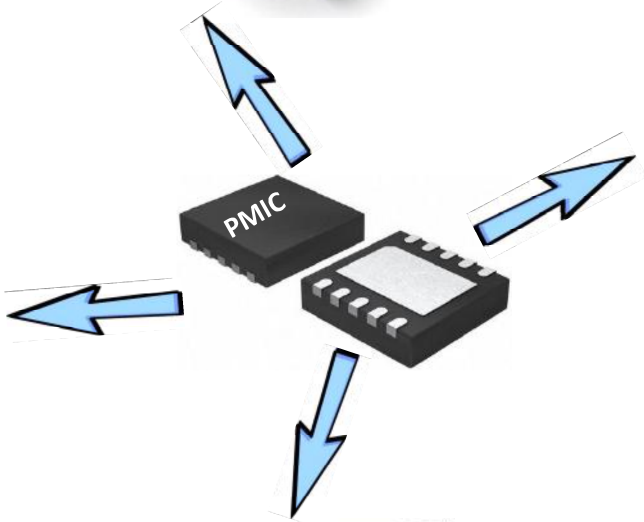




Total I_Q = 11.5uA

Application of Power Management ICs

LED Lightings
- Current Drivers



Cellphones
- Processor
- RF Power Amp
- Battery Charger
- Display Backlighting
- Camera Flash LED
- Battery Management

Wearables
- Ultra Low Power Circuits
- Sensors

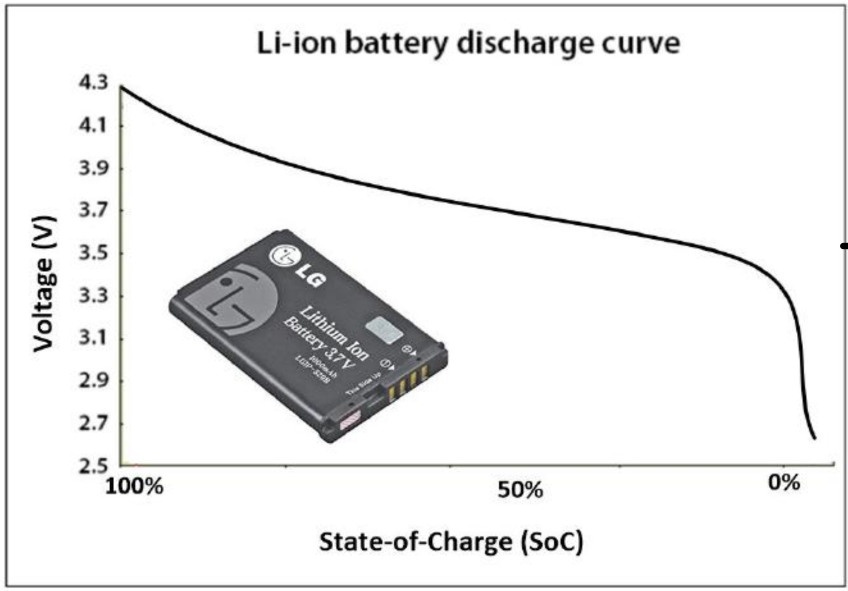
PCs, Laptops
- Processor
- Memories
- Serial Links
- Battery Chargers

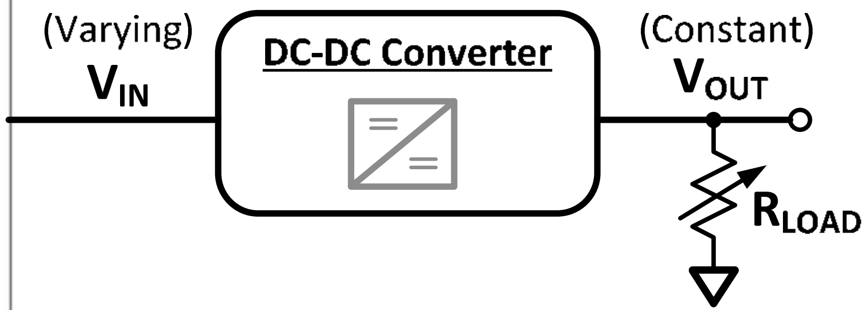
Power delivery for these applications is mostly met by DC-DC Converters

DC-DC Power Converter

- **Converts voltage from one domain to other**

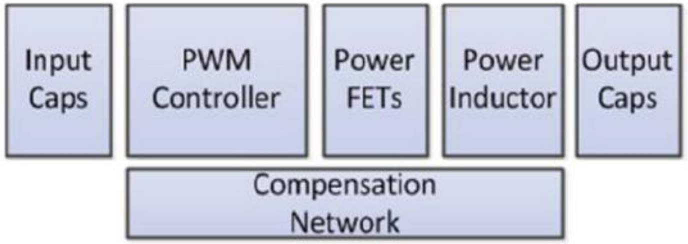
- **Provides regulated output voltage**
  - **Under varying conditions (input voltage, output current)**



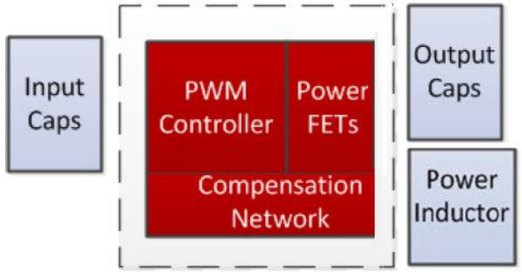


Discrete Vs. Integrated Power Converters

Discrete

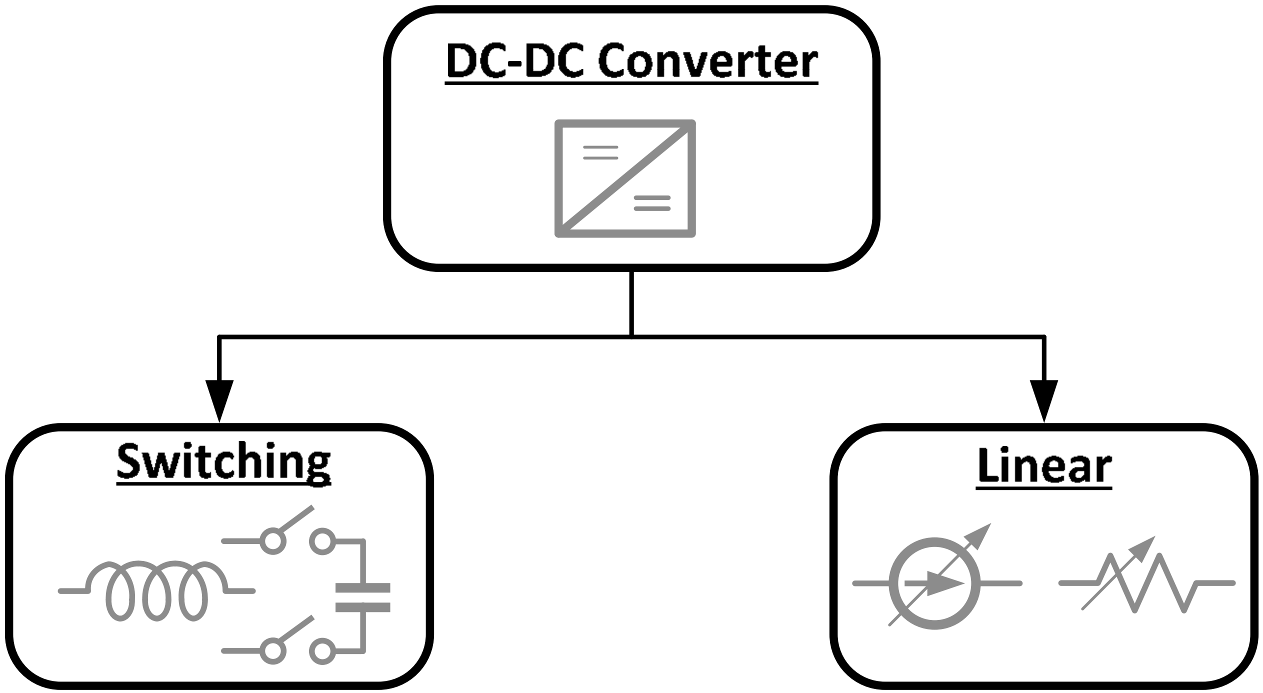


Integrated



VLSI Systems mostly use Integrated DC-DC Converters due to limited board space

DC-DC Converter Types



Inductive or Capacitive

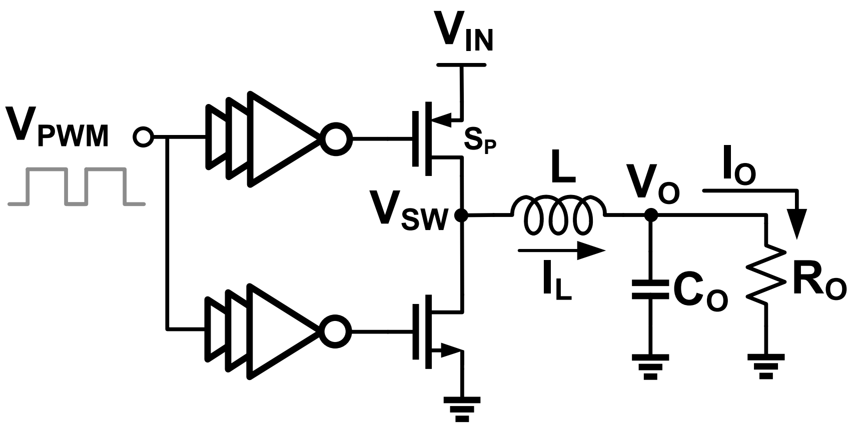
Can generate output voltage less, greater, inverting or equal to input voltage .

Low Drop-Out (LDO) Regulators

Can generate output voltage only less or equal to input voltage.

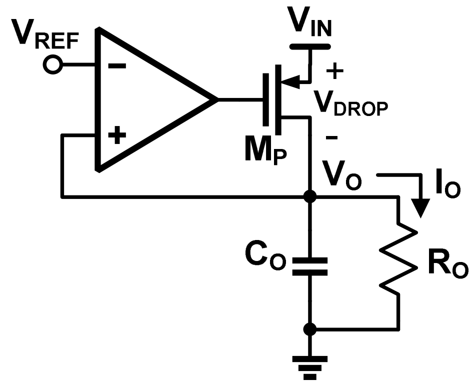
Switching vs Linear Regulator

Switching Regulator



- Regulation achieved by changing on/off time
- Switches are in either linear or cutoff → reduced losses
- High efficiency over wide range of V_O/V_{IN}

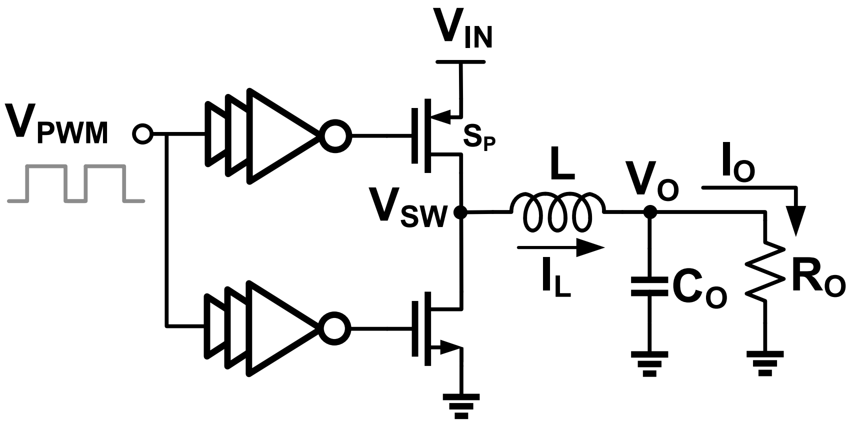
Linear Regulator



- Regulation achieved by dropping voltage
- Switches are in saturation → higher losses
- Poor efficiency when V_O/V_{IN} ratio is low

Switching vs Linear Regulator

Switching Regulator



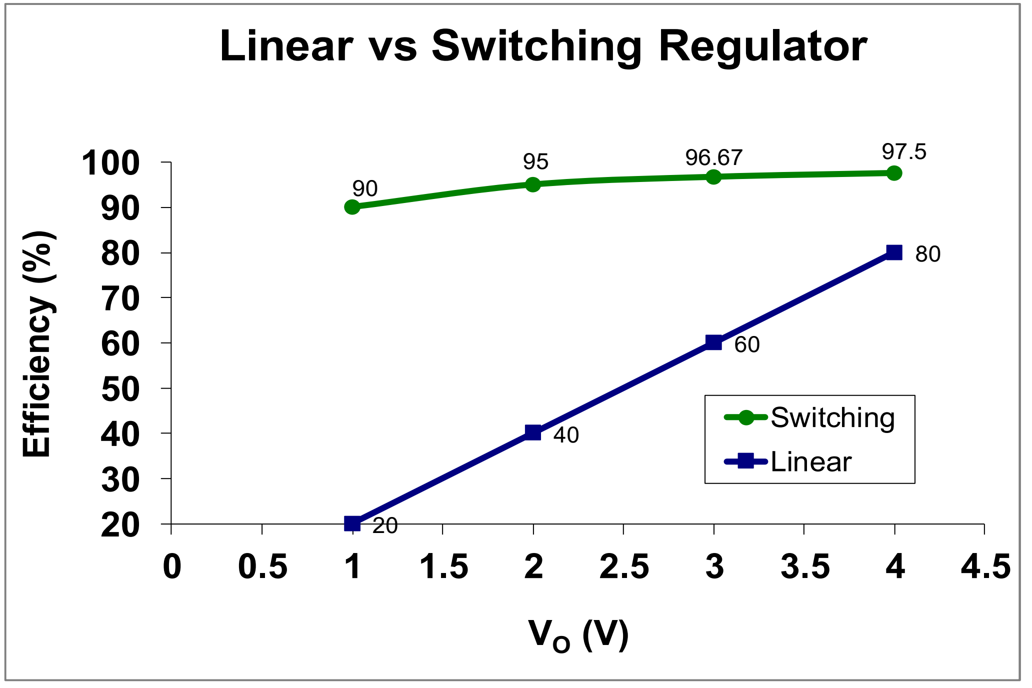
- Regulation achieved by changing on/off time
- Switches are in either linear or cutoff → reduced losses
- High efficiency over wide range of V_O/V_{IN}

More than 90% of power requirement is met by Switching Converters

Switching Vs Linear Regulator

- For Vin = 5V, Vo = 1V and I_{Load} = 1A
  - 80% power loss in the Linear regulator as compared to 10% in switching regulator
- For Vin = 5V, Vo = 4V and I_{Load} = 1A
  - 20% power loss in linear regulator as compared to 2.5% in switching regulator

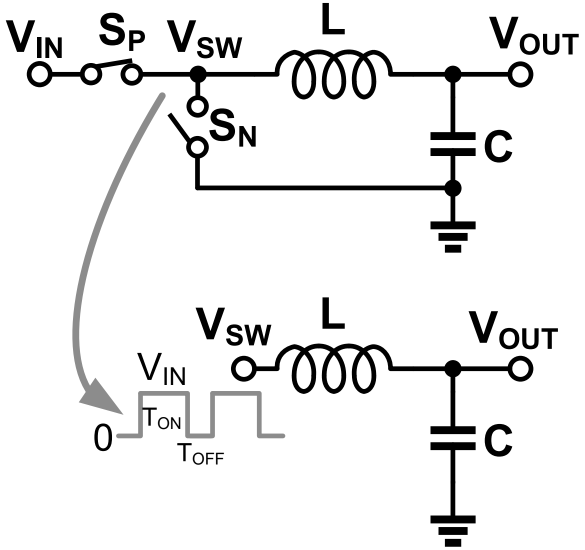
$$Efficiency\,(\eta) = \frac{Output\ Power}{Input\ Power}$$

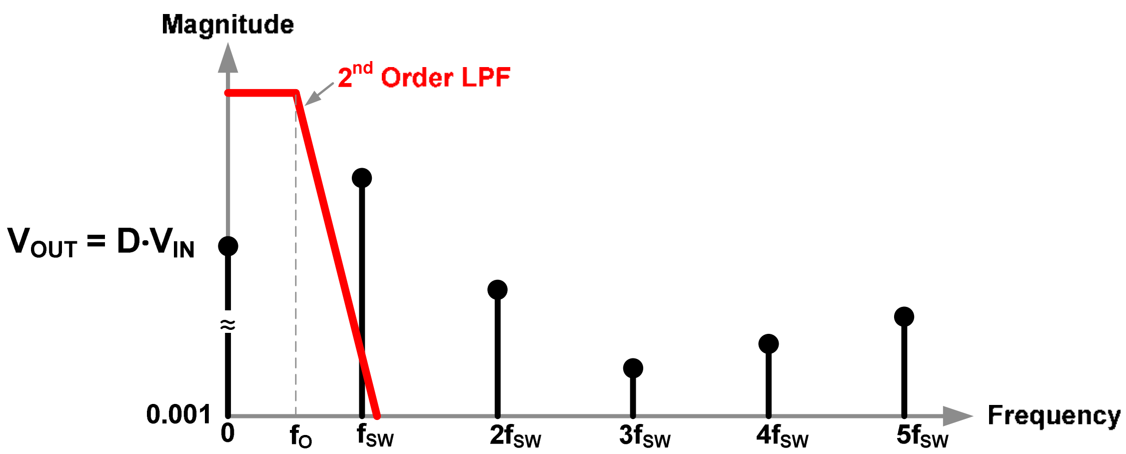


Basic Operation of Switching DC-DC Converter

- DC output voltage generated by filtering pulse width modulated waveform

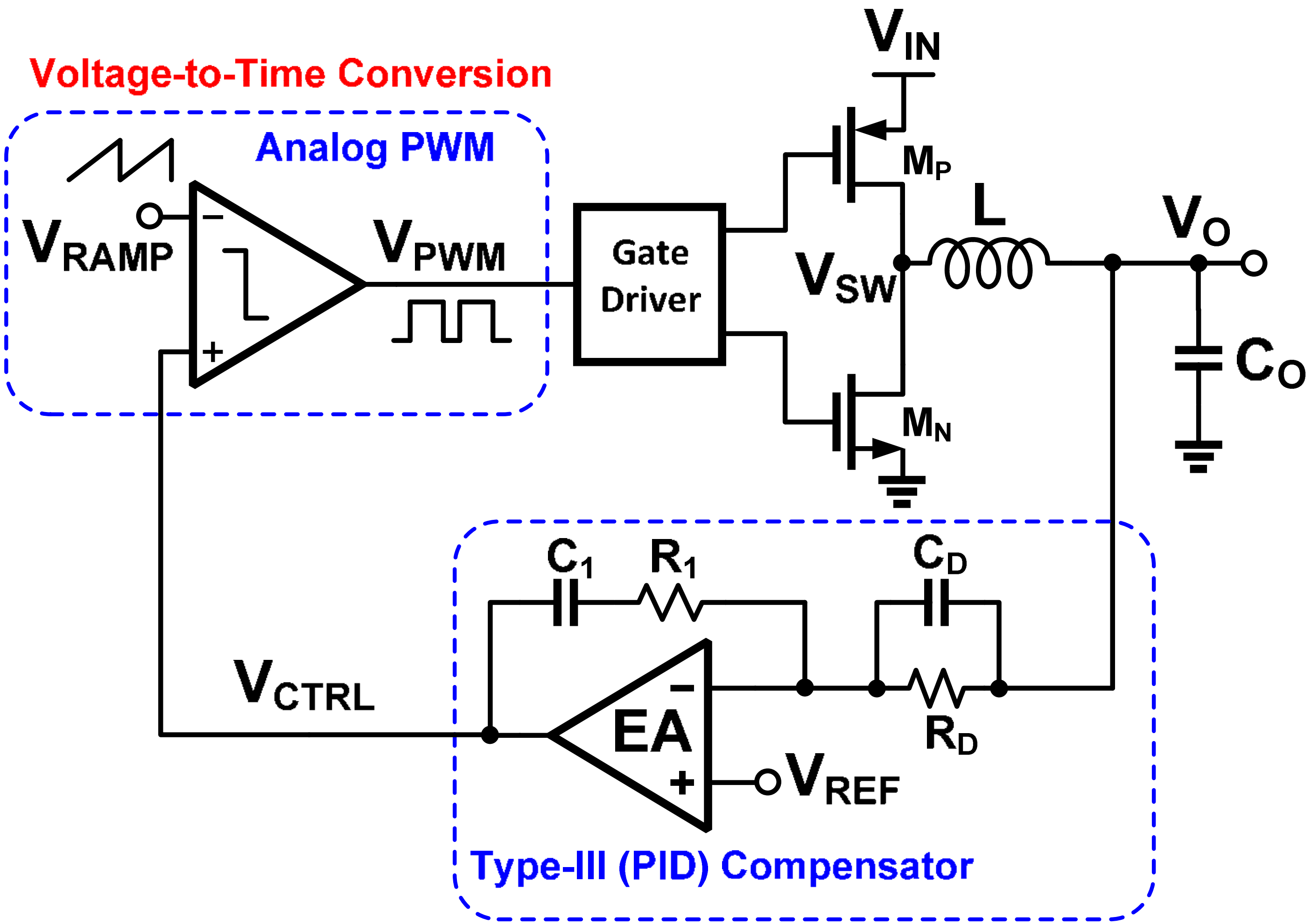
- V_{OUT} is regulated by controlling the pulse width or Duty Cycle, D



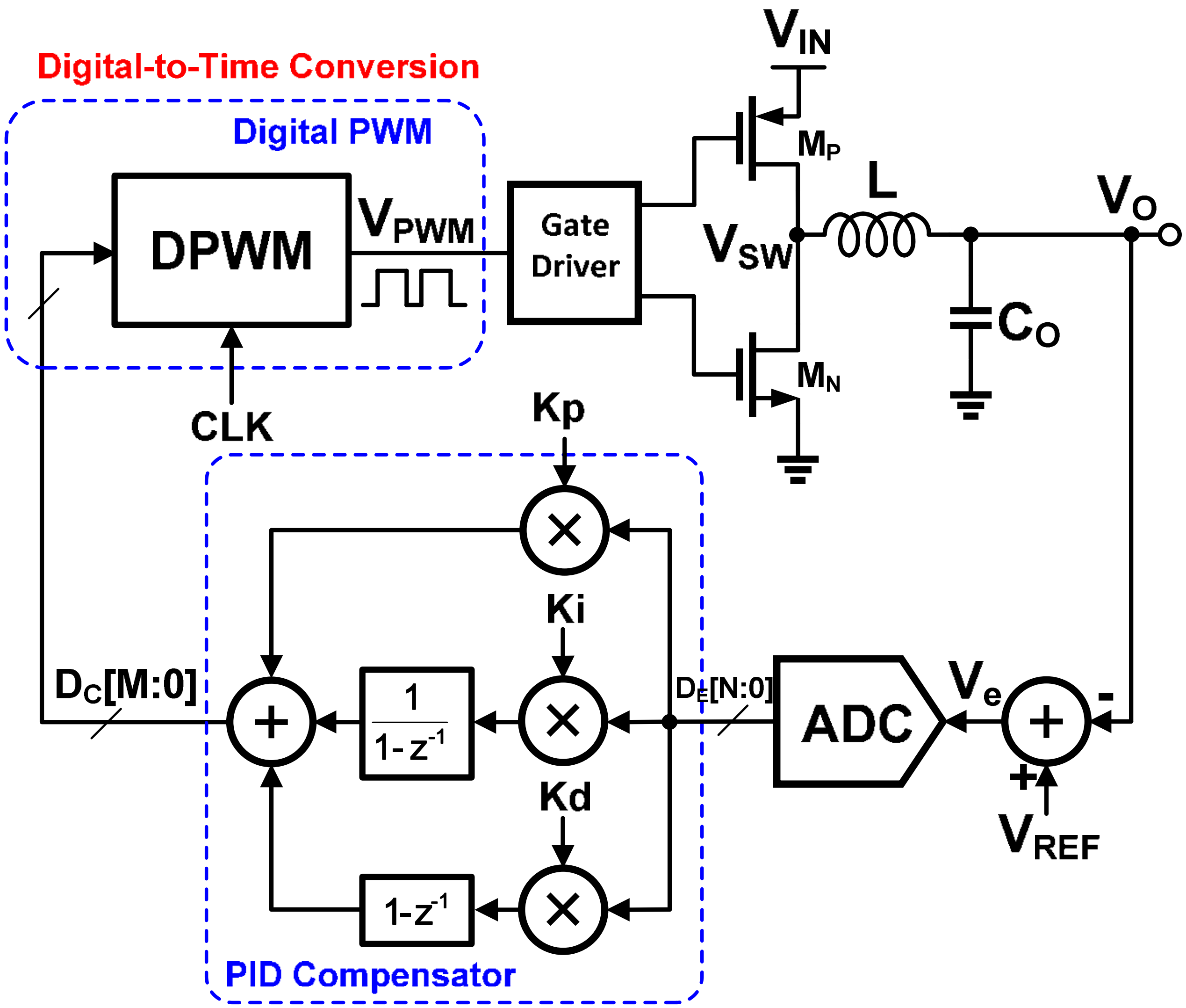


$$D = \text{Duty Cycle} = T_{ON}/T_{SW}$$

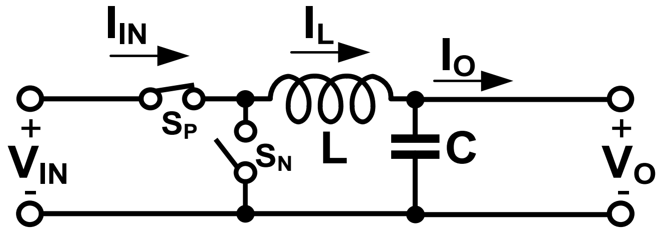
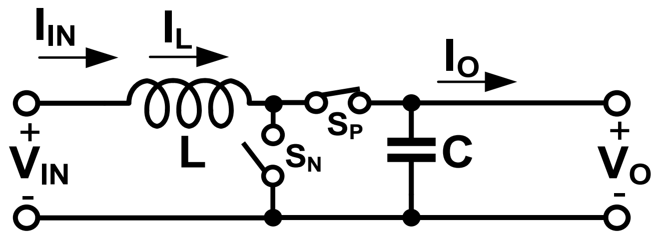
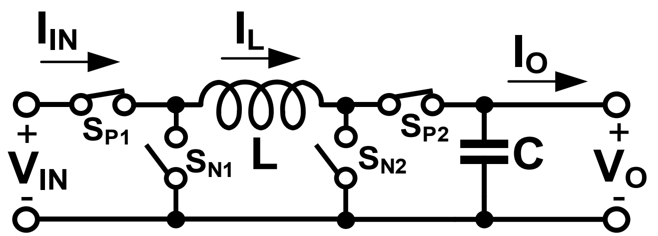
Closed Loop Control - Analog



Closed Loop Control - Digital

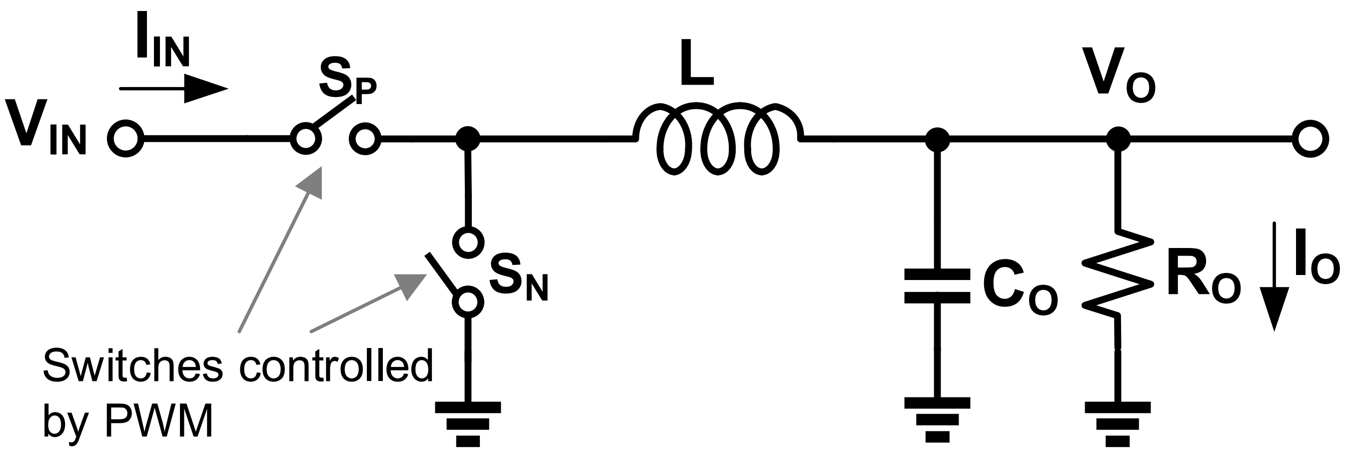


Switching Converter Types

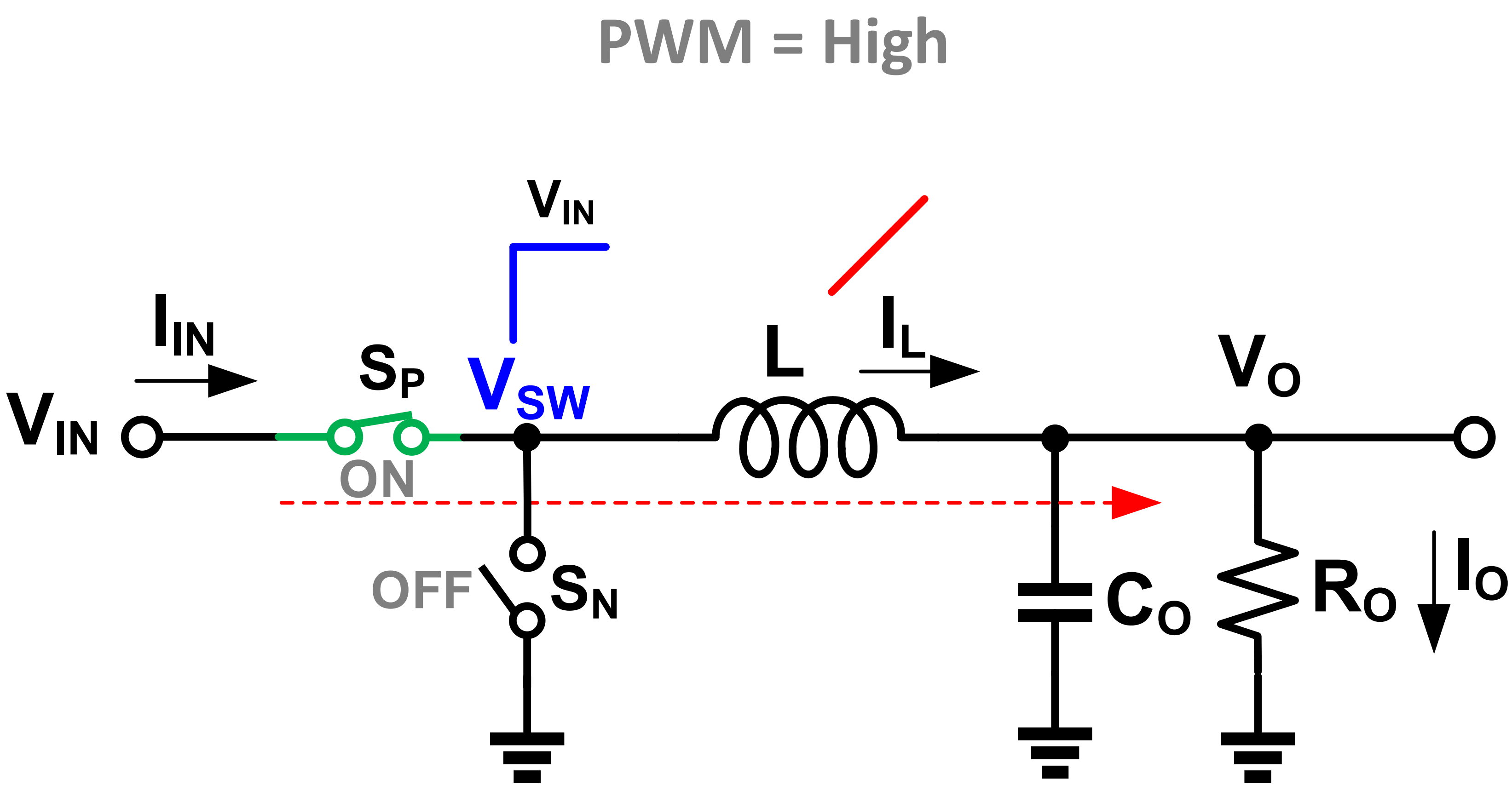
BUCK		$V_O = DV_{IN}$ $I_L = I_O$ $I_{IN} = DI_O$	$V_O < V_{IN}$
BOOST		$V_O = \frac{1}{1-D} V_{IN}$ $I_L = \frac{I_O}{1-D}$ $I_{IN} = I_L$	$V_O > V_{IN}$
BUCK BOOST		$V_O = \frac{D}{1-D} V_{IN}$ $I_L = \frac{I_O}{1-D}$ $I_{IN} = I_O$	$V_O \geq V_{IN}$ $V_O \leq V_{IN}$

Buck Converter

- **Buck (step-down) converter is used when output voltage is less than input voltage**
- **Uses two switches, S_P & S_N controlled by pulse width modulation (PWM) signal. These switches are usually implemented with MOSFETs**
- **Inductor and capacitor acts as lossless low pass filter and converter PWM into a DC output voltage, V_O**

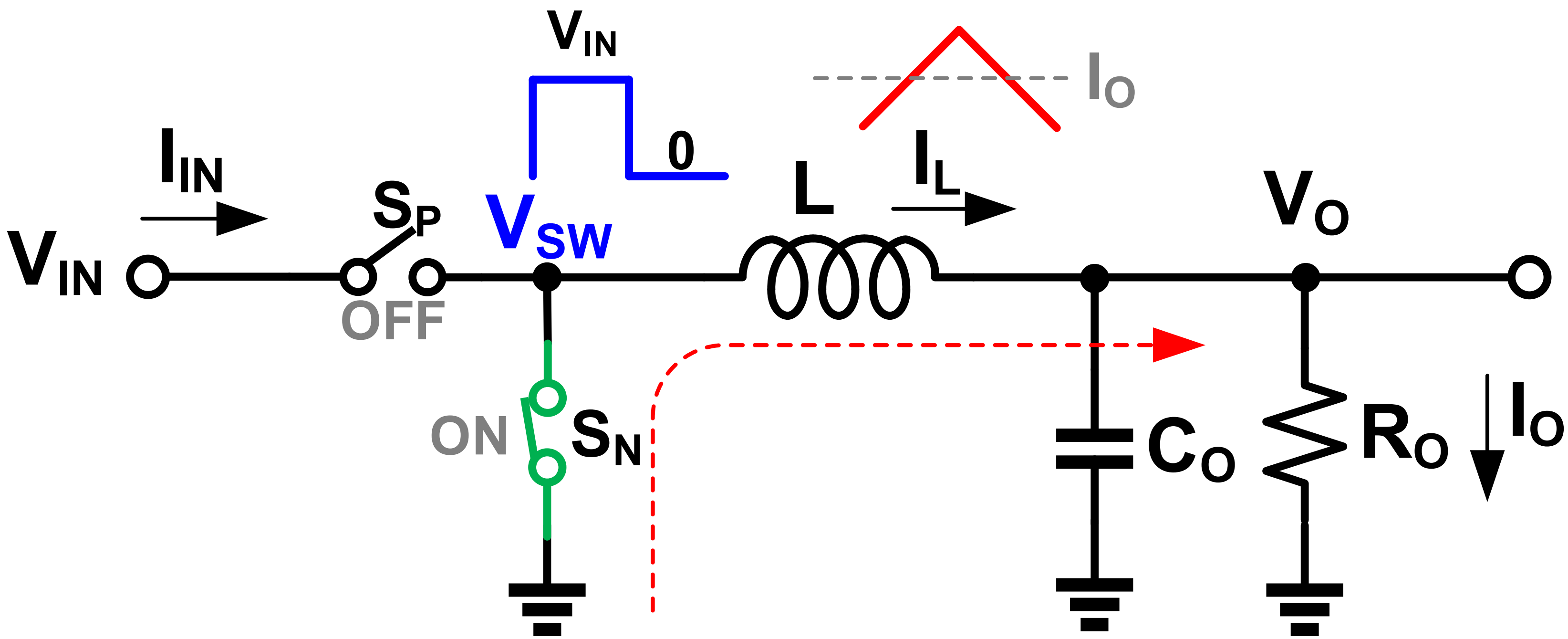


Operation of a Buck Converter

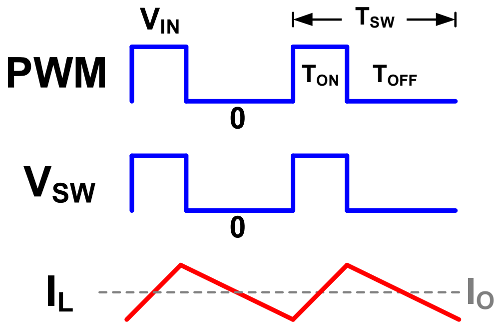


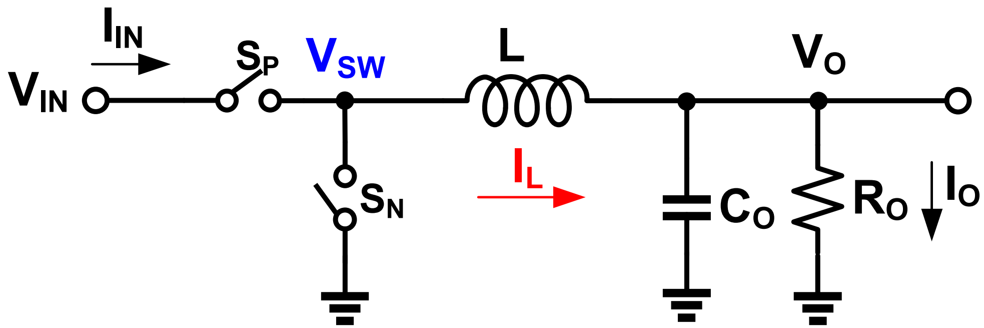
Operation of a Buck Converter

PWM = Low



Operation of a Buck Converter





- **For lossless inductor, average voltage across the inductor is zero**

  $V_{SW}\text{(avg)} - V_O = 0$

  $V_{SW}\text{(avg)} = D \cdot V_{IN}$; D = duty cycle of PWM signal = T_{ON}/T_{SW}

  $\rightarrow \boxed{V_O = D \cdot V_{IN}}$

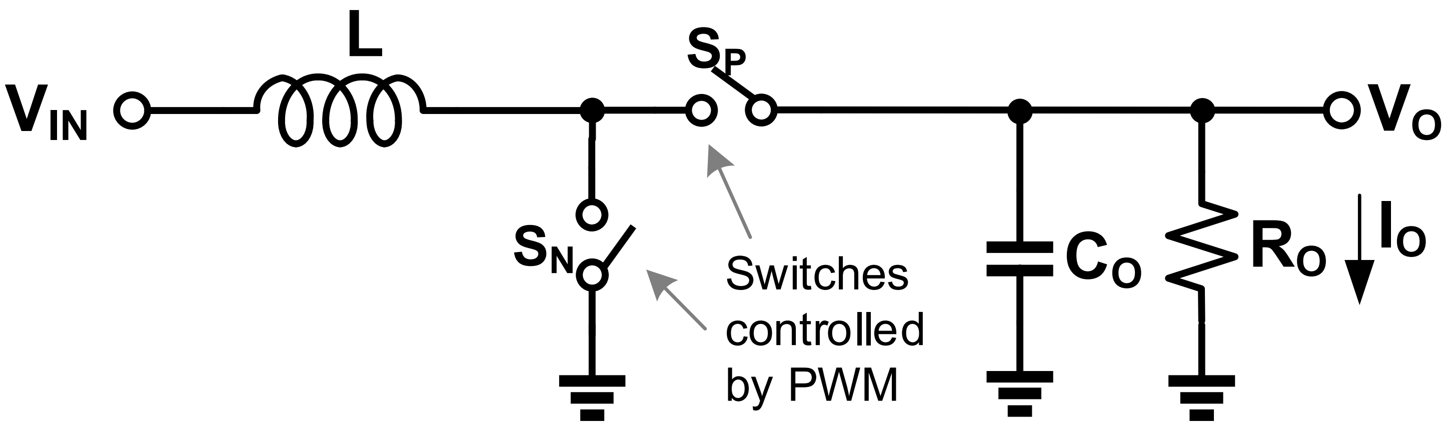
- **Under no loss,**

  $P_{IN} = P_{OUT}$ or $V_{IN} \cdot I_{IN} = V_O \cdot I_O$

  $\rightarrow \boxed{I_{IN} = D \cdot I_O}$ and inductor current, $\boxed{I_L = I_O}$

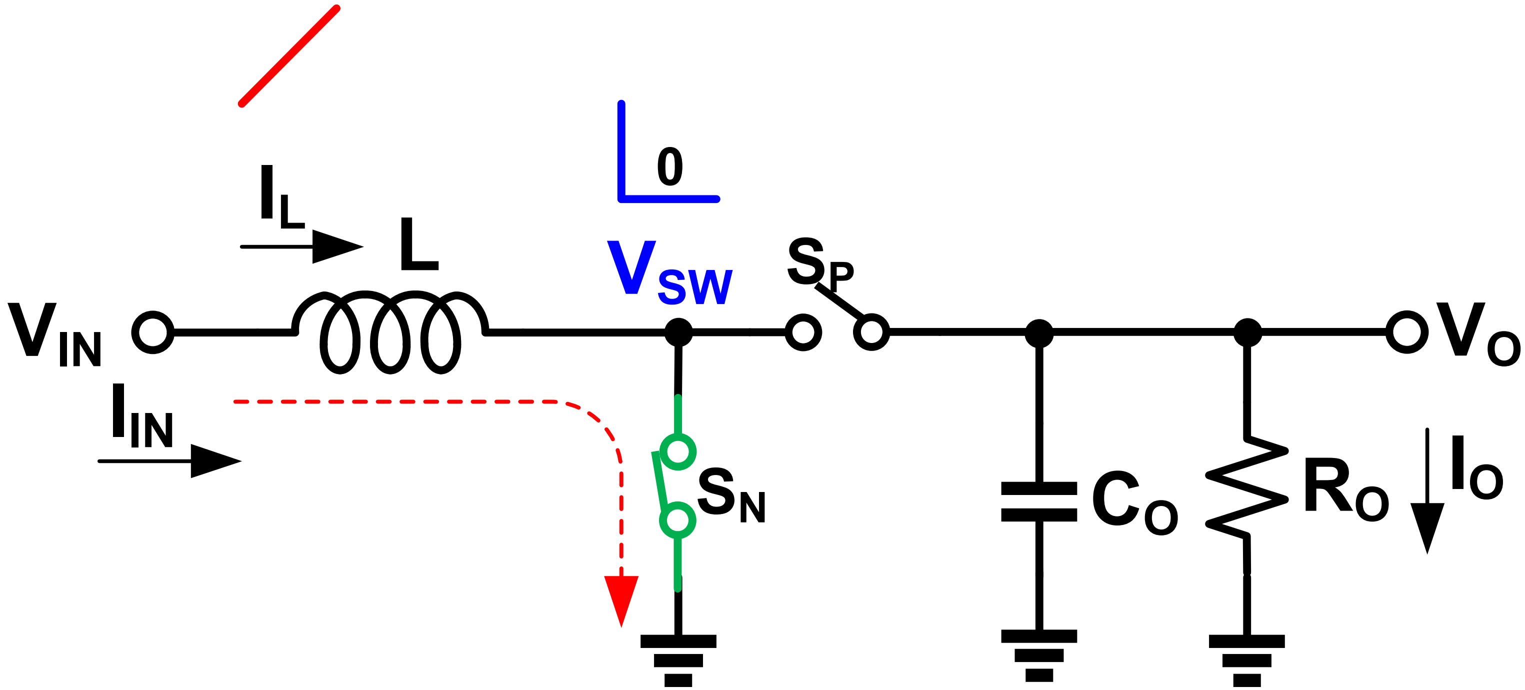
Boost Converter

- **Boost (step-up) converter is flipped version of buck converter and used when output voltage is more than input voltage**
- **Uses two switches, S_P & S_N controlled by pulse width modulation (PWM) signal.**

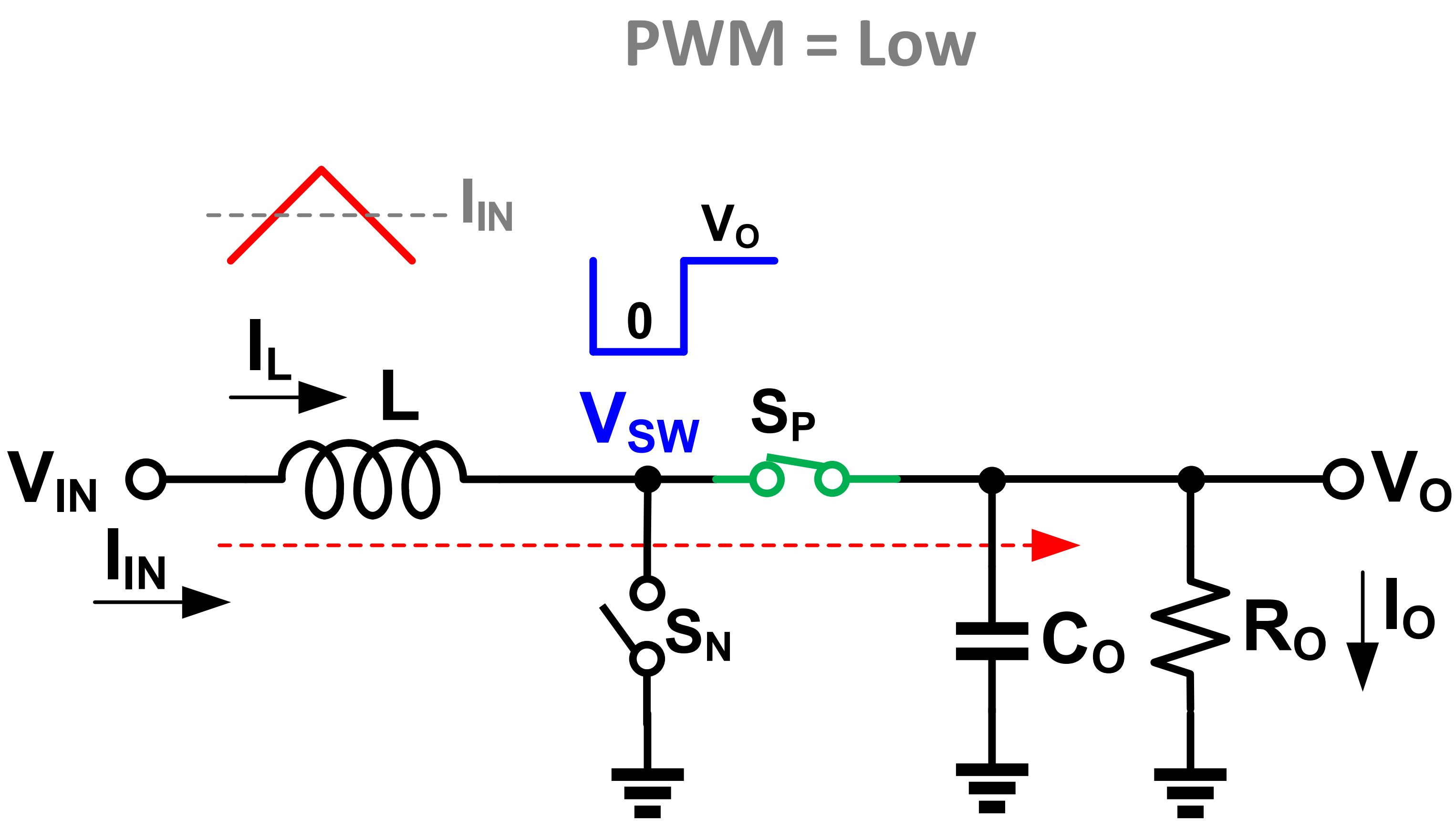


Operation of a Boost Converter

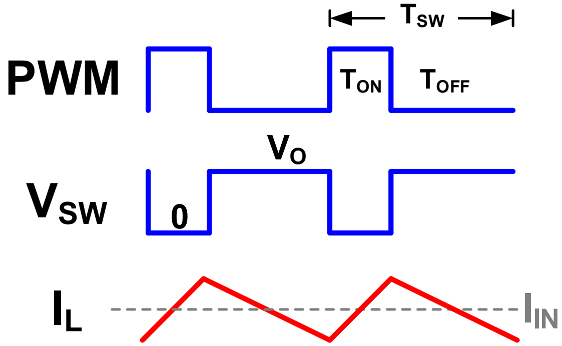
PWM = High

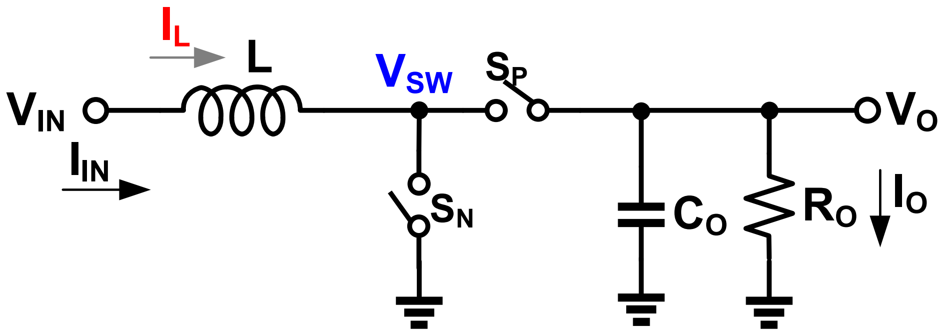


Operation of a Boost Converter



Operation of a Boost Converter





- **For lossless inductor, average voltage across the inductor is zero**

  $V_{IN} - V_{SW}\,(avg) = 0$

  $V_{SW}\,(avg) = (1-D)\cdot V_O$; D = duty cycle of PWM signal = T_{ON}/T_{SW}

  $\rightarrow \boxed{V_O = V_{IN}/(1-D)}$

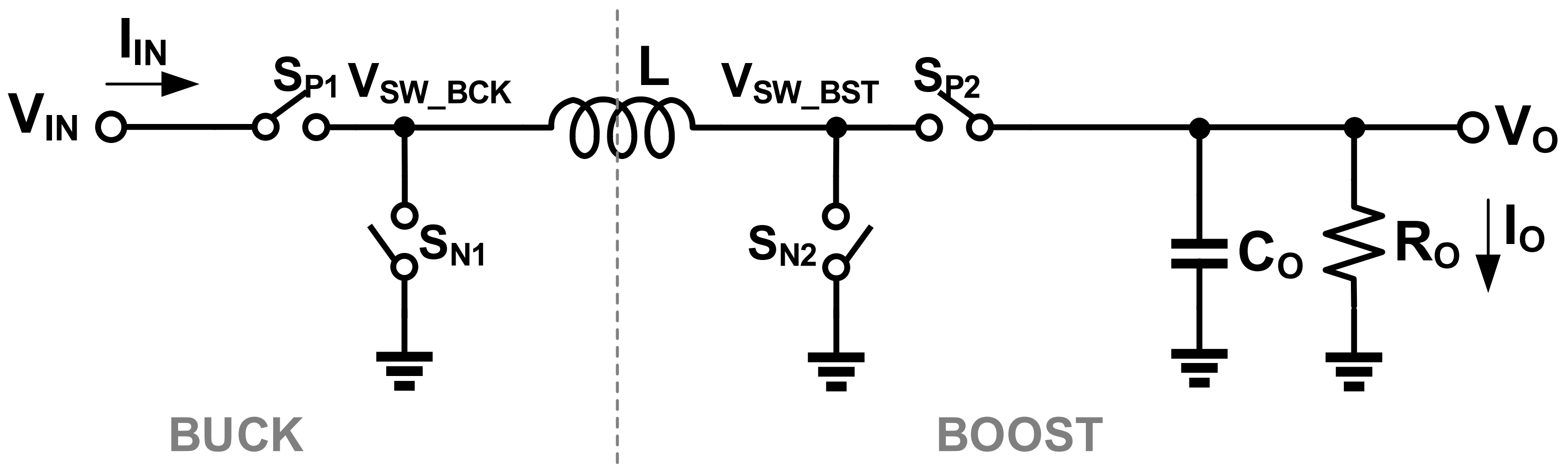
- **Under no loss,**

  $P_{IN} = P_{OUT}$ or $V_{IN}\cdot I_{IN} = V_O\cdot I_O$

  $\rightarrow \boxed{I_{IN} = I_O/(1-D)}$ and inductor current, $\boxed{I_L = I_{IN}}$

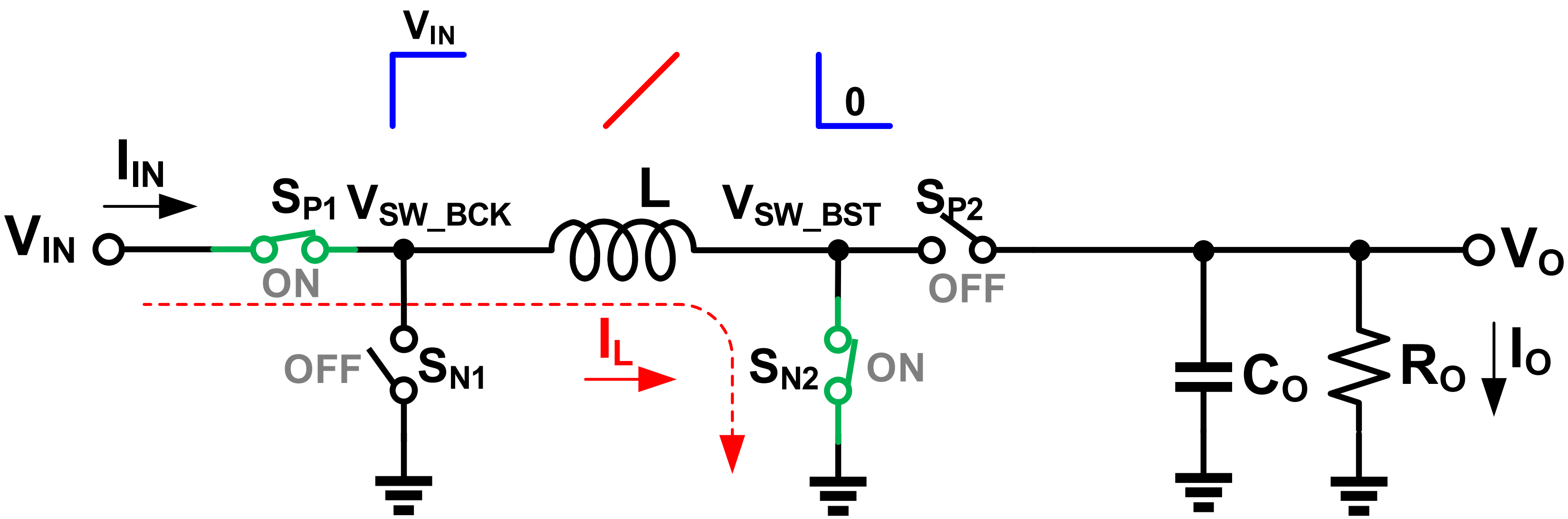
Buck-Boost Converter

- Buck-Boost converter combines both buck and boost.
- Buck-Boost converter is used when output voltage is either less, equal or more than input voltage
- Uses four switches, S_{P1}, S_{N1} and S_{P2}, S_{N2} controlled by pulse width modulation (PWM) signal.



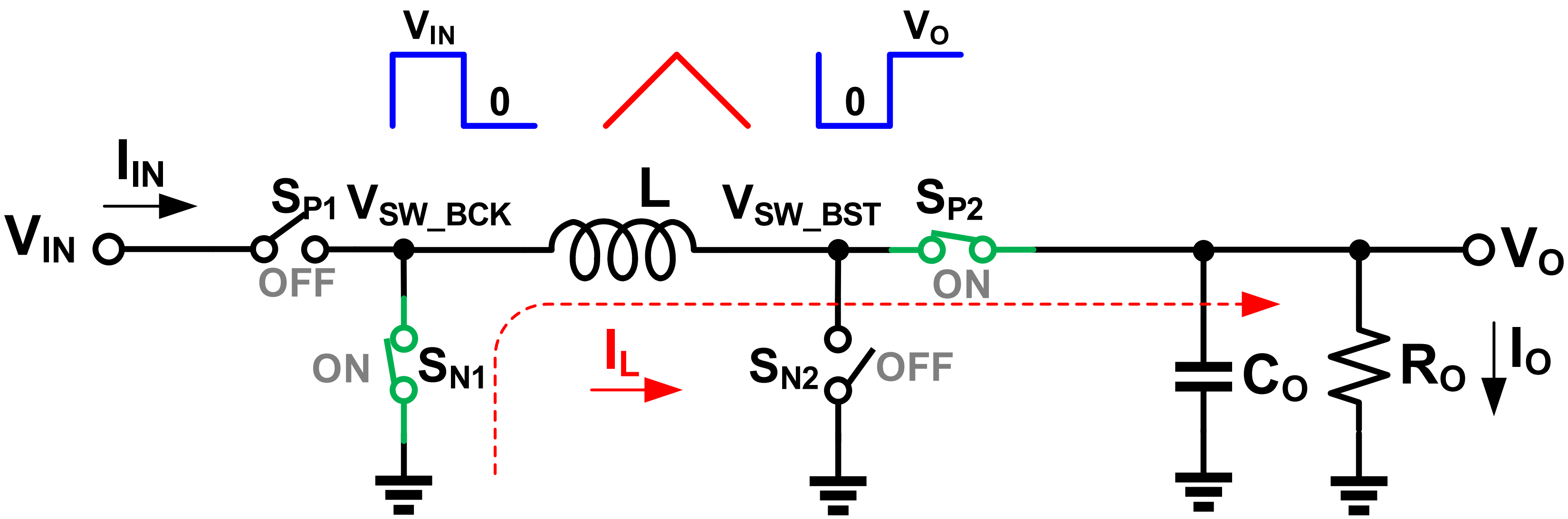
Operation of a Buck-Boost Converter

PWM = High

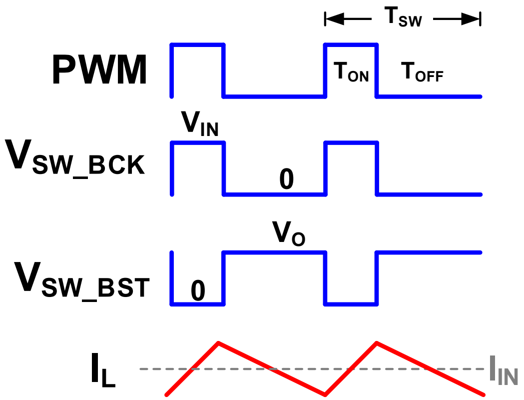


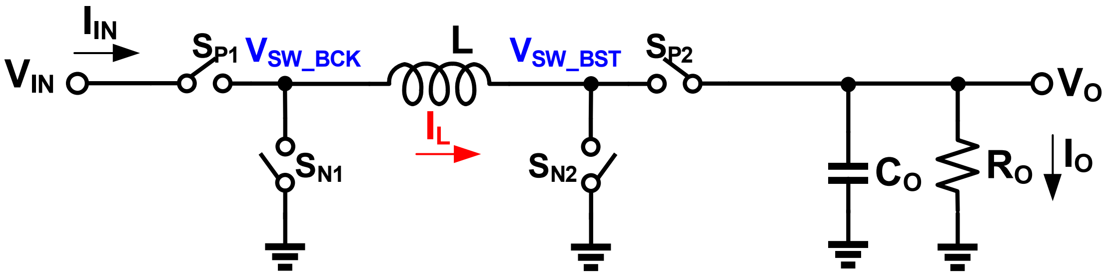
Operation of a Buck-Boost Converter

PWM = Low



Operation of a Buck-Boost Converter





- For lossless inductor, average voltage across the inductor is zero

  $V_{SW\_BCK}(avg) - V_{SW\_BST}(avg) = 0$

  $D \cdot V_{IN} = (1\text{-}D) \cdot V_O$

  $\rightarrow \boxed{V_O = \frac{D}{1-D} \cdot V_{IN}}$

  $D < 0.5 \rightarrow V_O < V_{IN}$: Buck

  $D = 0.5 \rightarrow V_O = V_{IN}$

  $D > 0.5 \rightarrow V_O > V_{IN}$: Boost

- Under no loss,

  $P_{IN} = P_{OUT}$ or $V_{IN} \cdot I_{IN} = V_O \cdot I_O$

  $\rightarrow \boxed{I_{IN} = \frac{D}{1-D} \cdot I_O}$

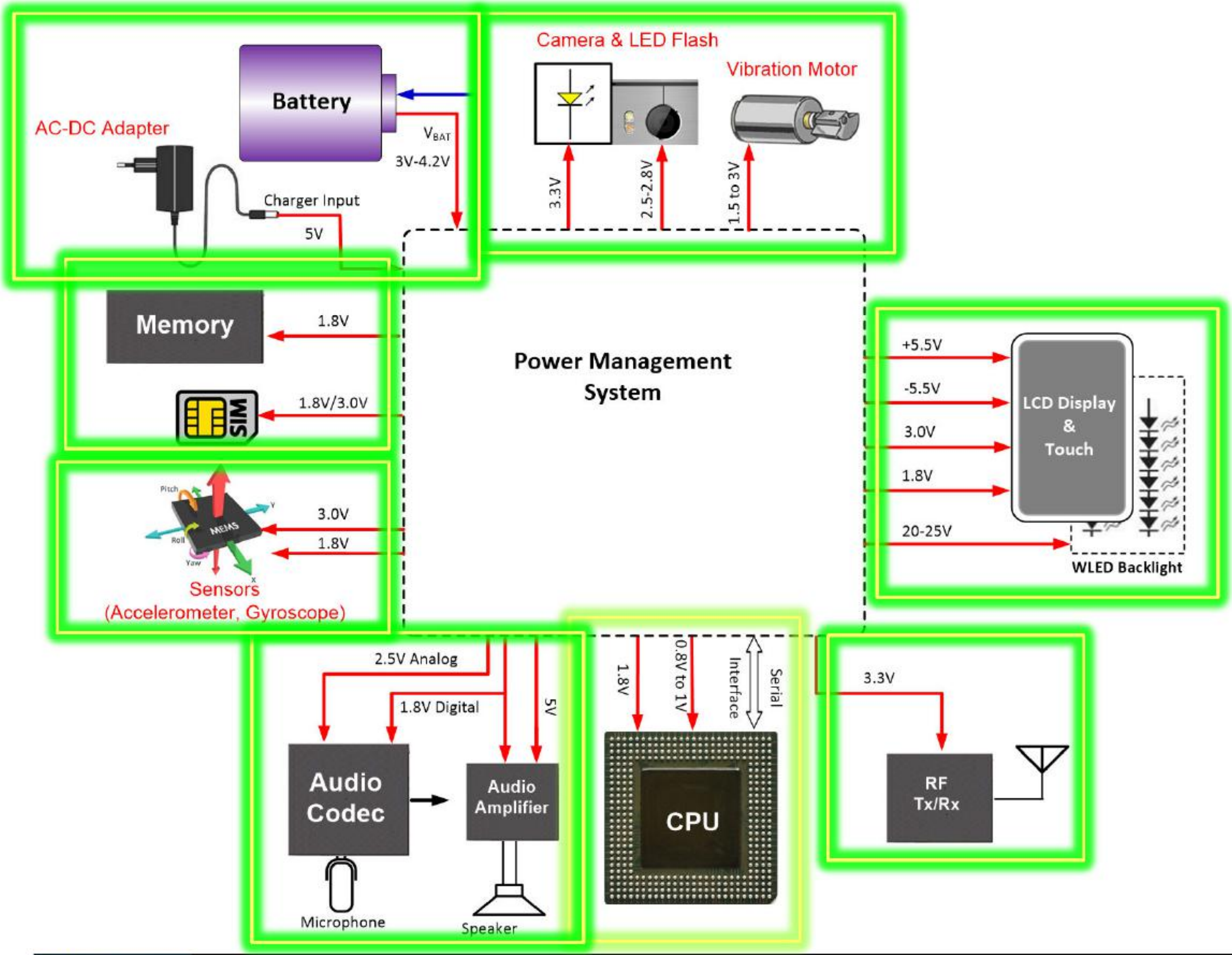
  Also, $I_{IN} = D \cdot I_L$

  Substituting $I_{IN} = \frac{D}{1-D} \cdot I_O$

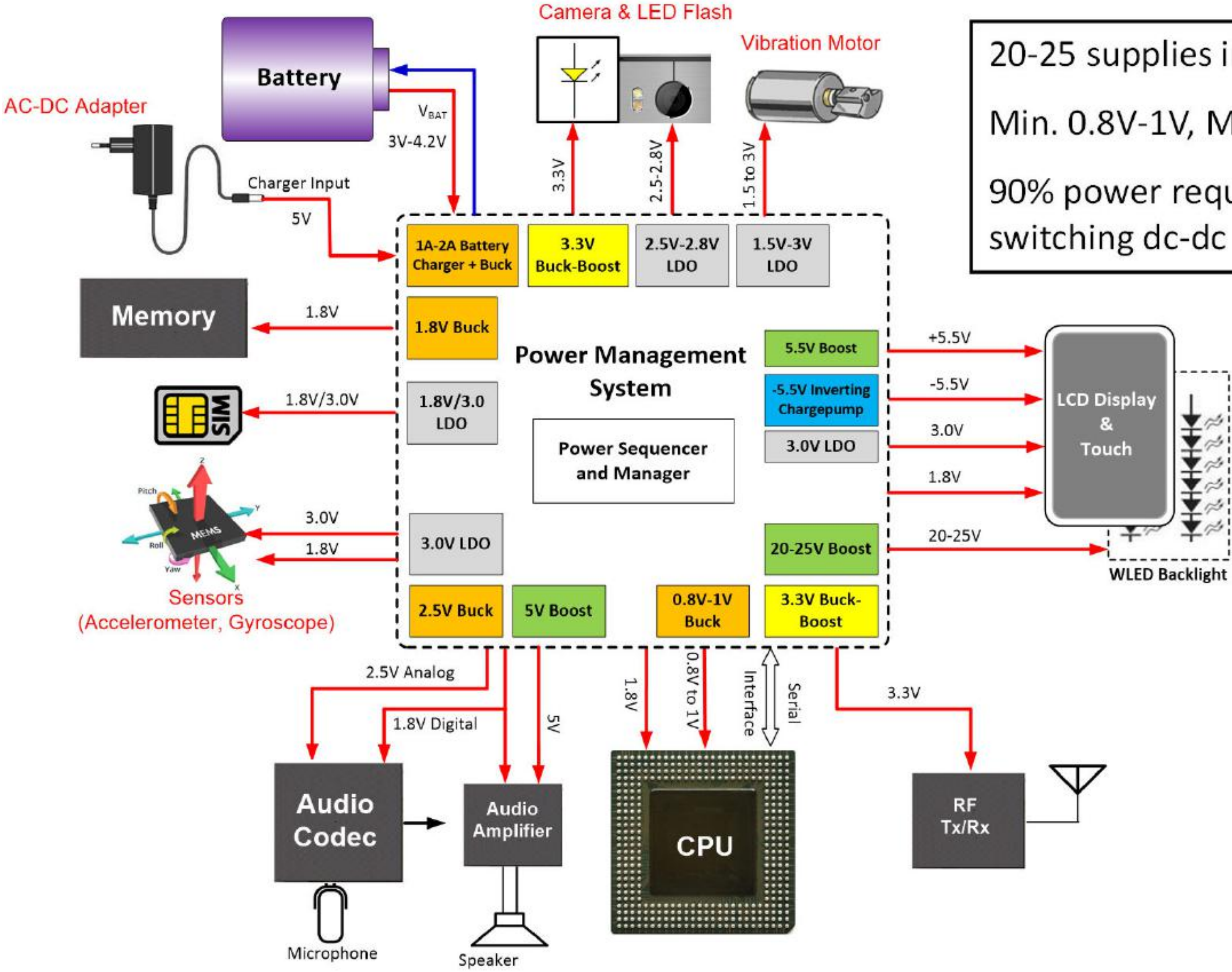
  $\rightarrow$ inductor current,

  $\boxed{I_L = \frac{1}{1-D} \cdot I_O}$

Power Management in a Smartphone



Power Management in a Smartphone

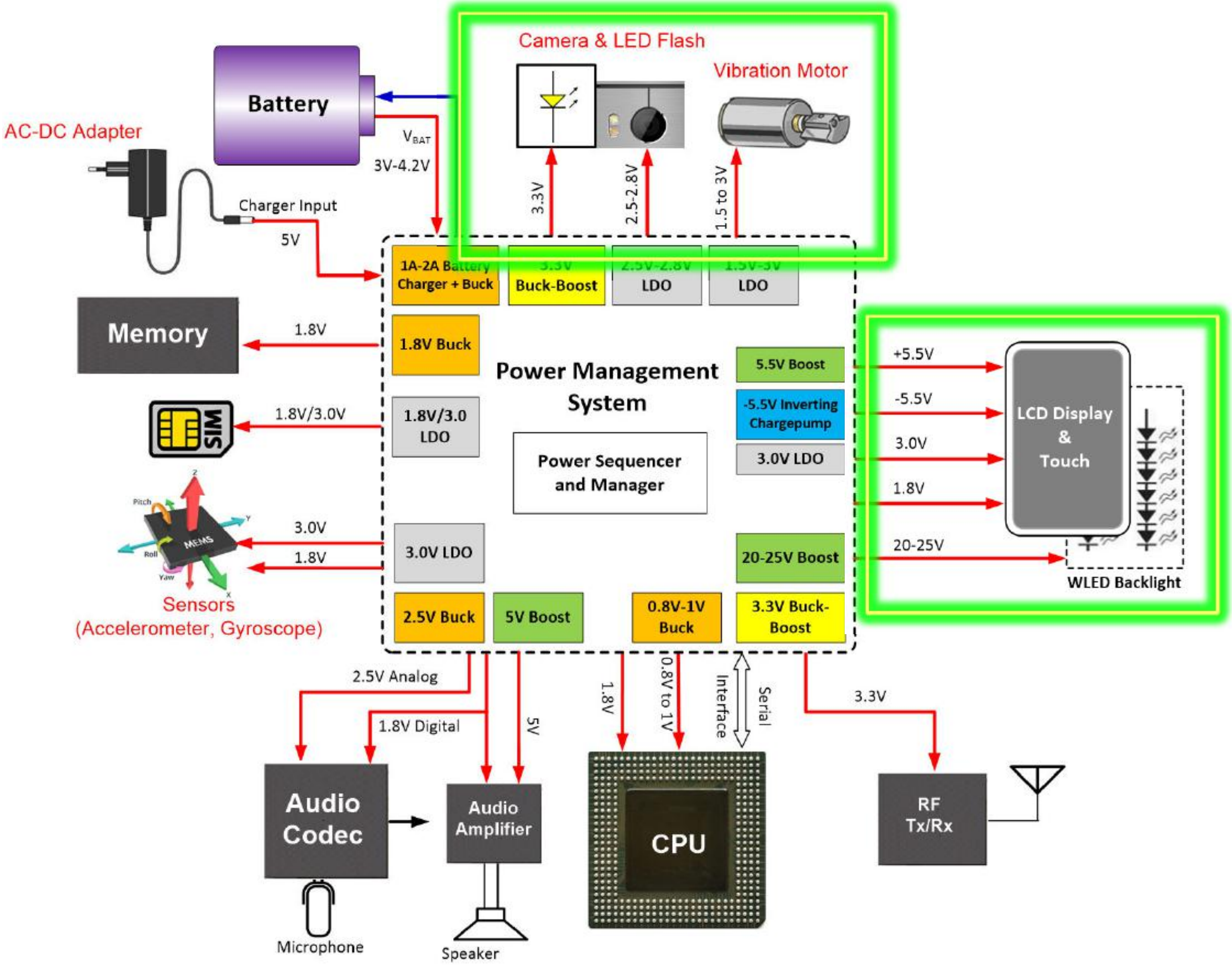


20-25 supplies in a Smartphone

Min. 0.8V-1V, Max. 20V-25V

90% power requirement is met by switching dc-dc converters

Power Management in a Smartphone



History of Display Technologies

1897 – Birth of CRT (Cathode Ray Tube)

1925 - CRT TV was invented and used until early 2000s with advancements in technologies like color TV, flat screen etc.

1964 - Invention of LCD. Used in modern LCD watch and calculators in 1972.

1980s – Color LCD displays and Organic LED (OLED) displays were invented

Early 2000: LCD technology started outperforming CRT in terms of both quality as wells as power consumption and played critical role in smartphones revolution and tablets later

History of Display Technologies

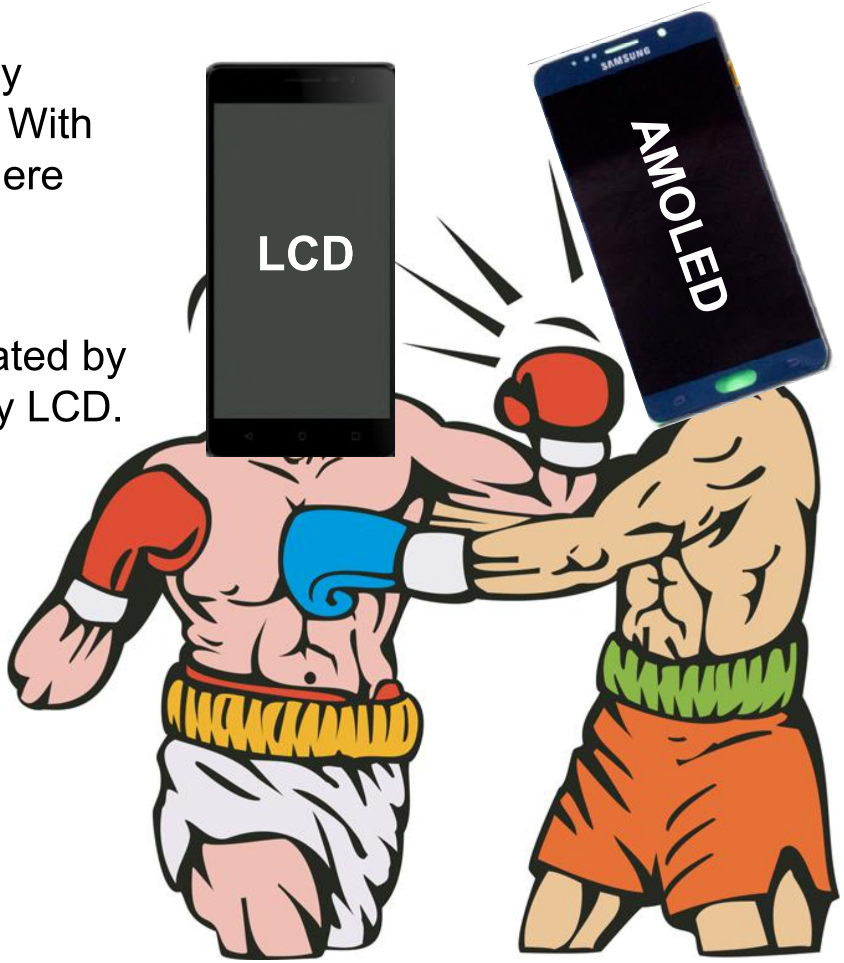
2007: iPhone, first commercially successful smartphone that is exclusively touchscreen was launched.

2010: Samsung Galaxy S series with AMOLED display launched

LCD Vs. AMOLED

Present: LCD and AMOLED are the two widely used displays in smartphones and tablet PCs. With advancements in both display technologies, there has been neck to neck competition.

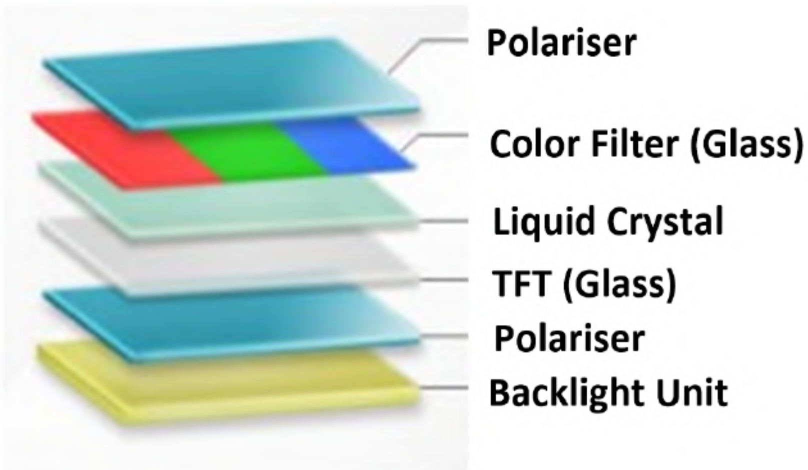
High end smartphone market is mostly dominated by AMOLED and mid and low tier is dominated by LCD.

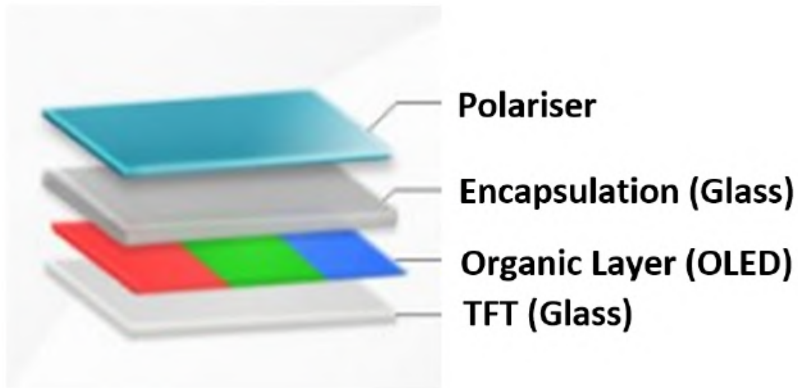


LCD Vs. AMOLED Structure

- **Uses multiple layers which limit the minimum achievable thickness (~1-1.5mm)**
- **Requires backlight**

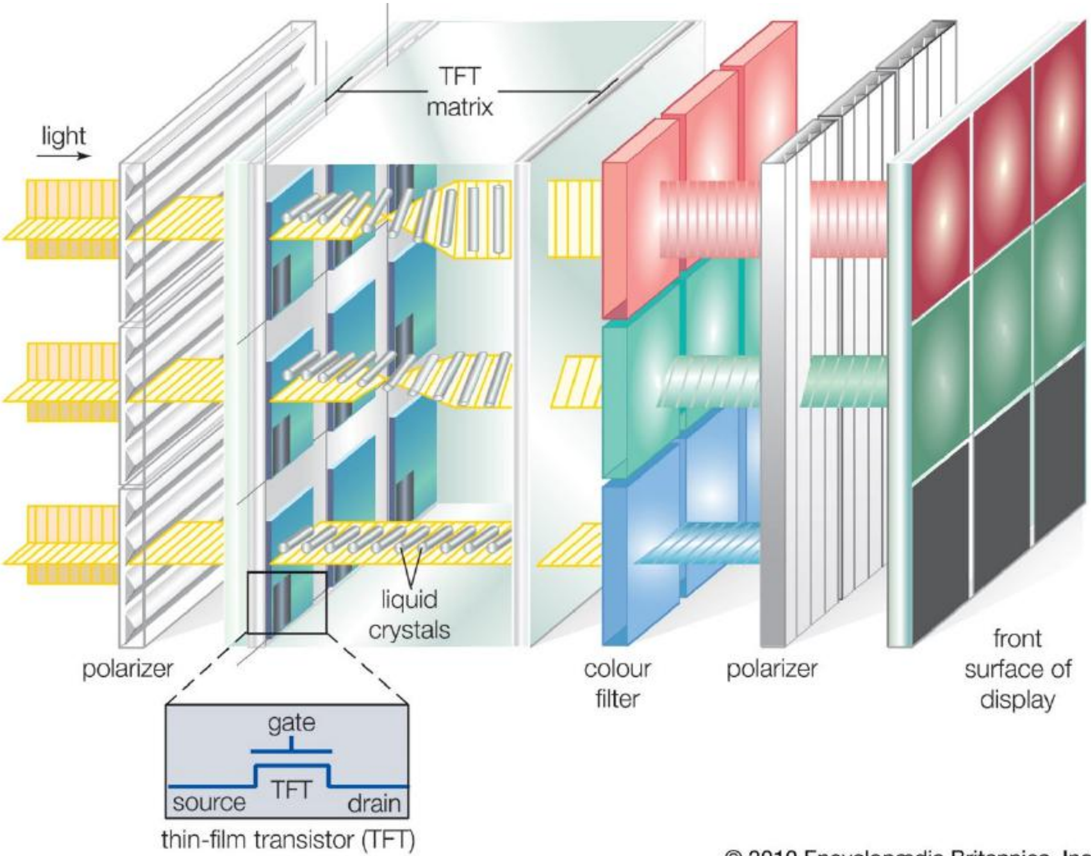
- **Uses fewer layers hence thickness is quite low (paper thin)**
- **No backlighting is needed**





How LCD Works

- Crystal alignment is changed when voltage is applied between two electrodes (through TFT)
- Voltage applied across LCD electrodes determines how much light will be passed and controls the intensity.



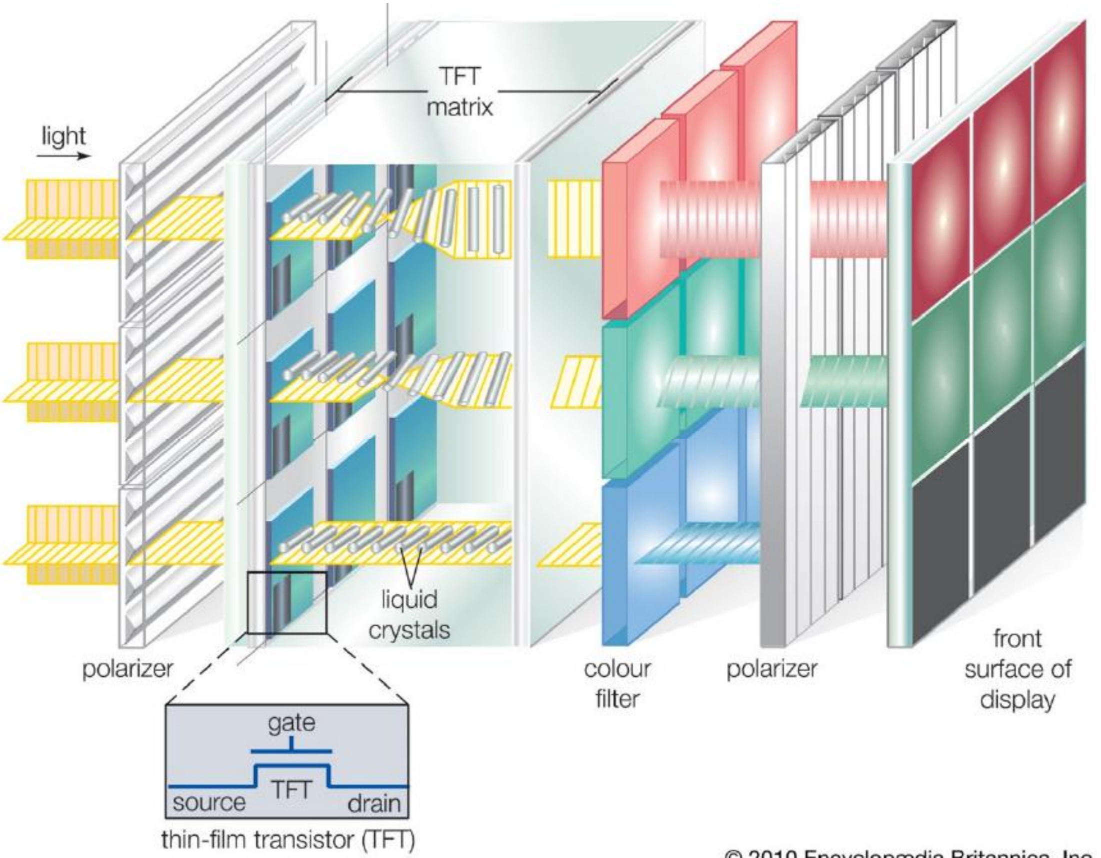
Lightest Pixel (ON with full intensity)

Light Pixel (ON with lesser intensity)

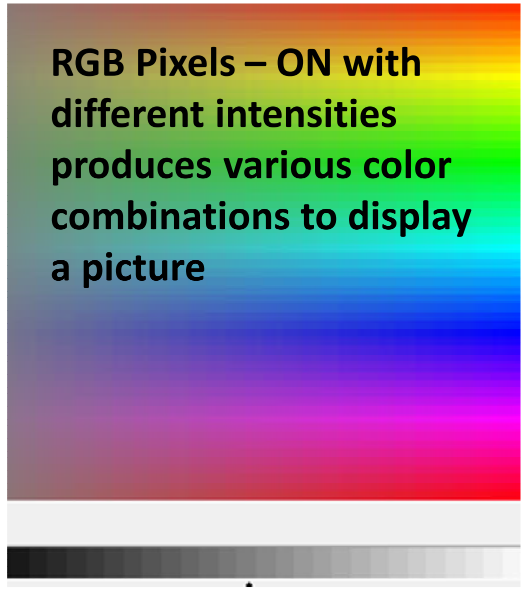
Dark Pixel (OFF)

LCD Color Depth

- **8-bit intensity of each color (R, G and B) provides 16 million ($2^8 x 2^8 x 2^8$) color combinations.**



Display Color Depth

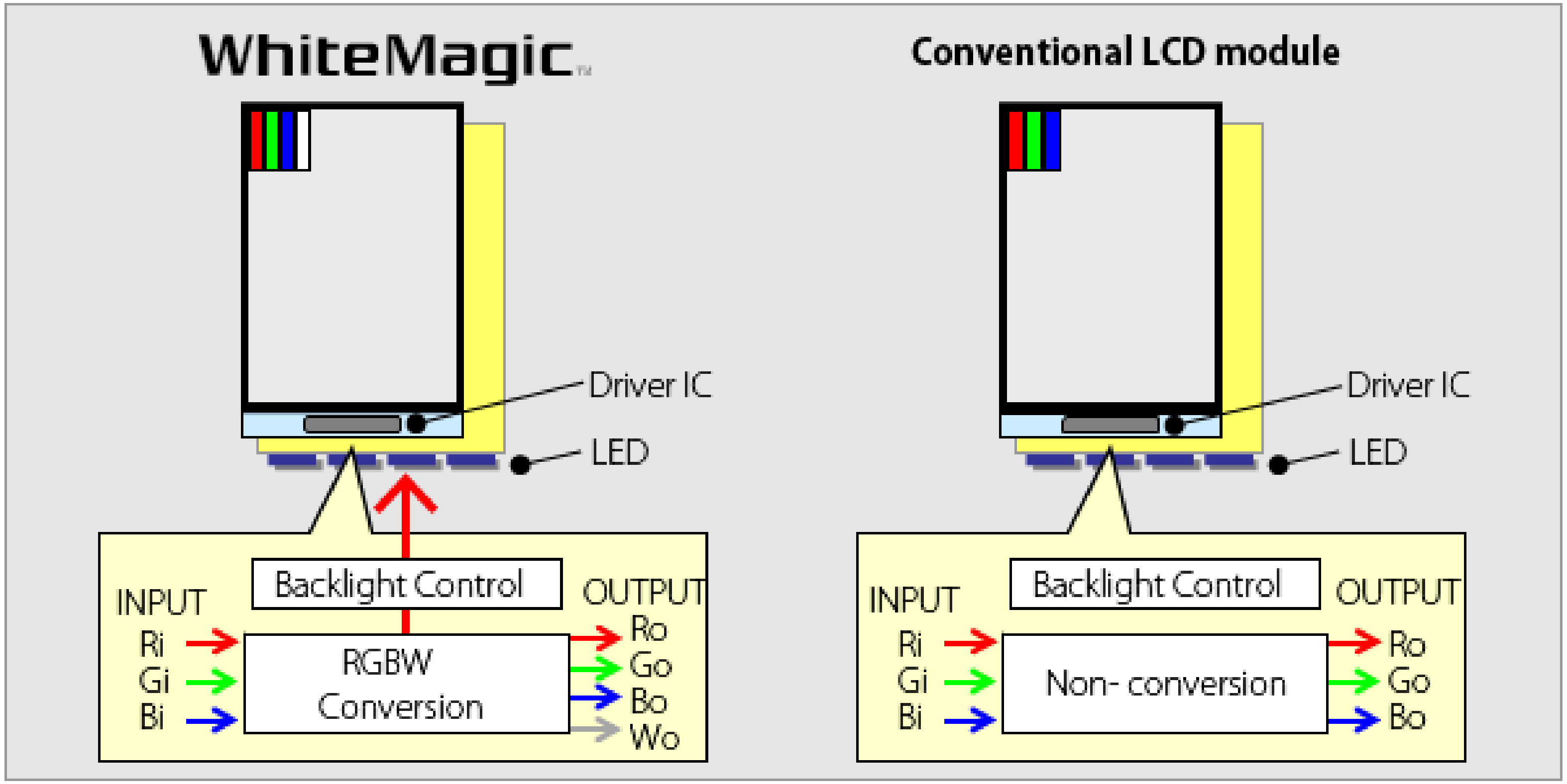


RGB Pixels – OFF (Black)

RGB Pixels – ON (White)

RGBW LCD Display

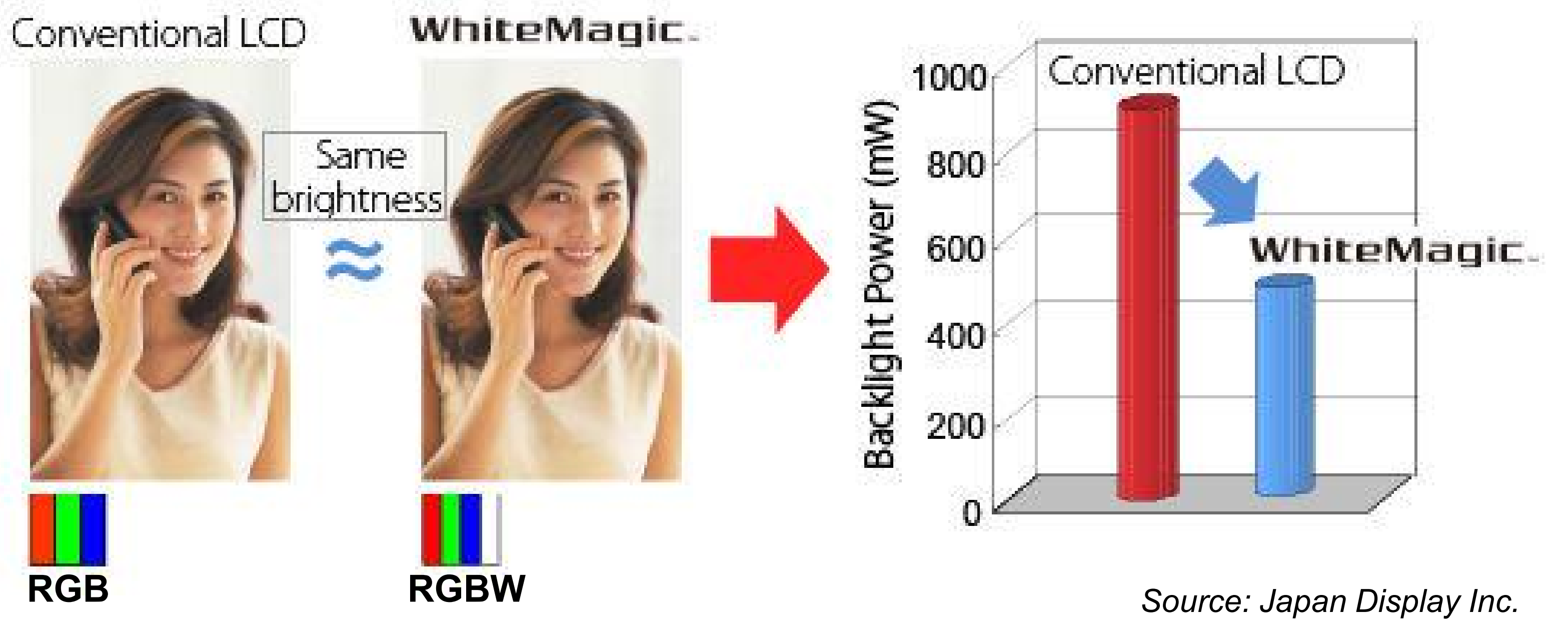
- **JDI (Japan Display Inc) WhiteMagic LCD technology adds while sub-pixel along with RGB (Also called RBGW)**



Source: Japan Display Inc.

Power Reduction with RGBW LCD Display

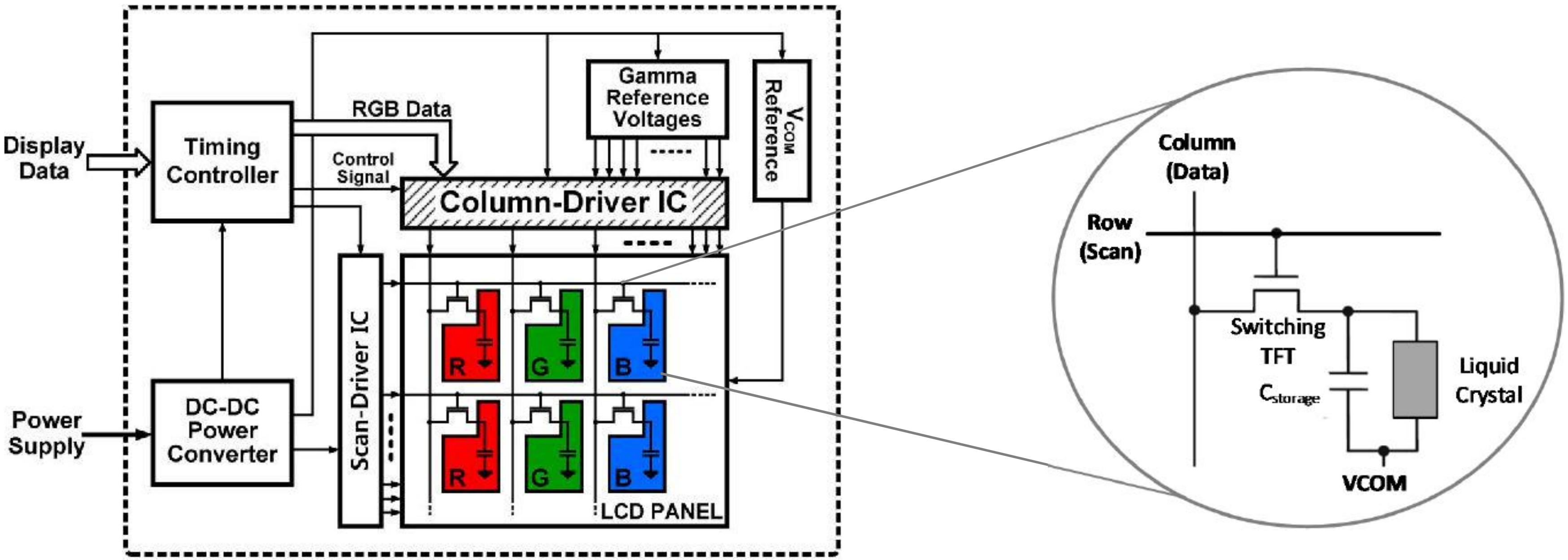
- **White pixel is transparent and passes the full white backlight making the pixel brighter**
- **For the same brightness, RGBW achieves ~40% power reduction without degrading the image quality**



Source: Japan Display Inc.

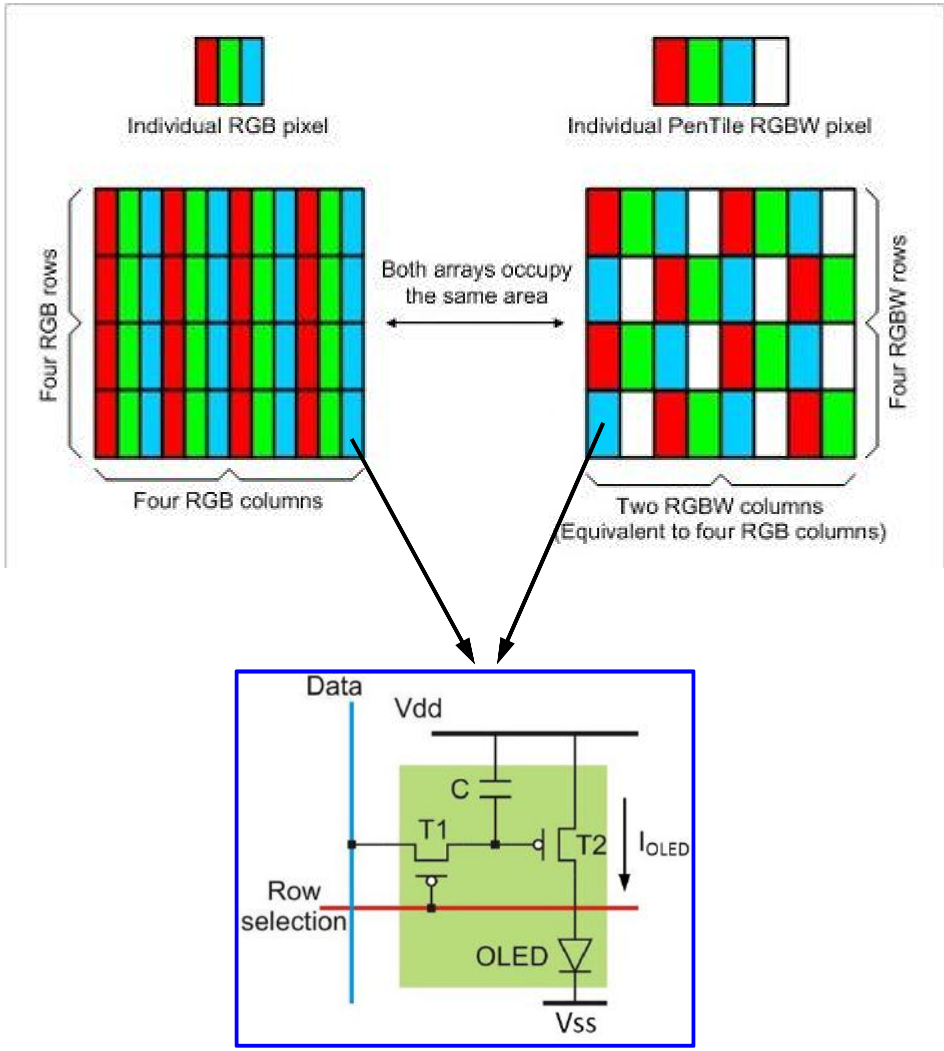
LCD Pixel Driver

- **LCD requires multiple supplies to drive a pixel.**
- **Some of the supplies are generated on display panel (inside DDIC) and some are generated outside the panel (on phone board)**



How AMOLED Works

- Each pixel is LED and three LEDs (R, G and B) forms one sub-pixel.
- Fourth LED (White) can also be added in a sub-pixel for better brightness
- Current in each OLED pixel is controlled to control the brightness and form color combinations
- Since each OLED is self lit, it doesn't require any backlight

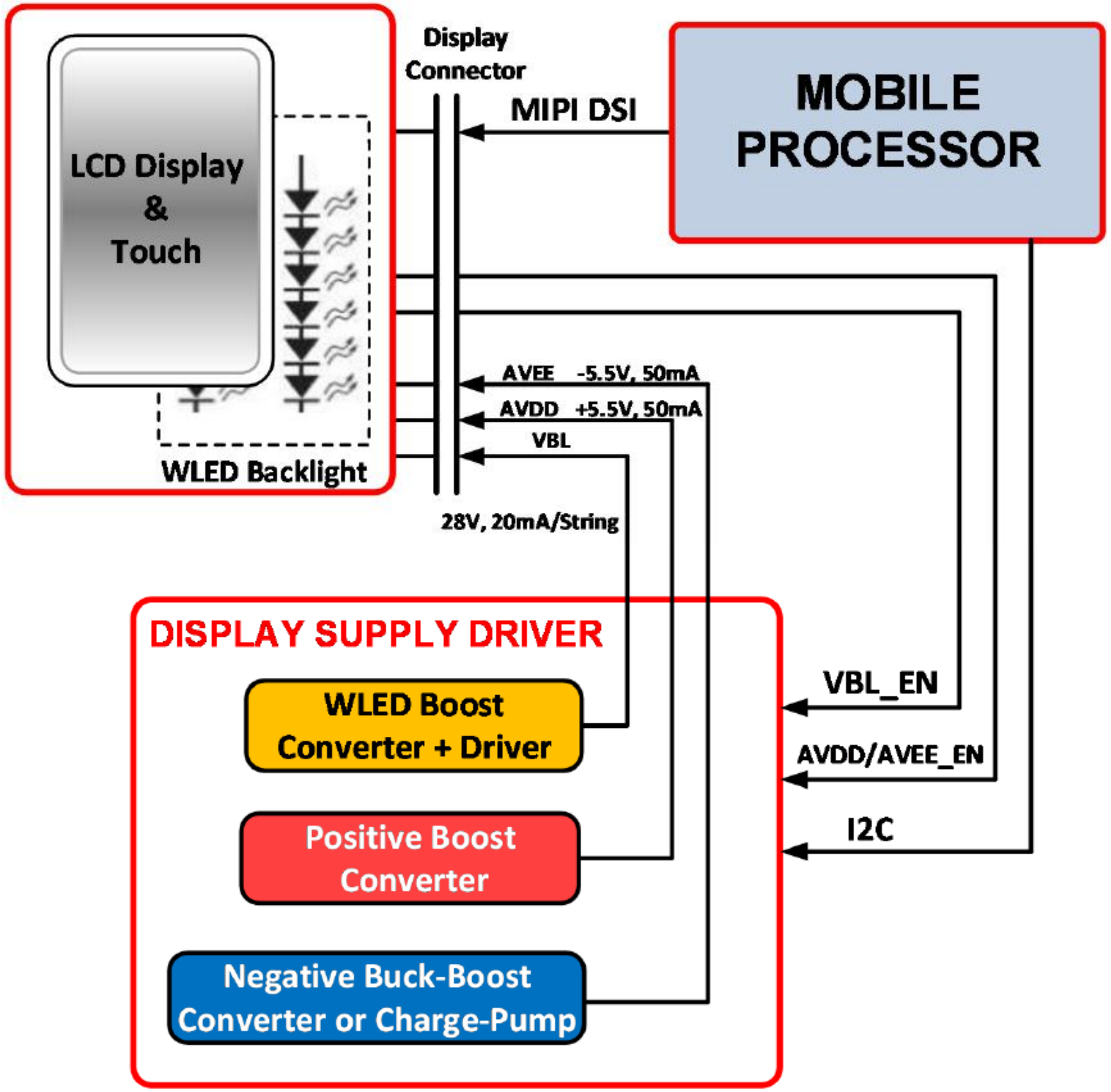


Power Management for LCD

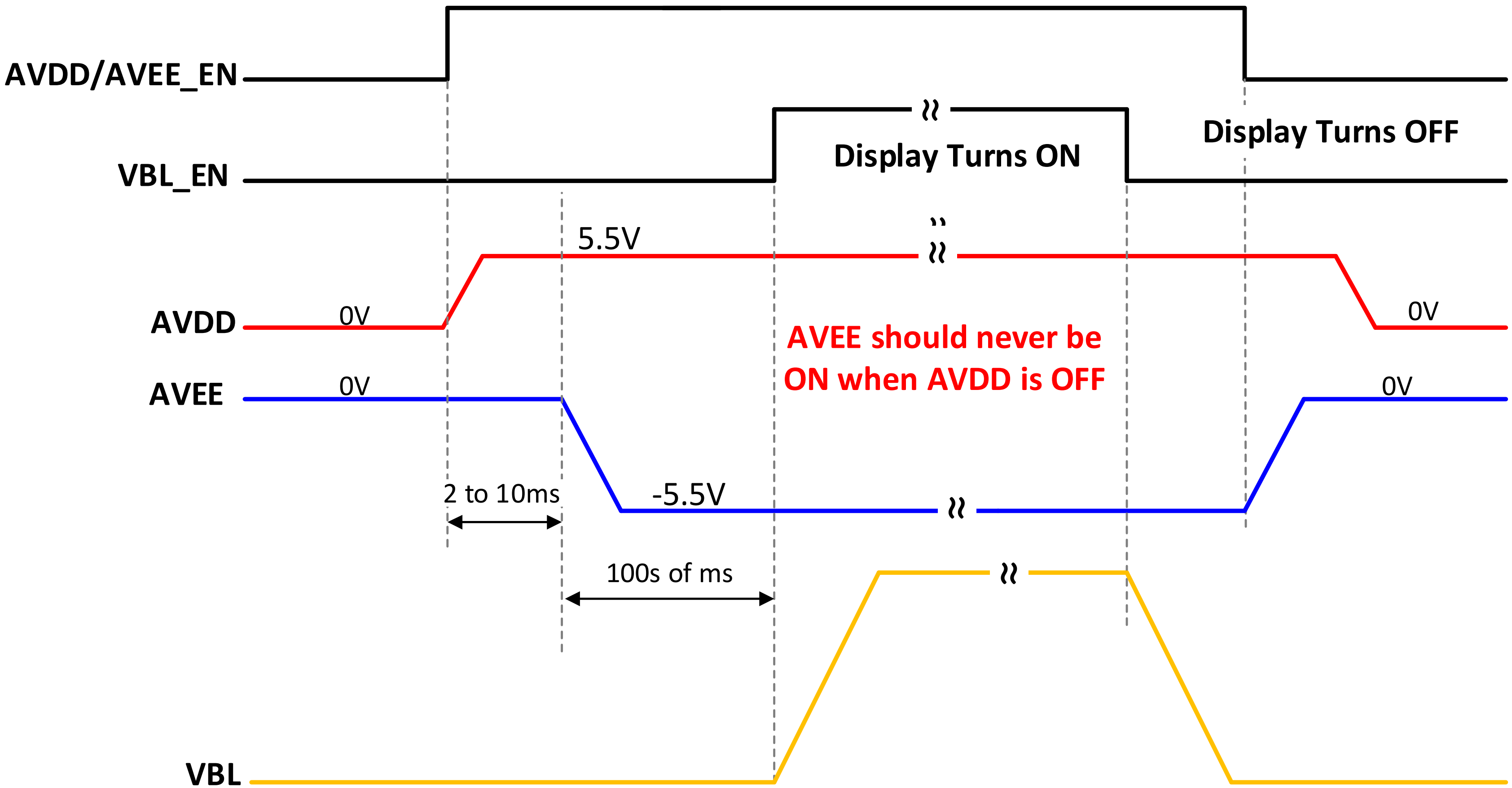
Power Supplies for Mobile Display (LCD)

Power Supply	Description	Value (Typ)	Supply Generation
VDDI	Digital Power Supply	1.8V	External (system VDD)
VDDA	Power Supply for Analog Systems	3.3V	Inside panel DDIC
VGH	TFT Row/Gate drive positive (ON) supply	15V	Inside panel DDIC
VGL	TFT Row/Gate drive negative supply	-10V	Inside panel DDIC
VCOM	LCD common electrode voltage	-2V – +2V	Inside panel DDIC
AVDD		5.5V	External (dedicated power IC)
AVEE		-5.5V	External (dedicated power IC)
VBL	Backlight supply	28V (for 8s2p) 14V (for 4s4p)	External (dedicated power IC)

LCD Power Supply Regulators



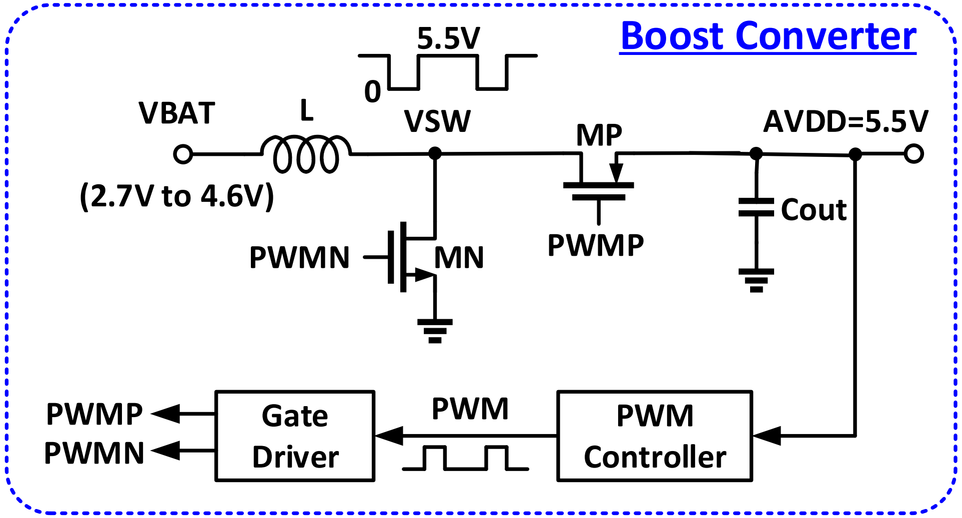
LCD Power-Up/Power Down Sequencing



Generating +/-5.5V

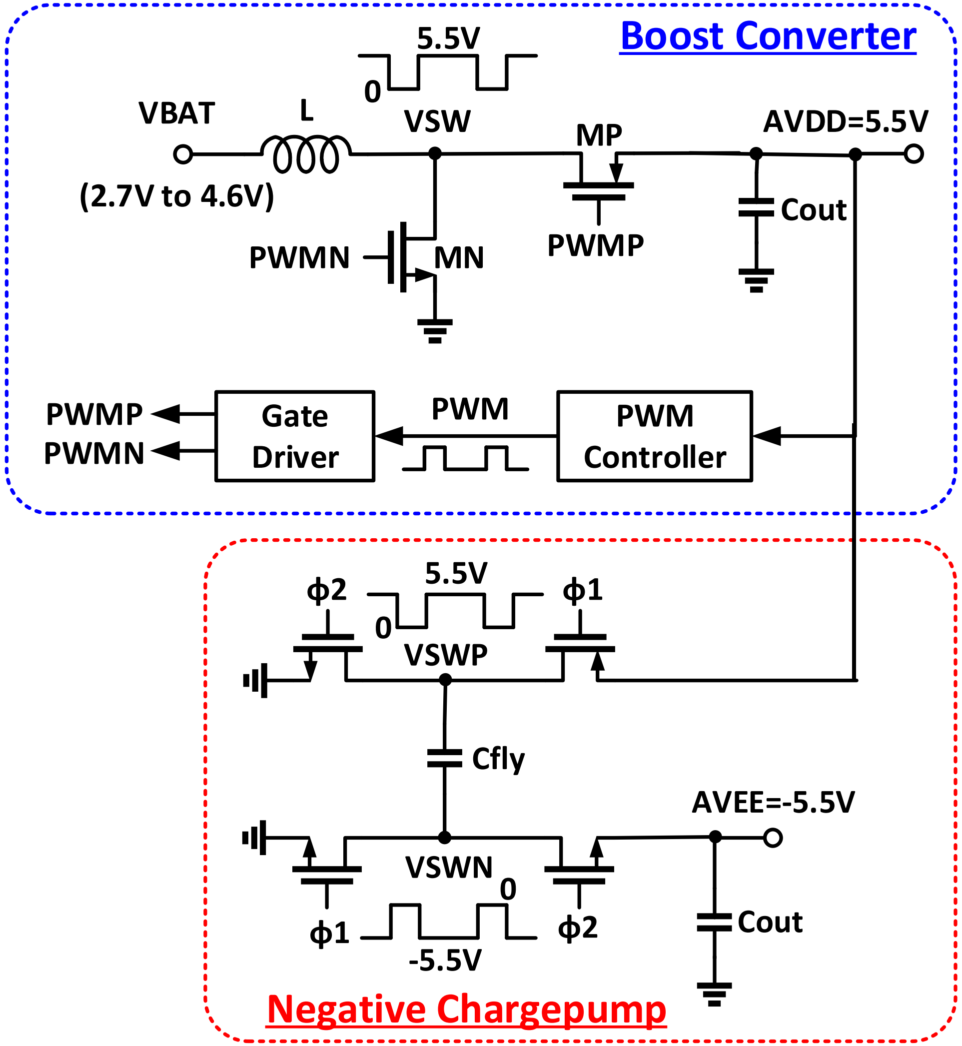
- **+5.5V can be generated from an inductive boost**

$$AVDD = \frac{1}{1-D} \cdot VBAT$$



Generating +/-5.5V

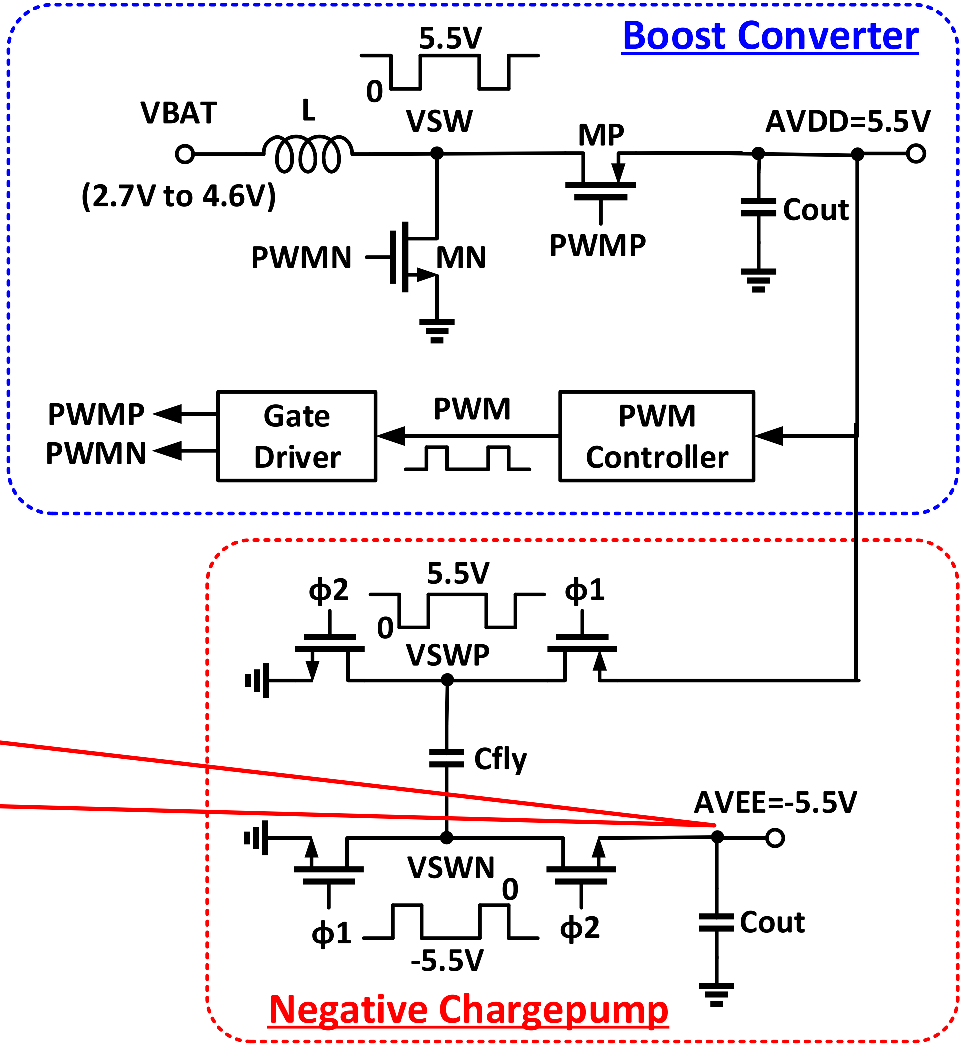
- **+5.5V can be generated from an inductive boost**
- **-5.5V can be generated from a negative chargepump**



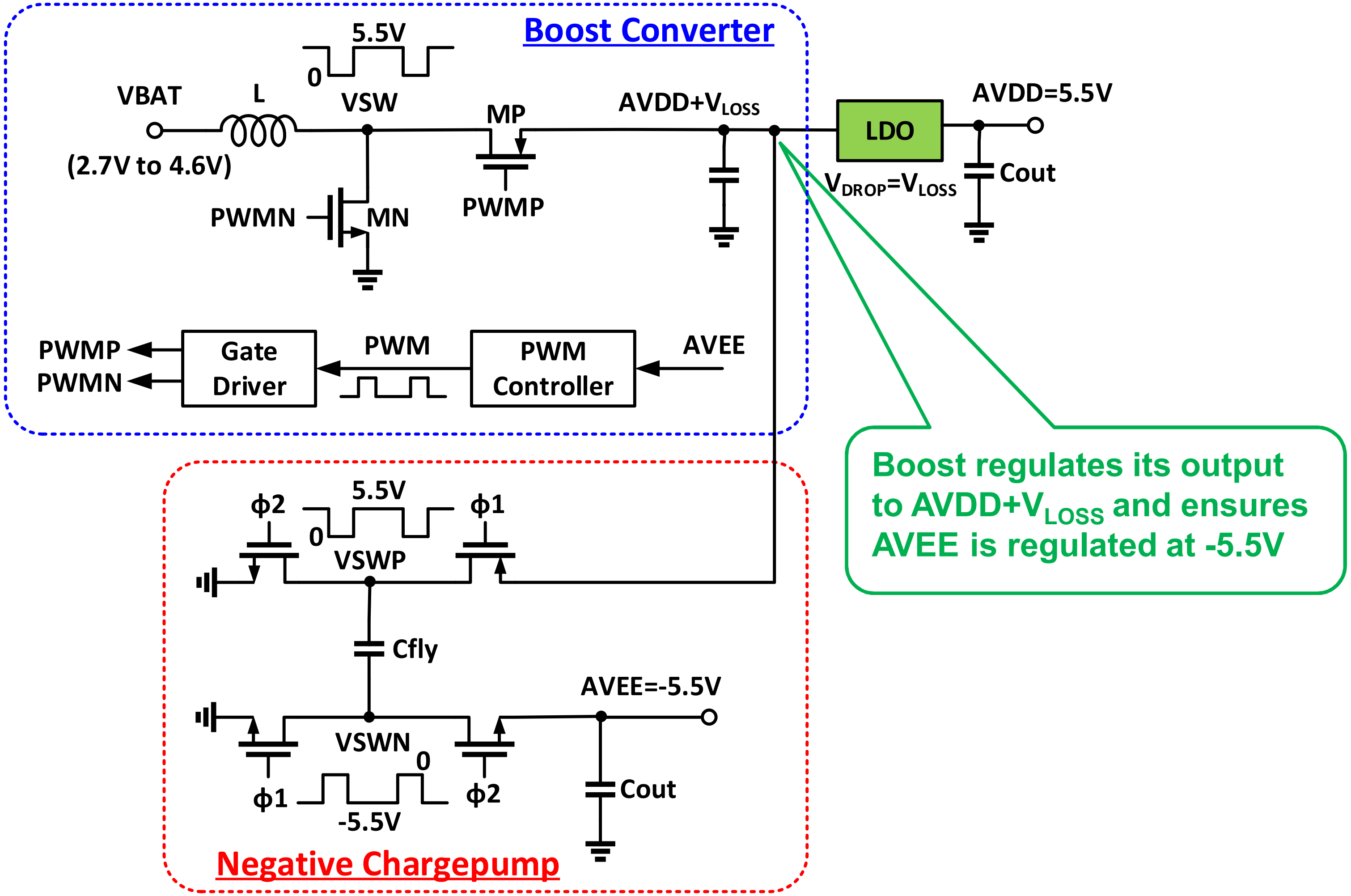
Generating +/-5.5V

- +5.5V can be generated from an inductive boost
- -5.5V can be generated from a negative chargepump

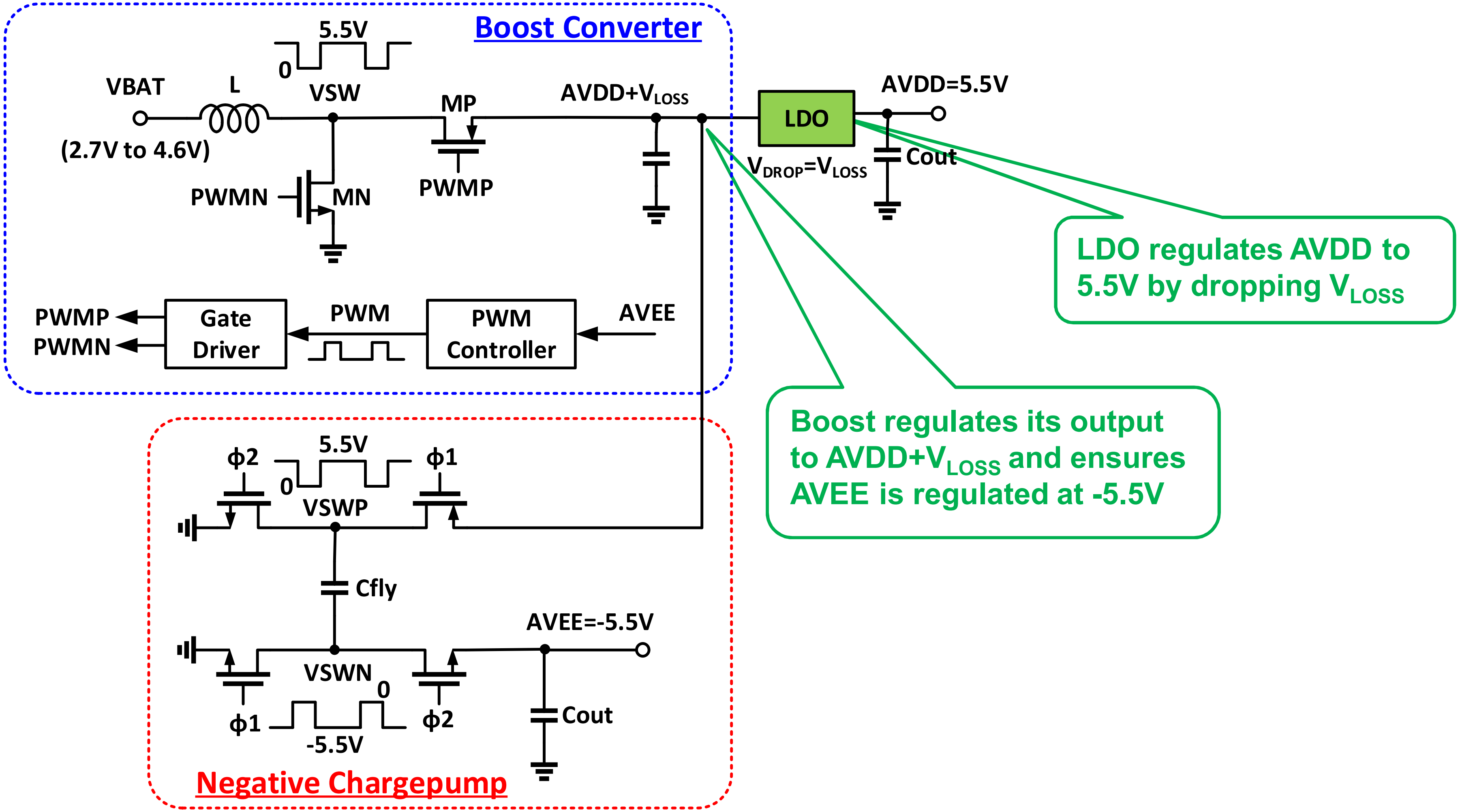
Losses in chargepump cause AVEE regulated above -5.5V
i.e. AVEE=-5.5V+V_{LOSS}



Compensating for Chargepump V_{LOSS}

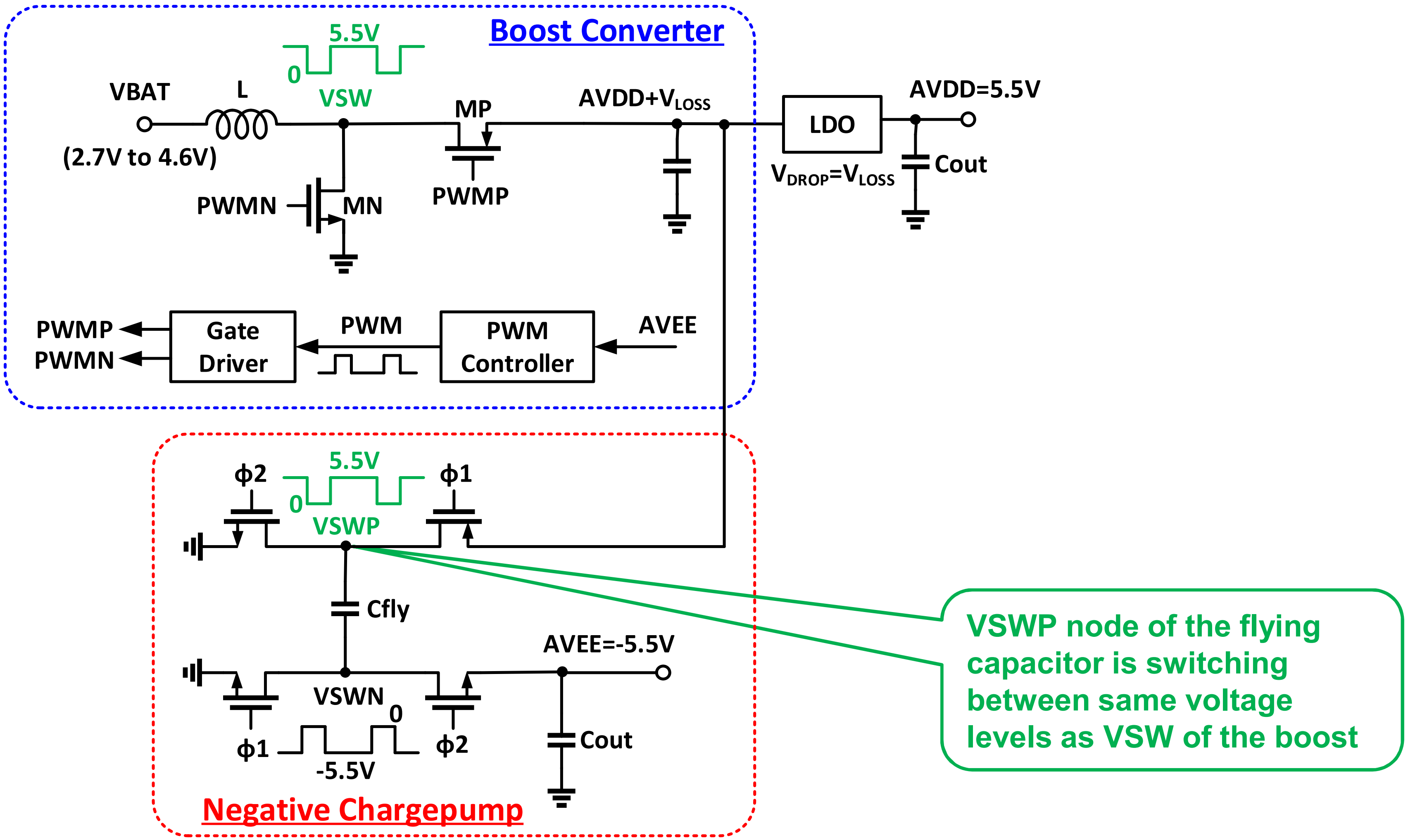


Compensating for Chargepump V_{LOSS}

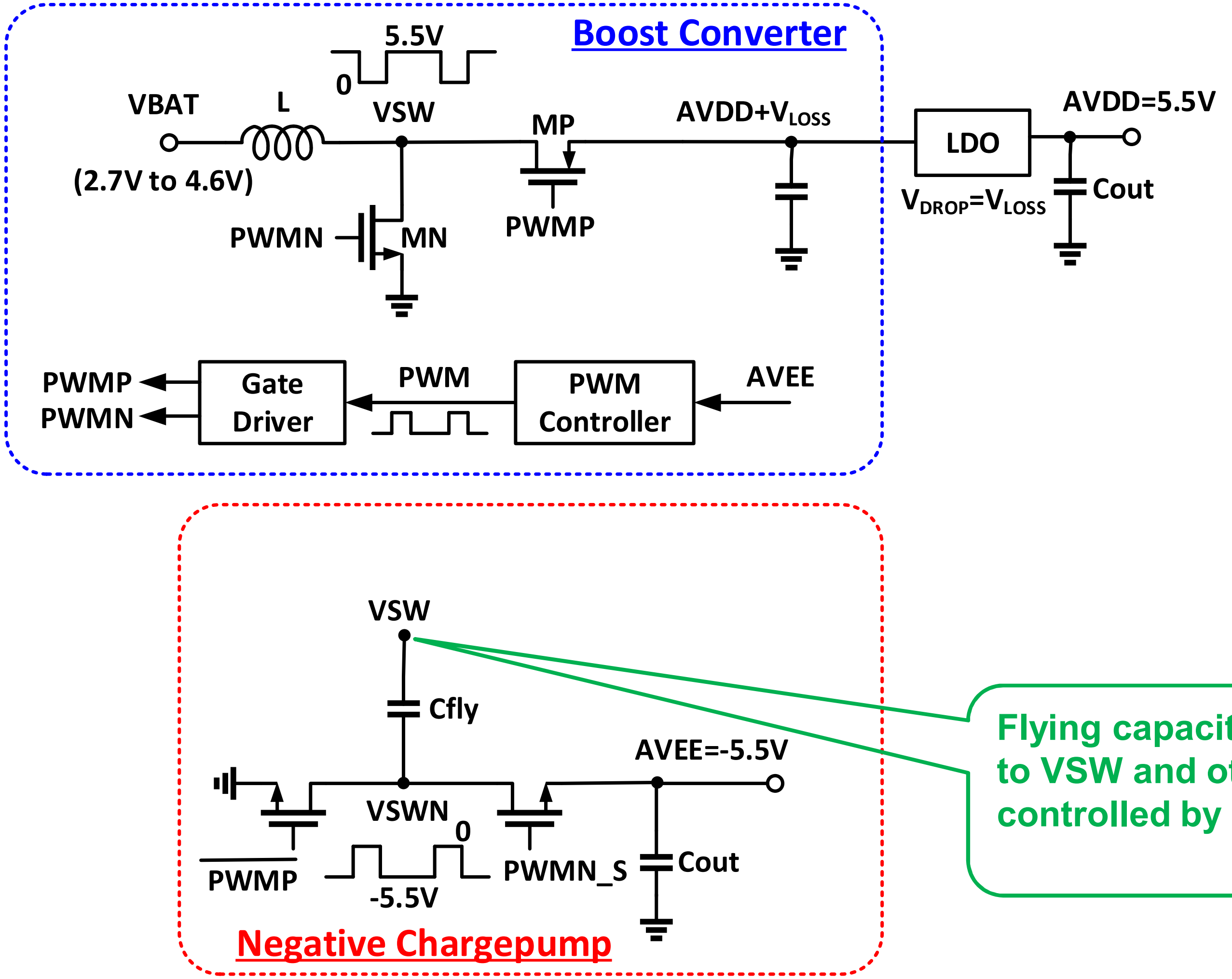


Ref: TI's tps65132 datasheet

Switch reduction from Chargepump

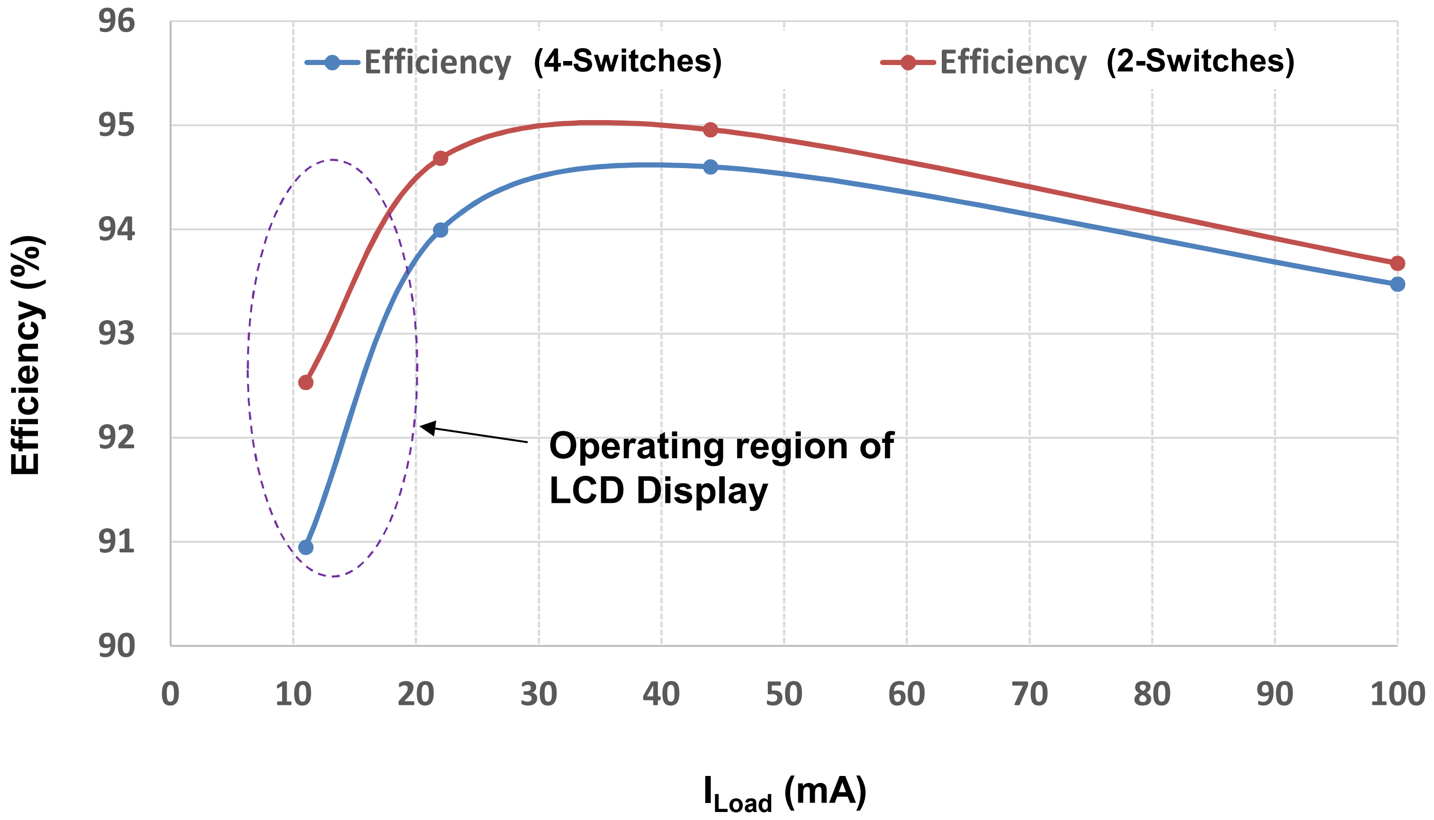


Switch reduction from Chargepump



Flying capacitor can be connected to VSW and other two switches are controlled by PWM

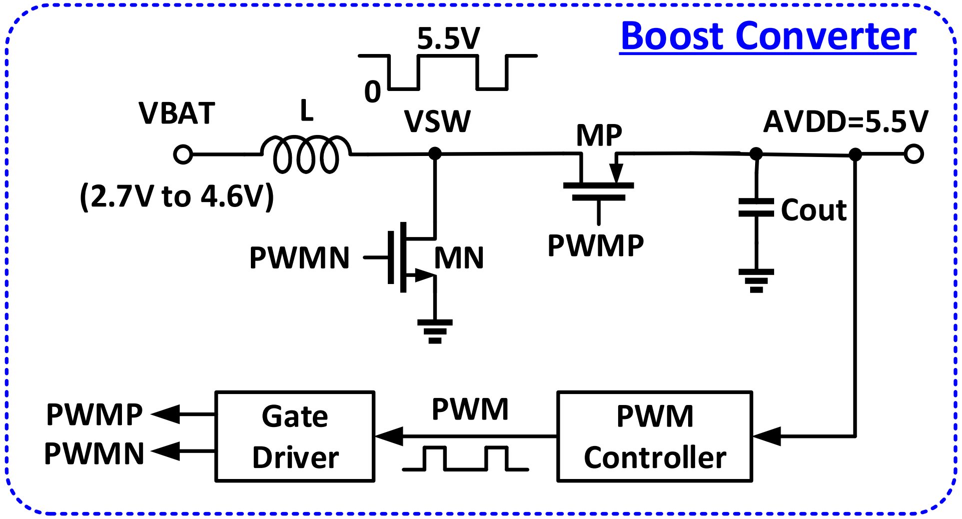
Efficiency Improvement with Switch reduction



Generating +/-5.5V

- **+5.5V can be generated from an inductive boost**

$$AVDD = \frac{1}{1-D} \cdot VBAT$$



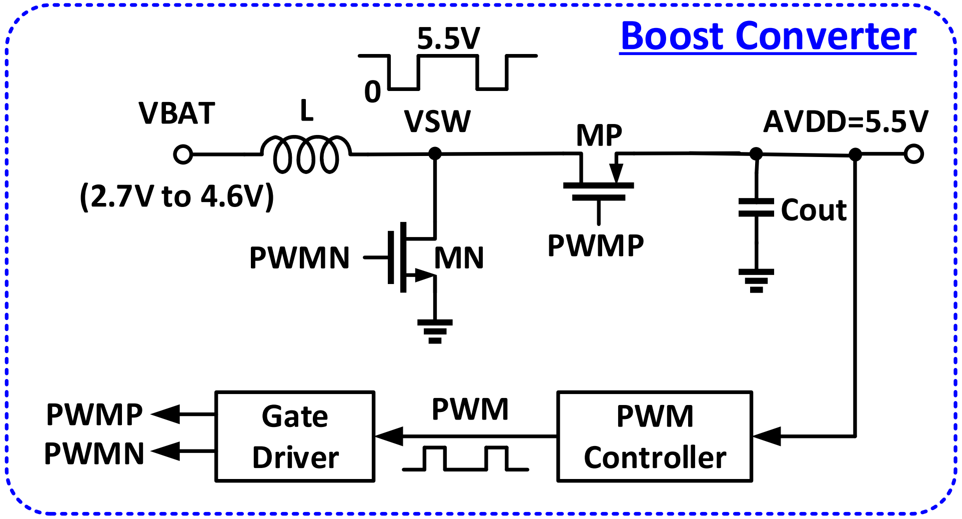
Generating +/-5.5V

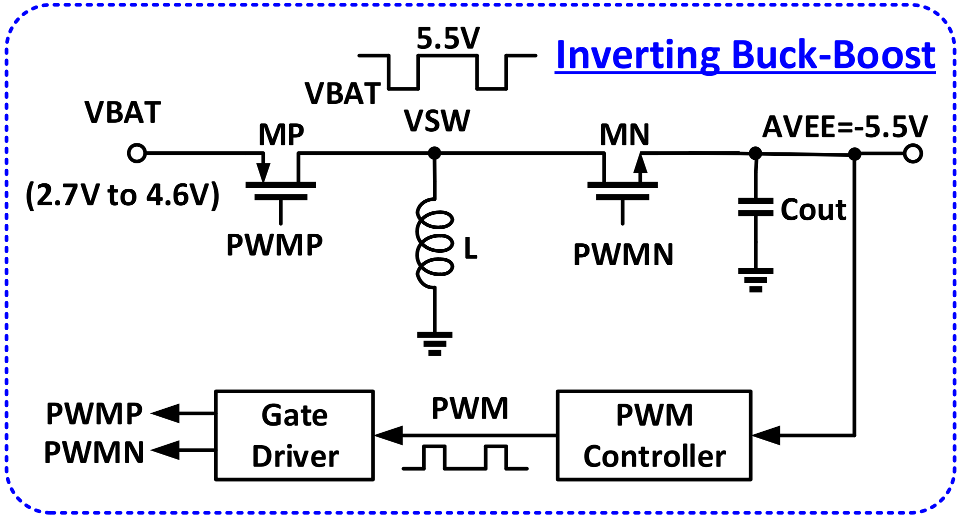
- +5.5V can be generated from an inductive boost

$$AVDD = \frac{1}{1-D} \cdot VBAT$$

- -5.5V can be generated from an inductive buck-boost

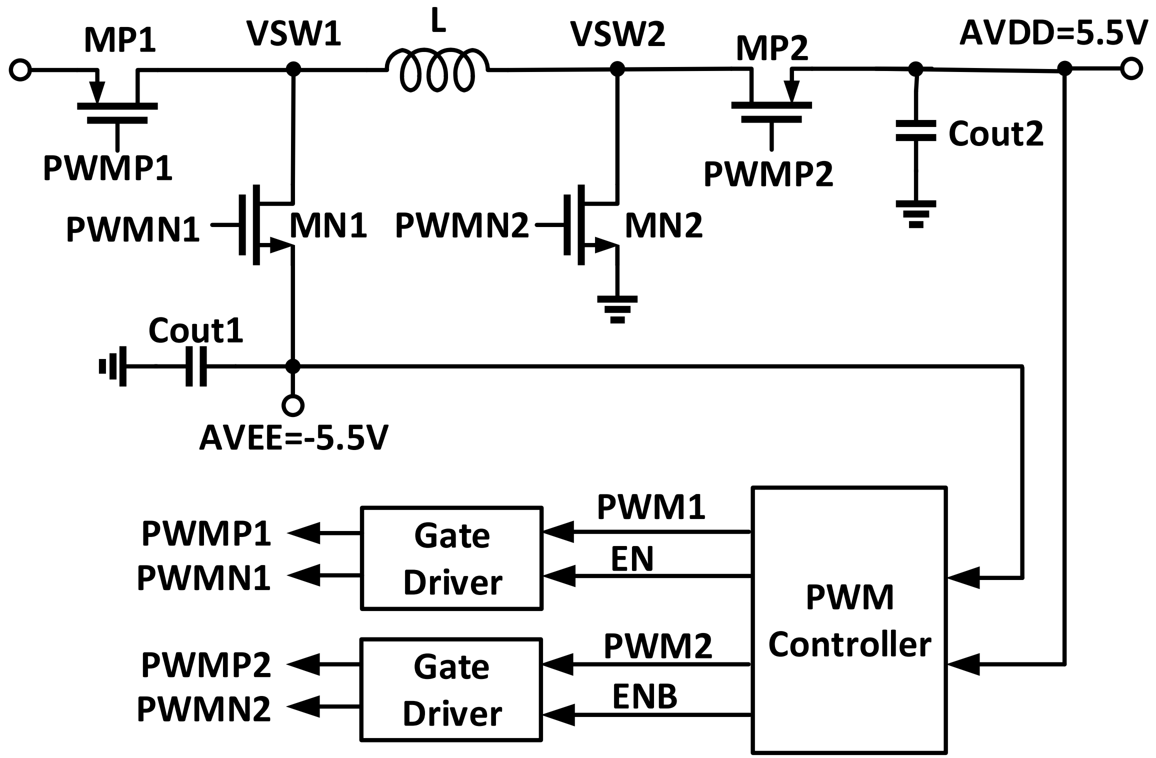
$$AVEE = -\frac{D}{1-D} \cdot VBAT$$



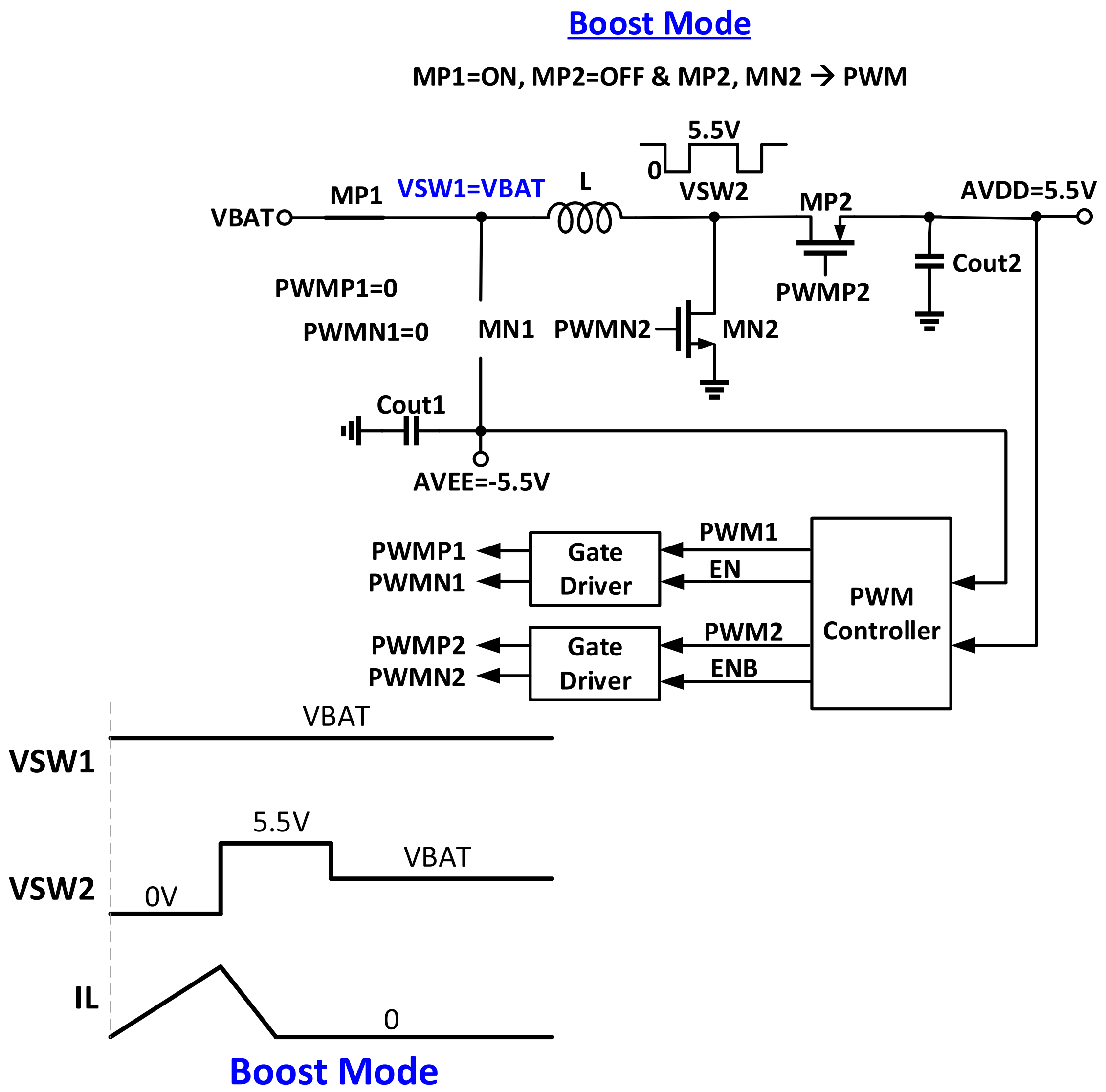


Single Inductor Dual Output (SIDO) Converter

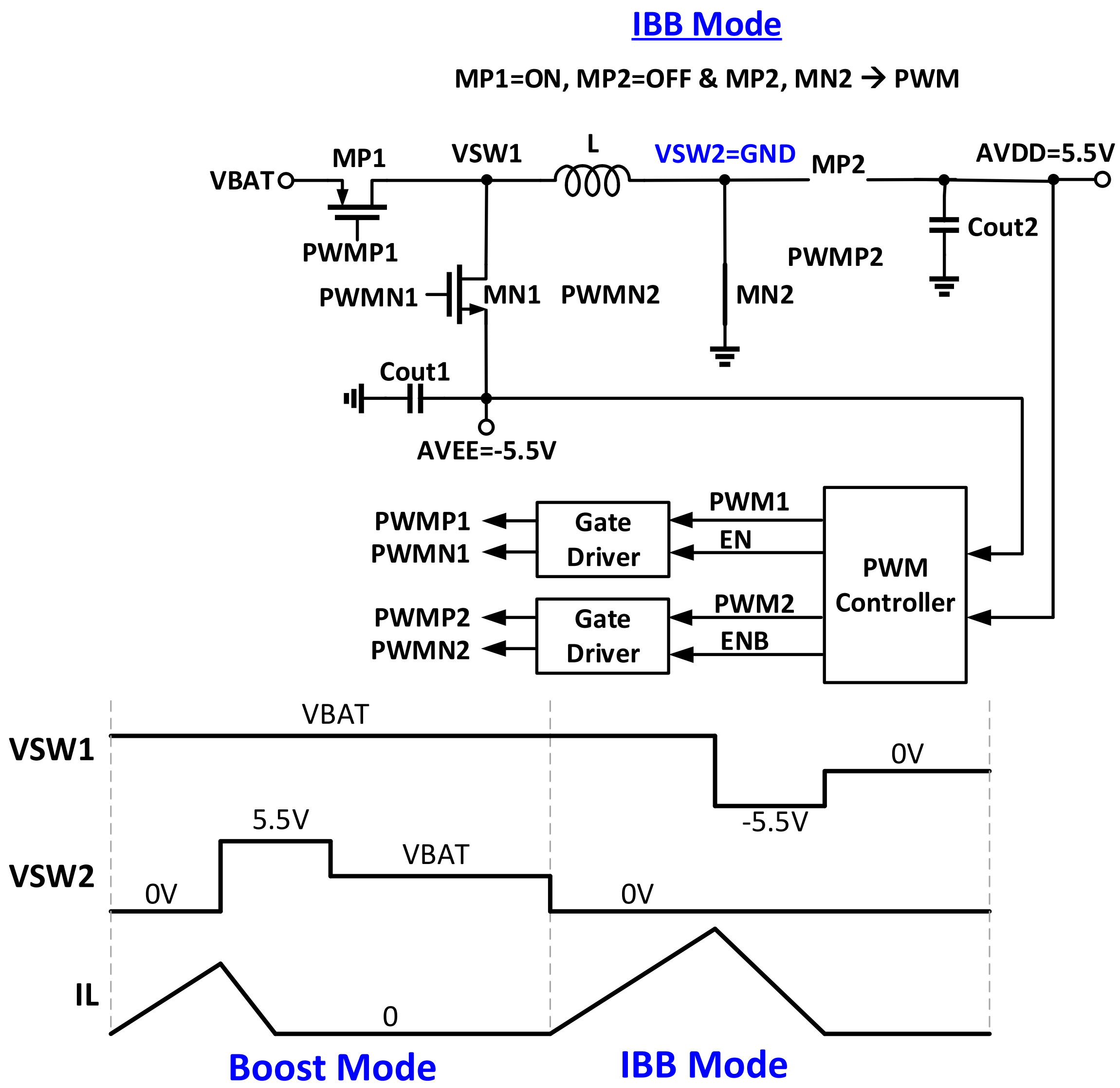
- Uses single inductor to generate both AVDD and AVEE
- PWM is time multiplexed between Boost and Inverting Buck-Boost
- Mostly used in DCM or CCM-DCM boundary to avoid cross regulation



SIDO Operation

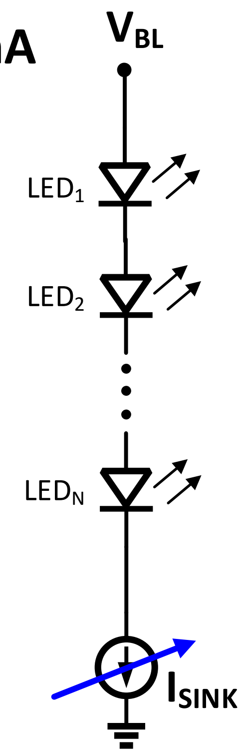


SIDO Operation



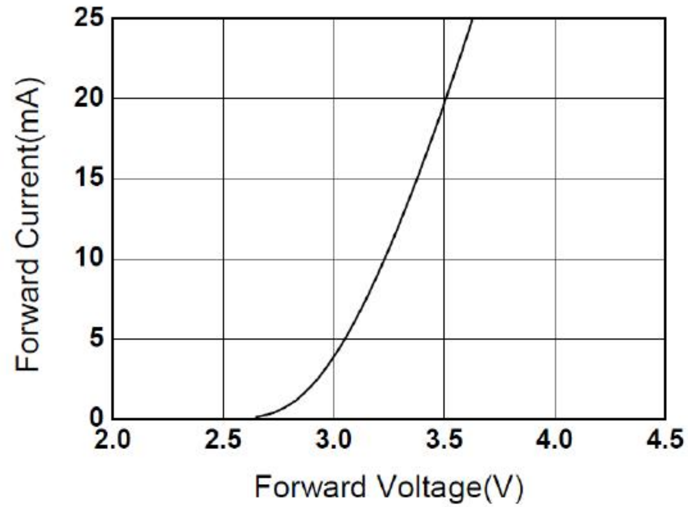
LCD Backlight

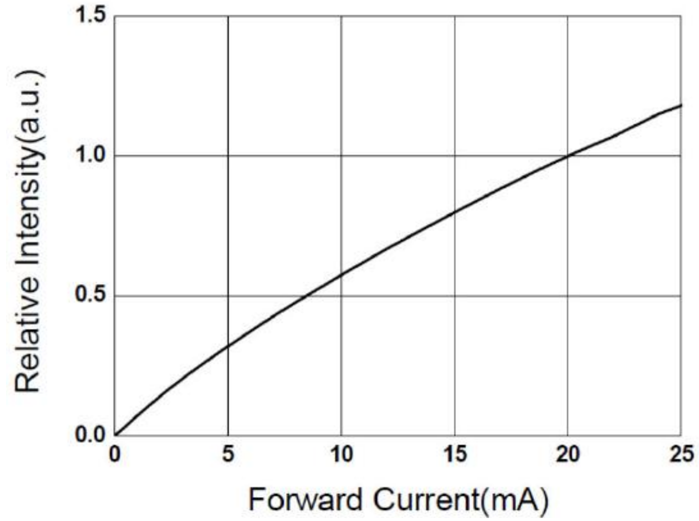
- **LCD backlight is provided by multiple white LED connected in series**
- **Power supply VBL can be supplied externally or generated inside the LED driver**
- **Full scale is LED current is ~20mA**



$V_{BL}=N\cdot V_F+V_{SENSE}$

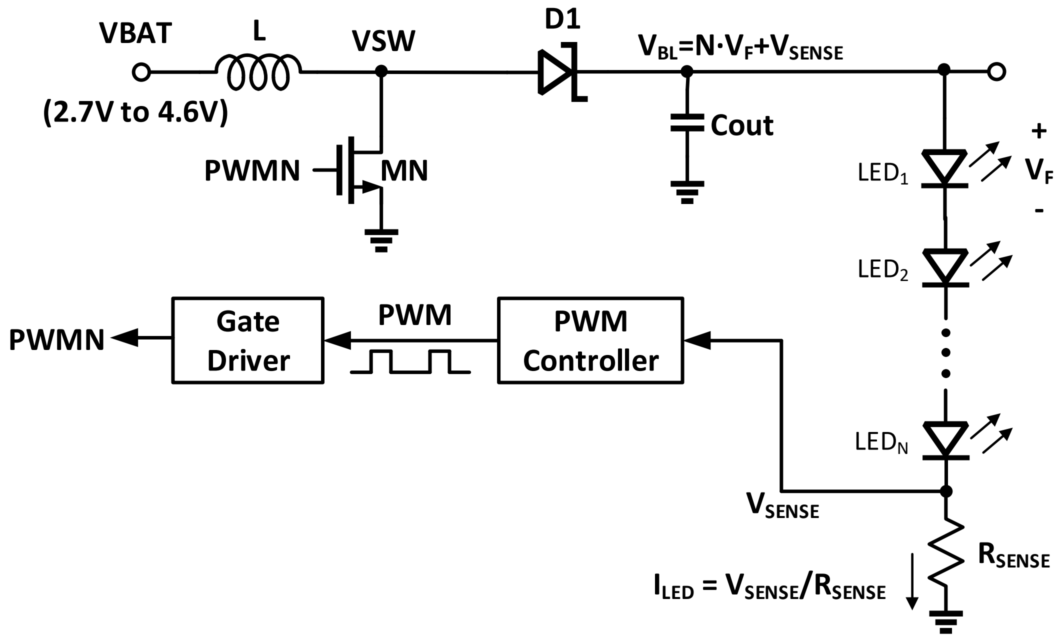
LED brightness α I_{LED}





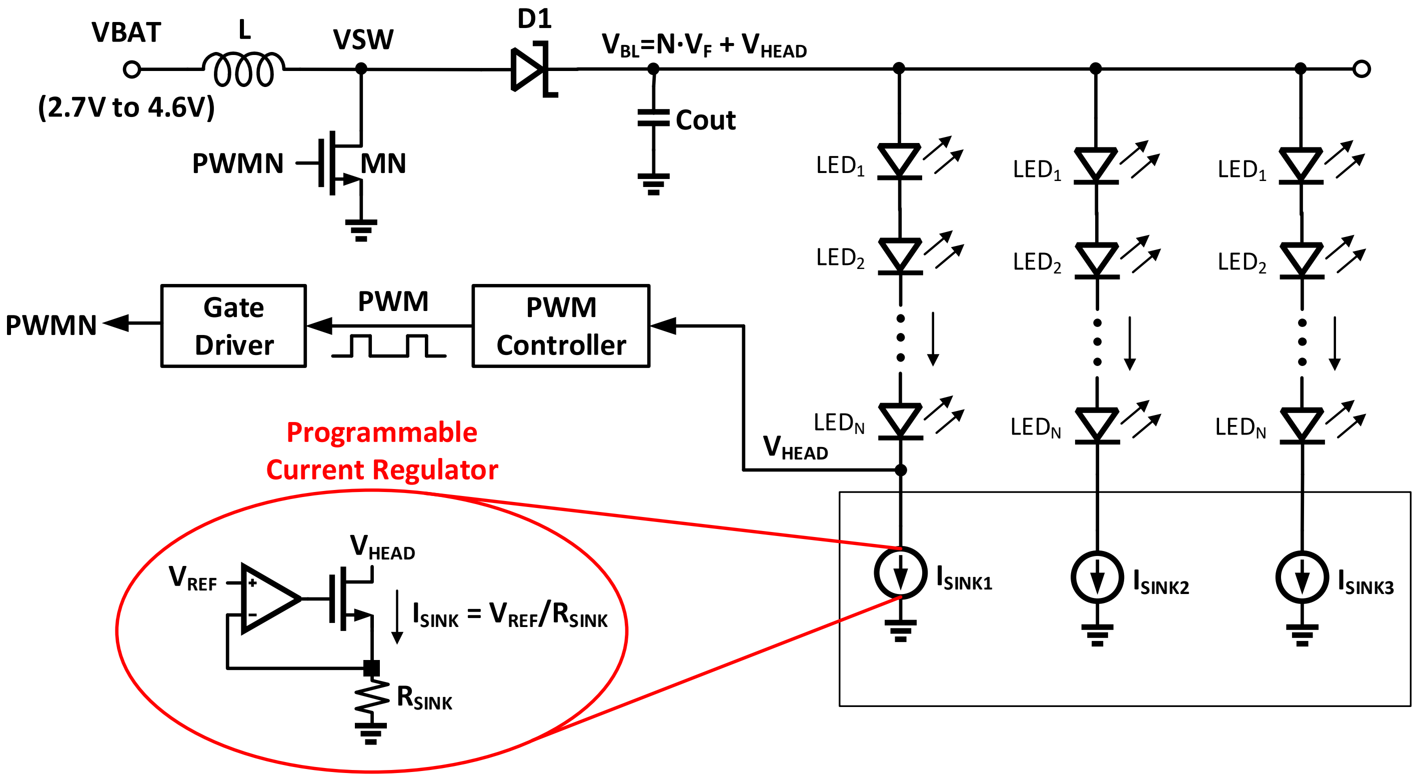
LCD Backlight Power Supply + Driver

- **LCD backlight is supplied by LED drivers driven with a constant current**
- **Multiple LEDs are usually connected in series thus requiring much higher voltage (~28V for 8 LEDs)**
- **Simplest way is drive LEDs is boost converter with external current sense resistor**
- **Works only for single string**



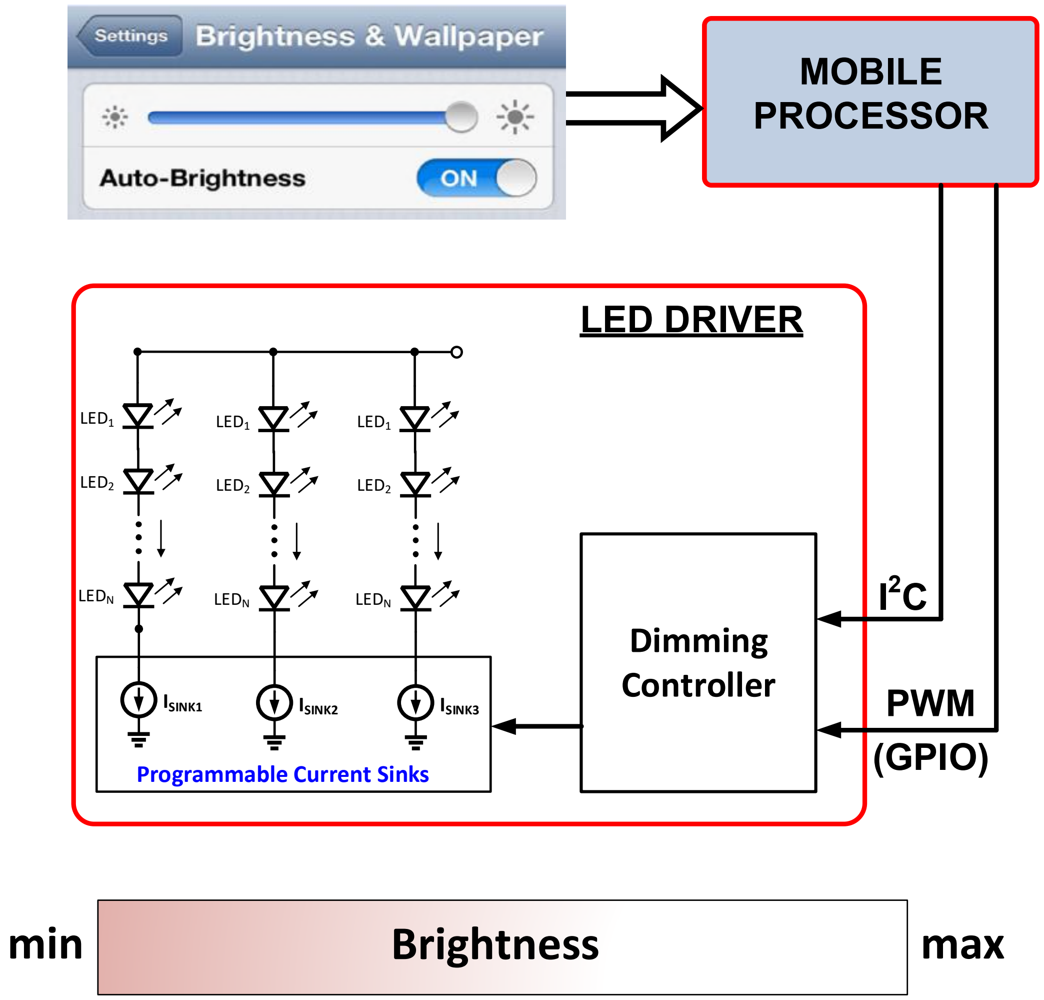
LED Driver for Parallel Strings

- Usually LCD panels for smartphones require 16-24 LEDs (8s2p or 8s3p) hence requiring independent current sinks for each string
- V_{HEAD} is regulated to minimum voltage required to keep current sinks in saturation region



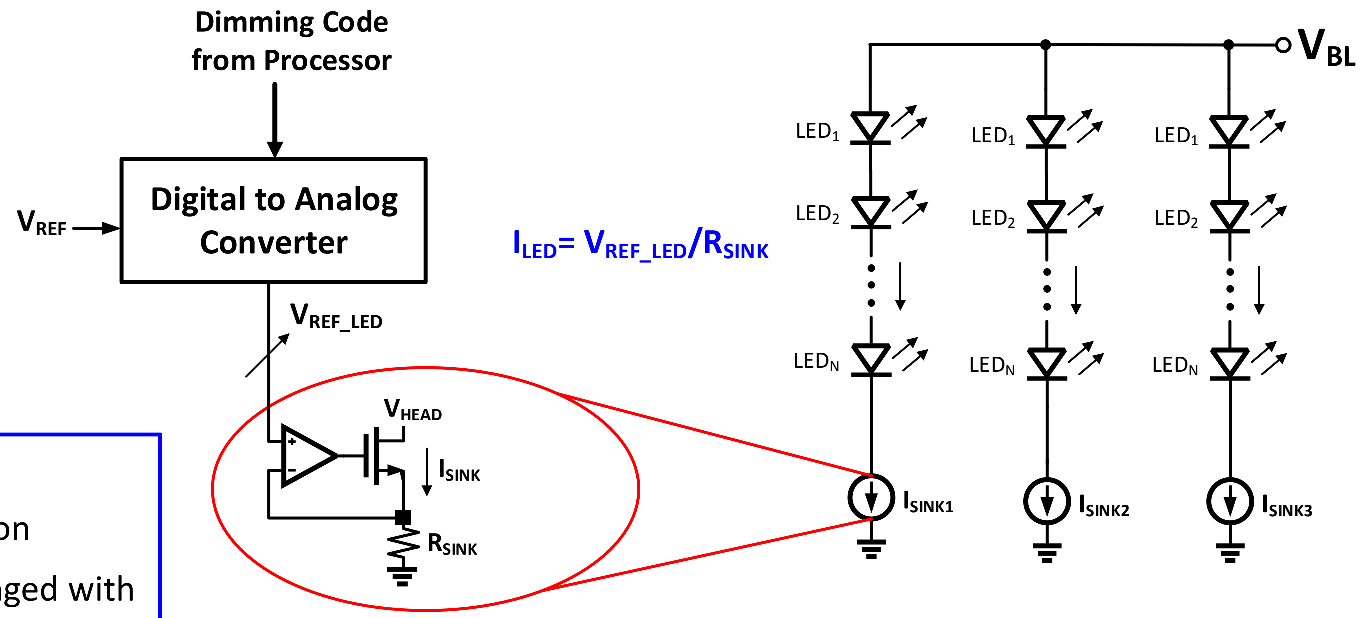
Controlling Backlight Brightness (Dimming)

- **Two ways to control the brightness**
  - **PWM or Digital Dimming**
  - **Analog Dimming**



Analog Dimming

- Analog dimming is achieved by converting the digital dimming code to an analog reference voltage through D/A converter
- Alternatively R_{SINK} can also be programmed
- For smooth dimming, usually 7-8 bit of D/A resolution is used



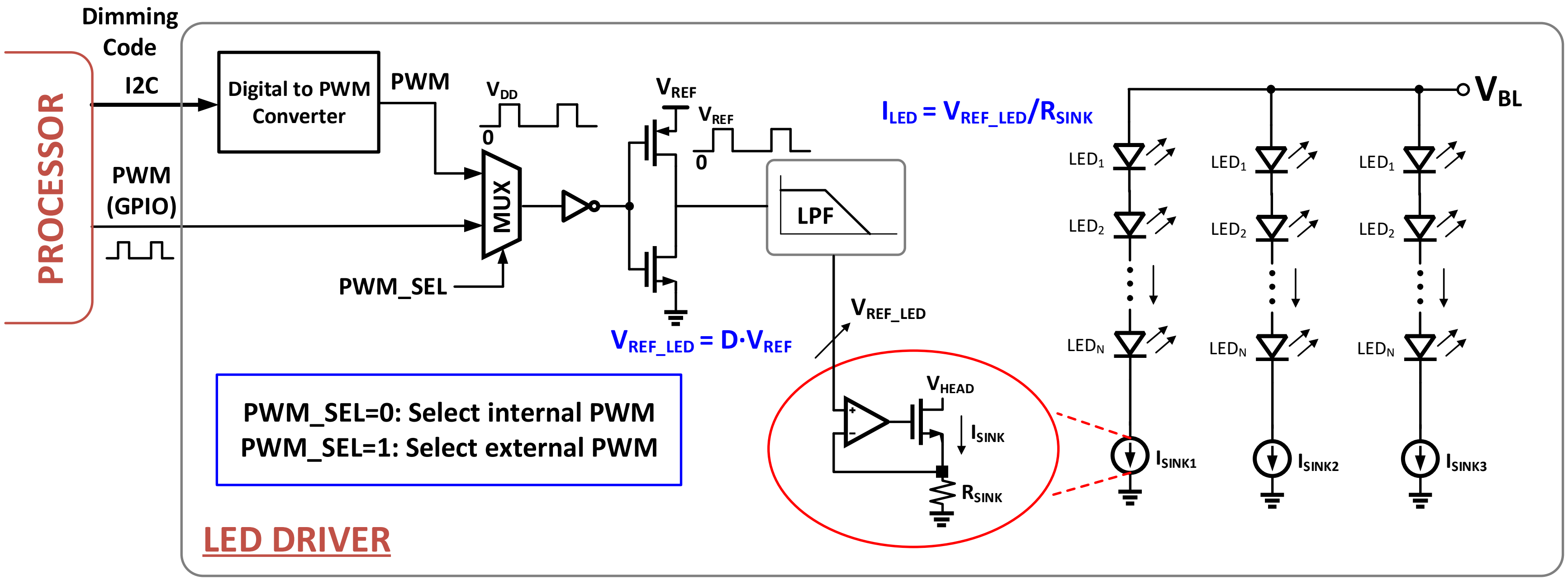
Full scale I_{LED}= 20mA

With 8-bit D/A conversion

LED current can be changed with step size = 20mA/256 = ~80µA

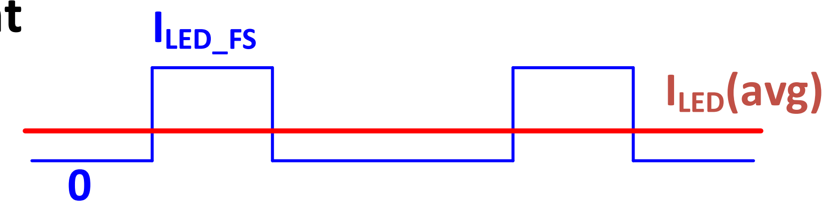
Analog Dimming using PWM

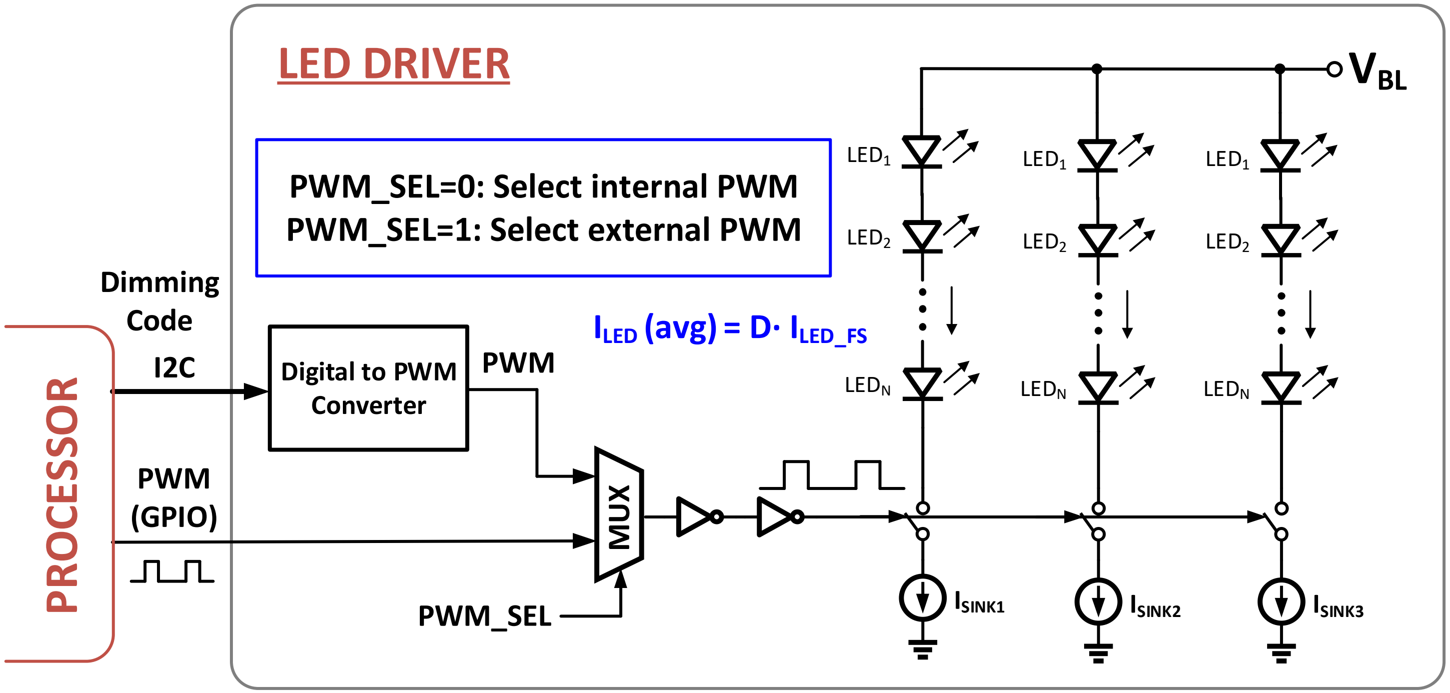
- V_{REF} is modulated with PWM duty cycle and low pass filtered to get V_{REF_LED}
- Doesn't require D/A converter
  - Area efficient
  - Reduces design complexity



Digital or direct PWM Dimming

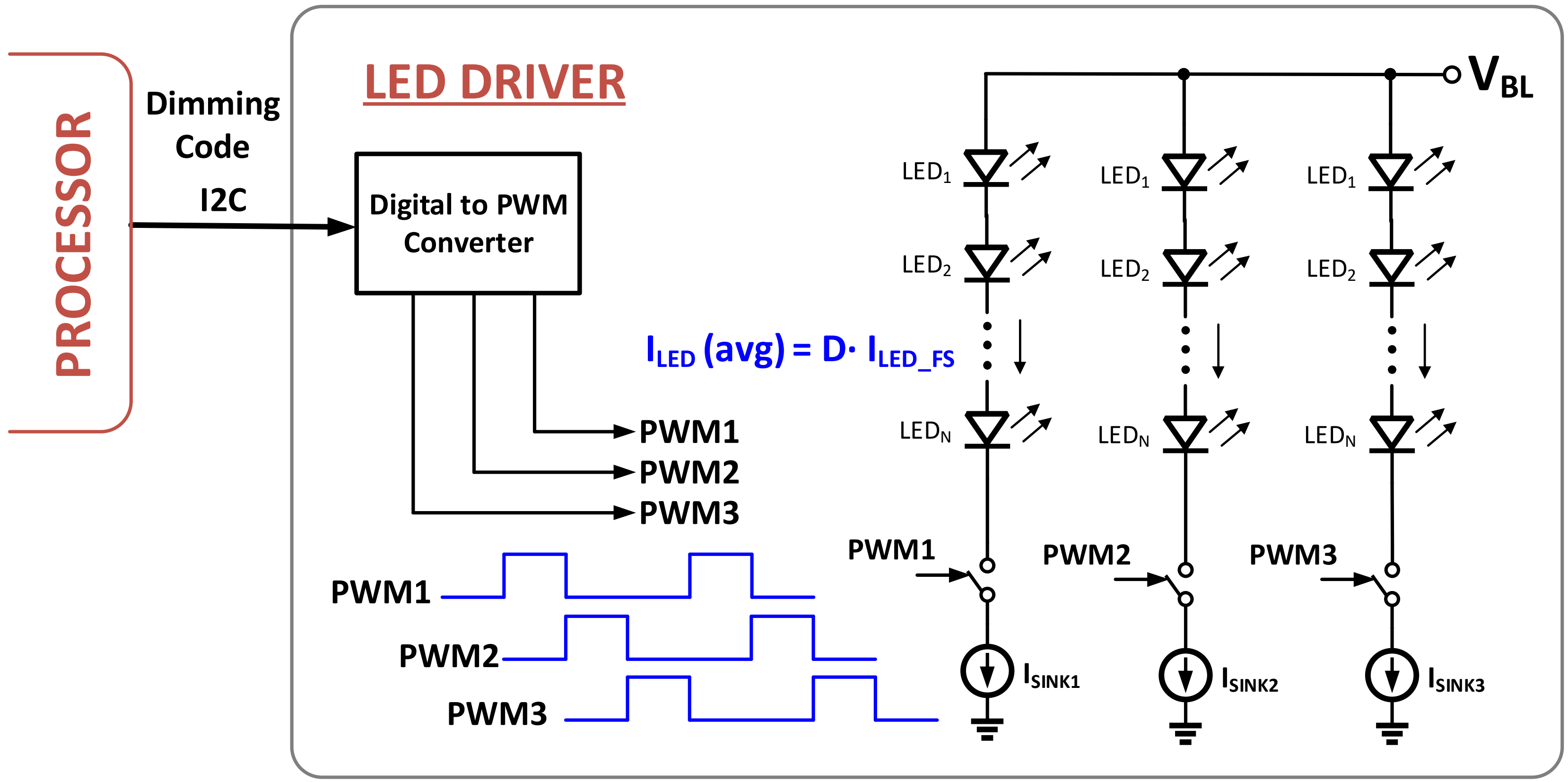
- Full scale LED current (I_{LED_FS}) is directly modulated with PWM duty cycle at frequency high enough (≥ 1 kHz) to be filtered by the human eyes
- EMI concerns due to switching current
  - Peak current = $3 \cdot I_{LED\_FS}$





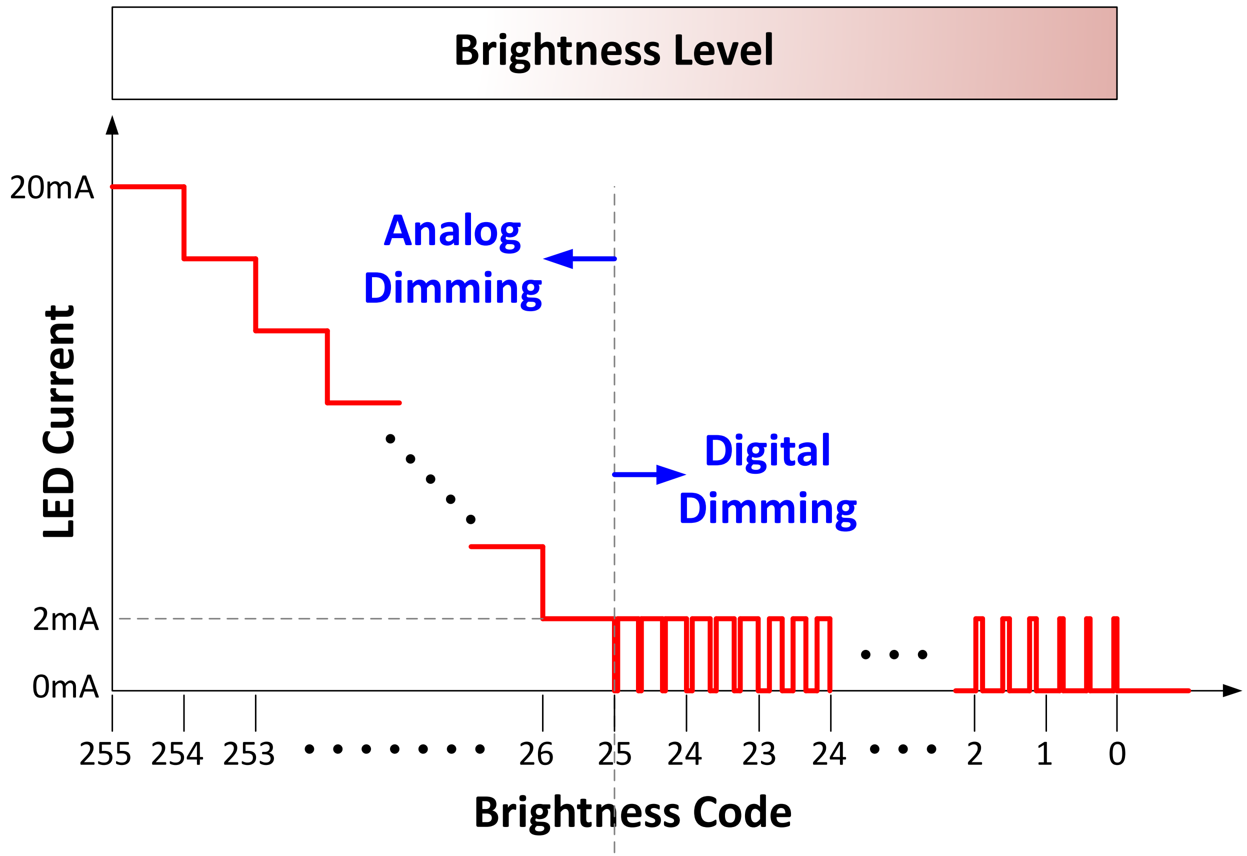
Staggered PWM Dimming

- EMI can be mitigated by switching each LED string at different times
- Suitable mainly with internal PWM as external PWM requires 3 GPIOs



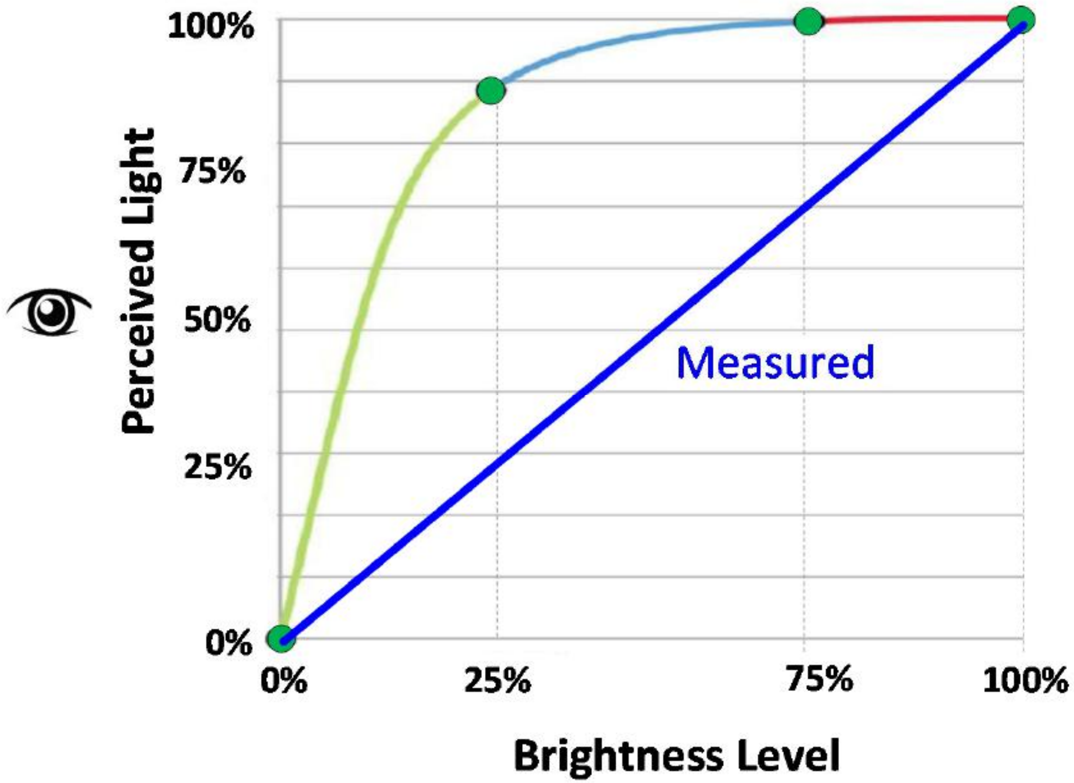
Hybrid Dimming

- **Hybrid dimming combines both analog and digital to address the concern of:**
  - **Flicker in analog dimming due to noise at very low brightness**
  - **EMI in digital dimming due to high switching current**



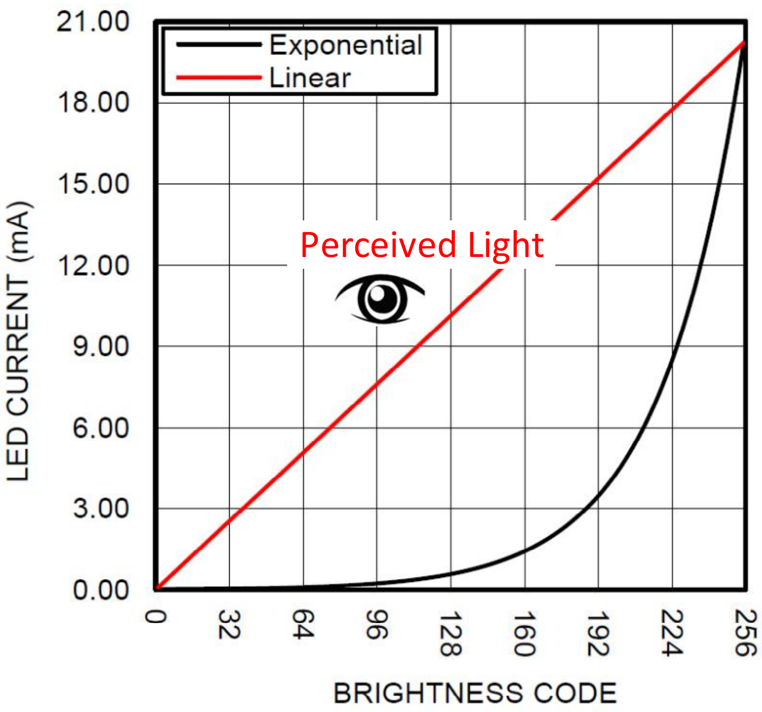
Human Perception of Brightness Level

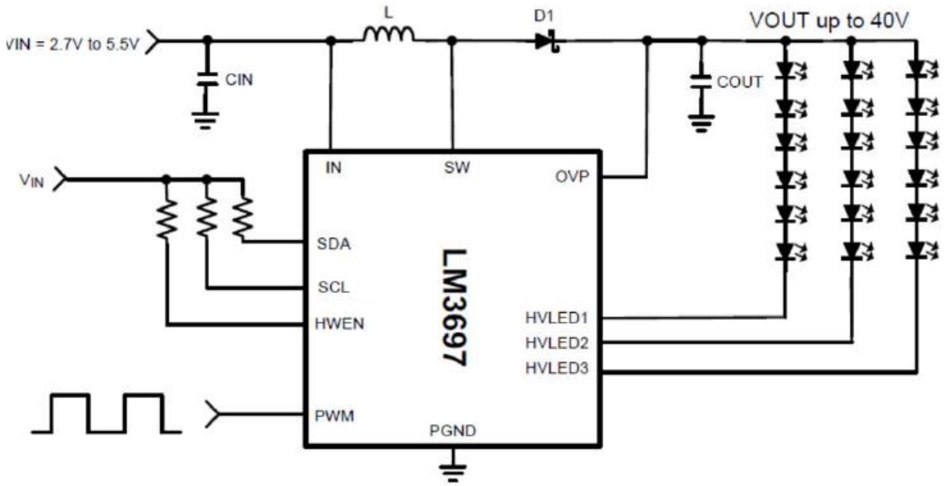
- **Human eyes perceive light in logarithmic manner**
- **With linear brightness control, eyes observe very little change in brightness above 50% while steeper change in light observed at low brightness**



Exponential Mapping of Brightness Code

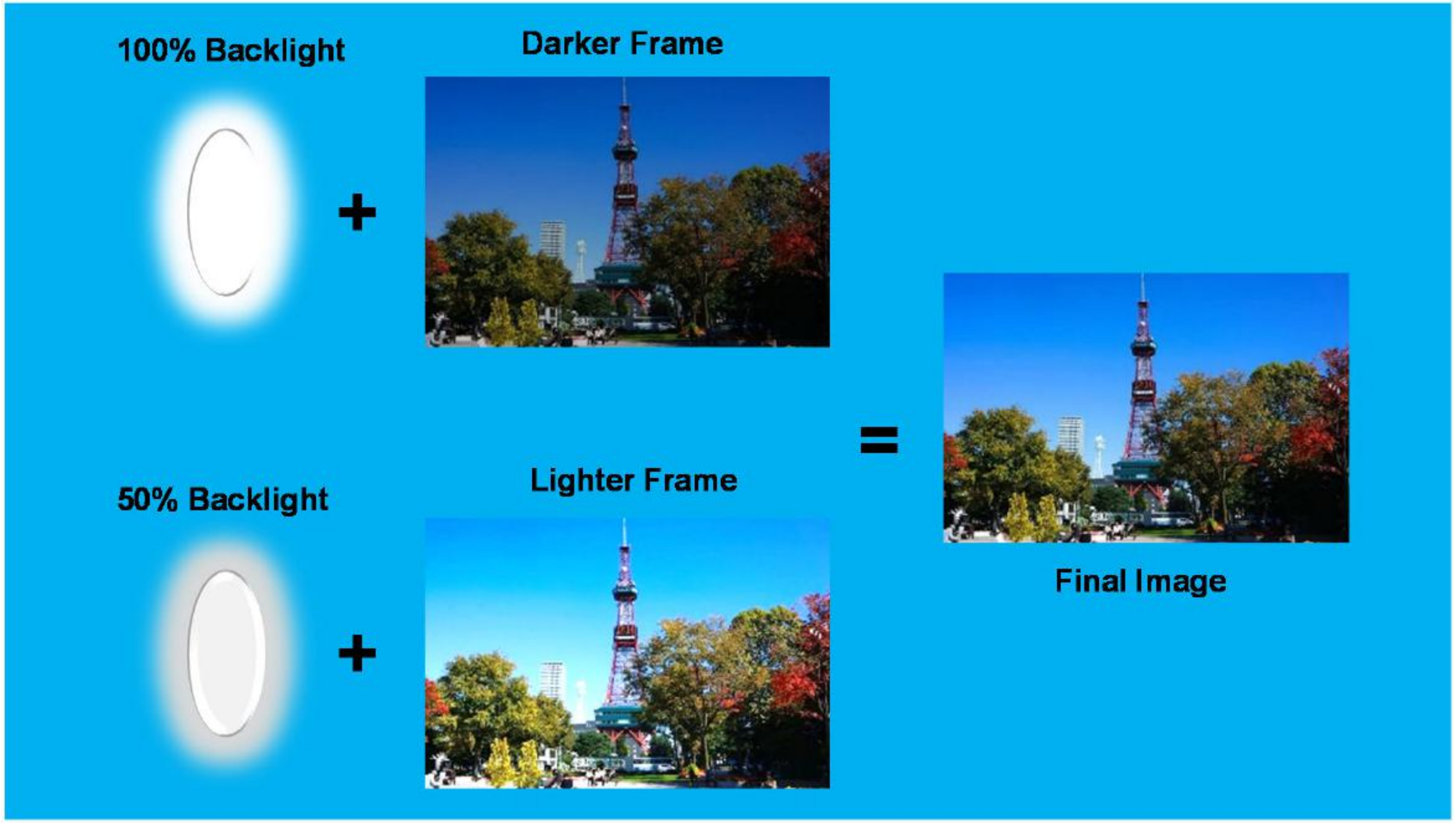
- **Instead of controlling the brightness in linear manner, codes are mapped to exponentially which appears linear to human eyes**



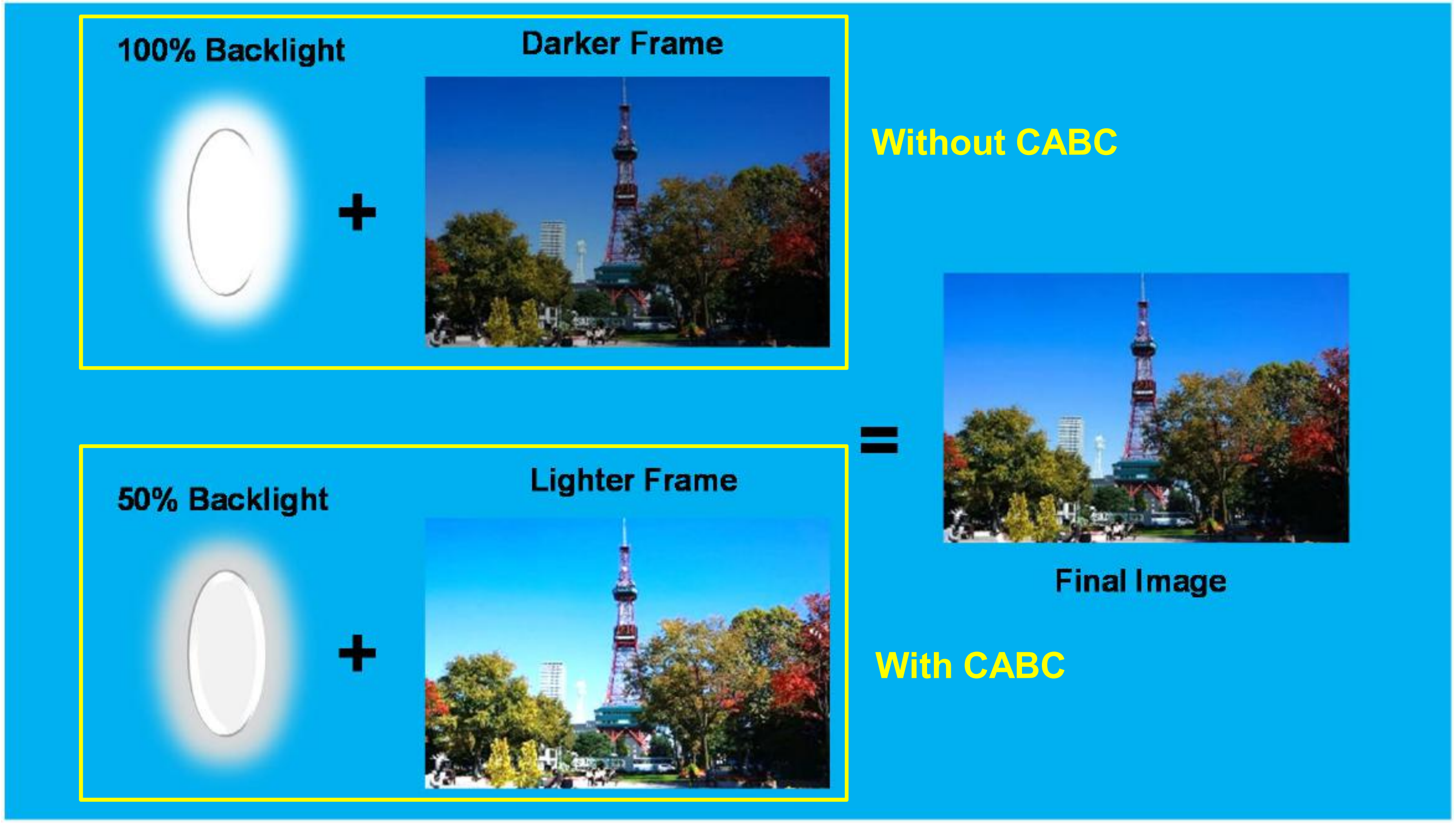


Source: Texas Instruments

Content Adaptive Brightness Control

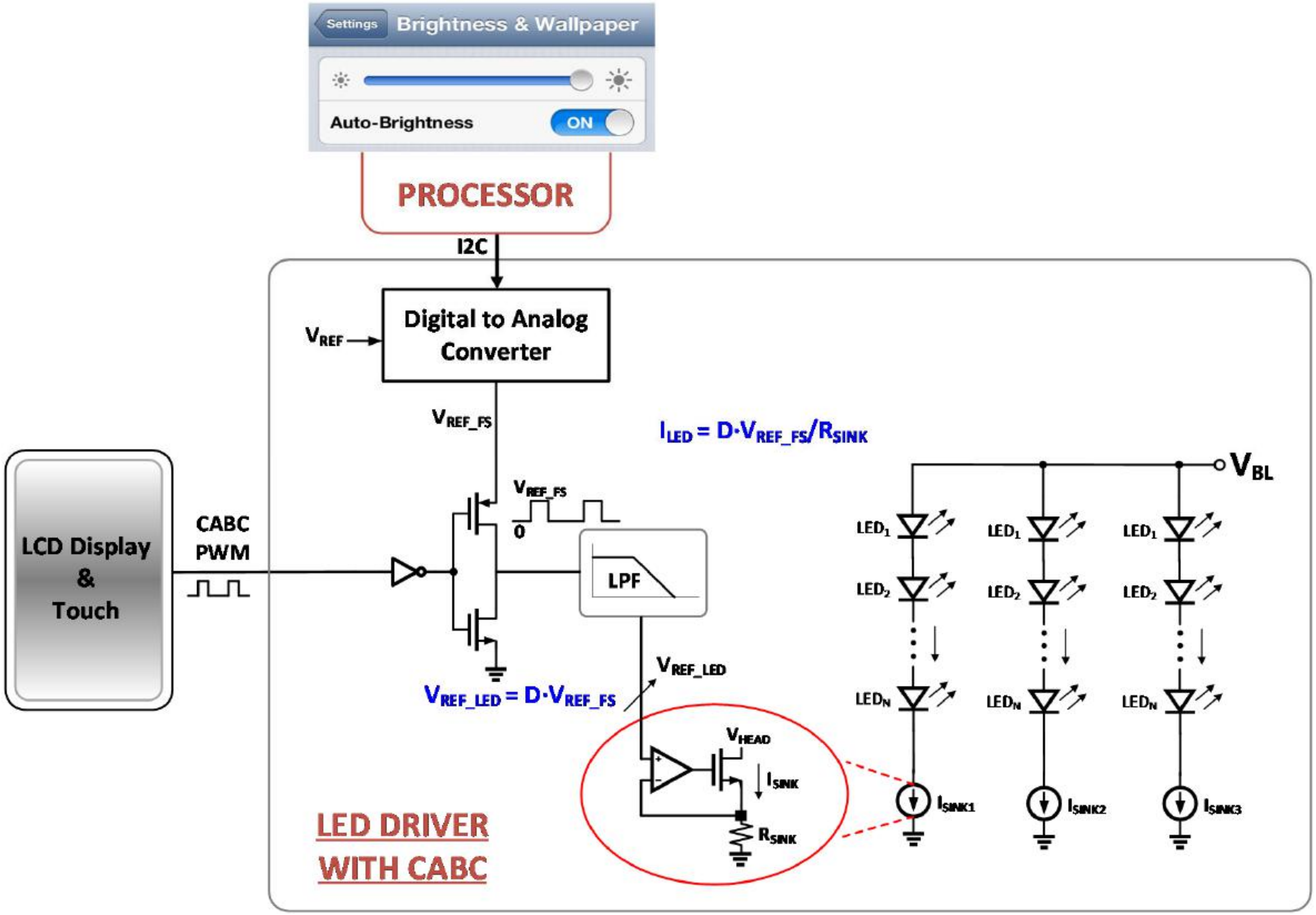


Content Adaptive Brightness Control



CABC adaptively changes backlight depending upon the image intensity

LED Driver with CABC

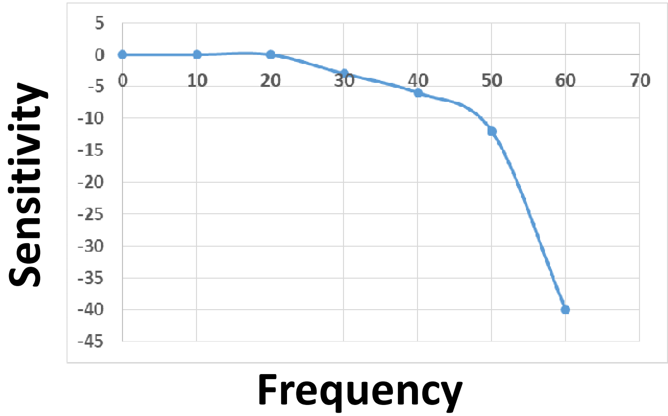


Flicker in Display Panels

- **Flicker is caused by period change in display brightness level at frequency below the human visual perception (usually below 100 Hz)**

Flicker Perception of Human Eye

Frequency	Factor	
(Hz)	dB	Ratio
0	0	1.000
10	0	1.000
20	0	1.000
30	- 3	0.708
40	- 6	0.501
50	- 12	0.251
60	- 40	0.010



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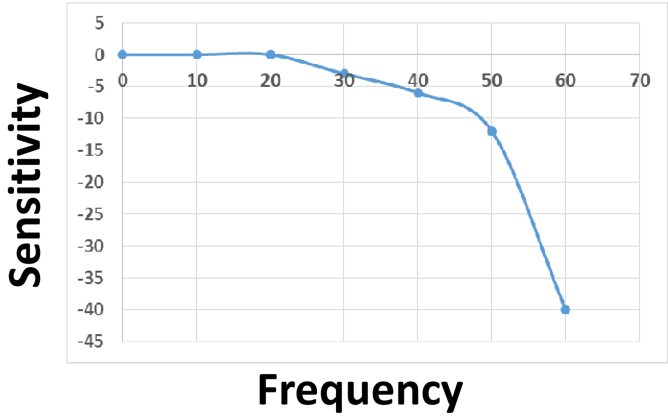
50	- 12	0.251
60	- 40	0.010



Flicker @10Hz

Flicker @60Hz

Sources of Flicker

1. Unstable power supply
2. Un-matched gamma in Positive and Negative frame
3. Low refresh rate
4. Un-optimized Vcom level

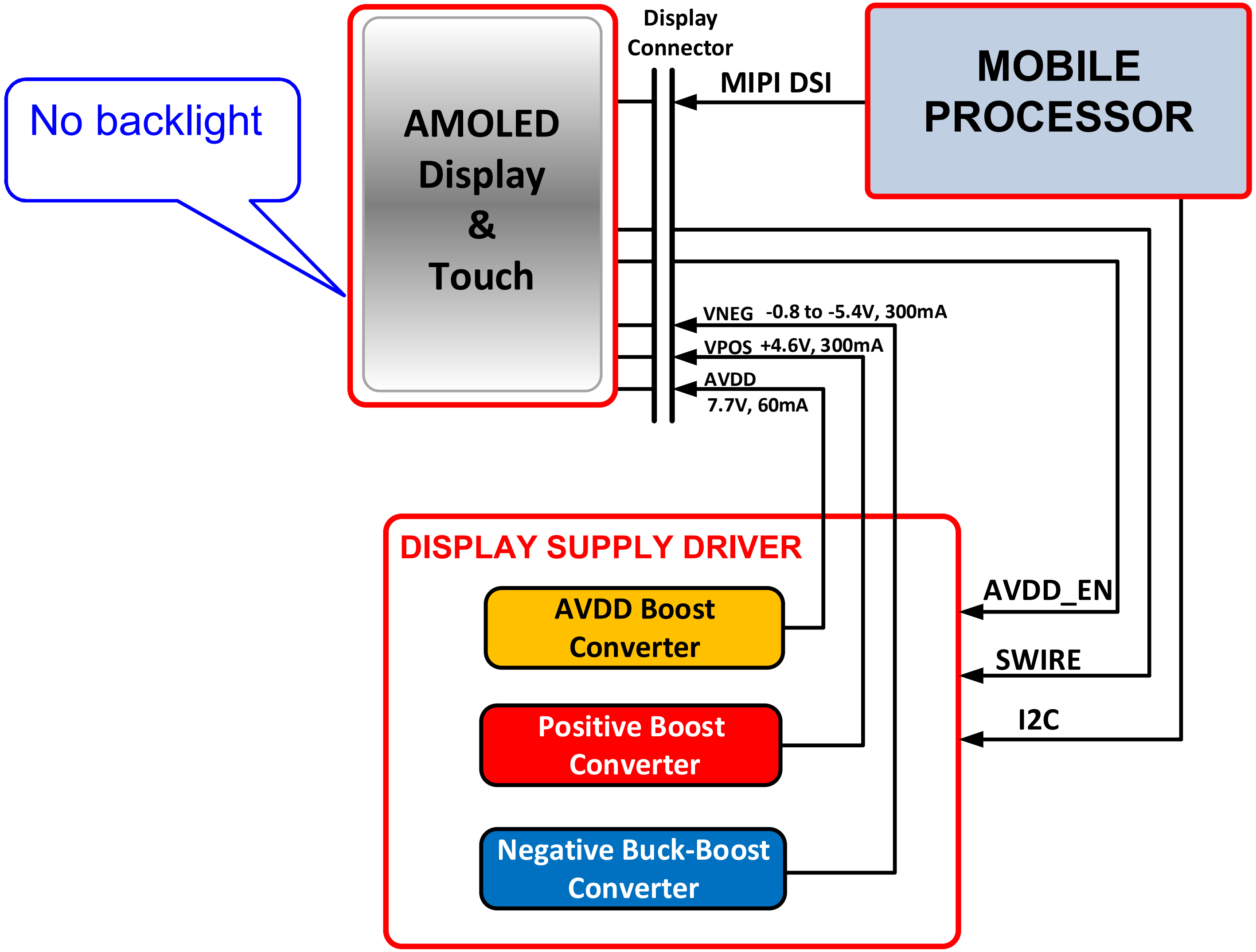
2,3 & 4 are non-power management related

Flicker in LCD

- Flicker in LCD is mainly caused by unstable backlight which is driven by LED drivers
- Instability in LED current could be caused by low frequency ripple in output voltage due to low frequency load and line transient

Power Management for AMOLED Displays

AMOLED Power Supplies



Power Supplies for AMOLED Display

Power Supply	Description	Value (Typ)	Supply Generation
VDDI	Digital Power Supply	1.8V	External (system VDD)
VDDA	Power Supply for Analog Systems	3.3V	Inside panel DDIC
VPOS	Positive Supply	4.6V	External (dedicated power IC)
VNEG	Negative Supply	-1.4V to -5.4V	External (dedicated power IC)
AVDD	High Voltage Analog for TFT	7.7V	External (dedicated power IC)

- **VPOS is fixed and has tight accuracy and ripple requirement**
- **VNEG is programmable and accuracy requirement is not as tight as VPOS**

Why Fixed VPOS?

- When TFT is ON gate voltage is sampled and held on Cs
- When TFT is OFF, any low frequency noise at VPOS will modulate I_{LED} (through M_{P2}) and cause flicker
- Low frequency noise may be caused by GSM burst during call (burst frequency = 217Hz) or 120Hz noise from wall adapter when charger is plugged in

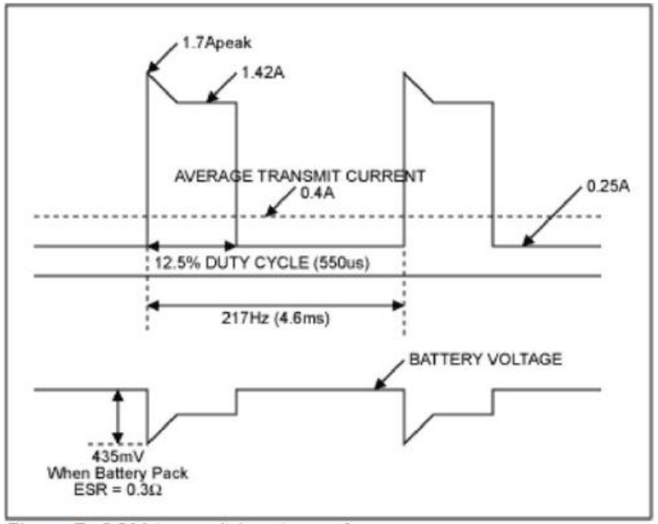
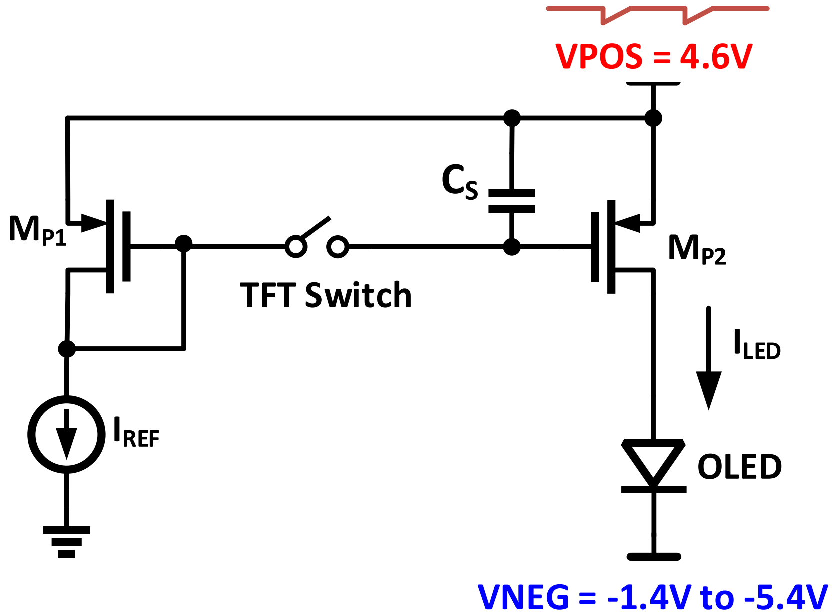


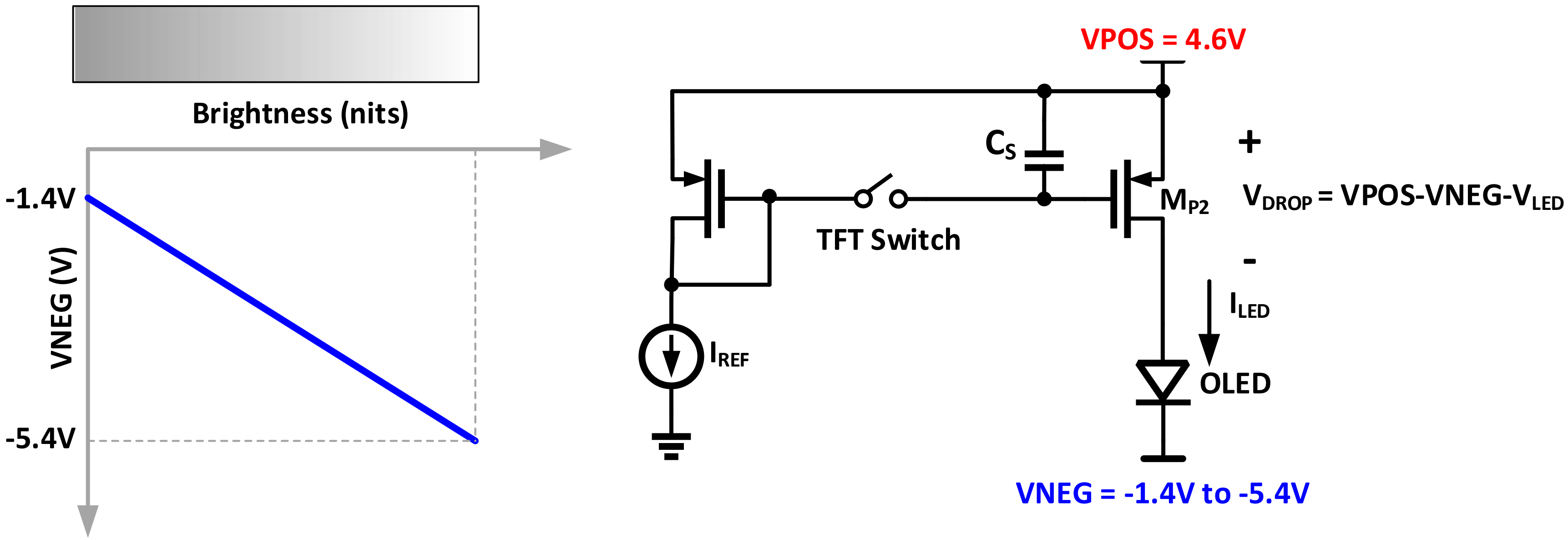
Figure 7. GSM transmit burst waveform.



Source: Maxim

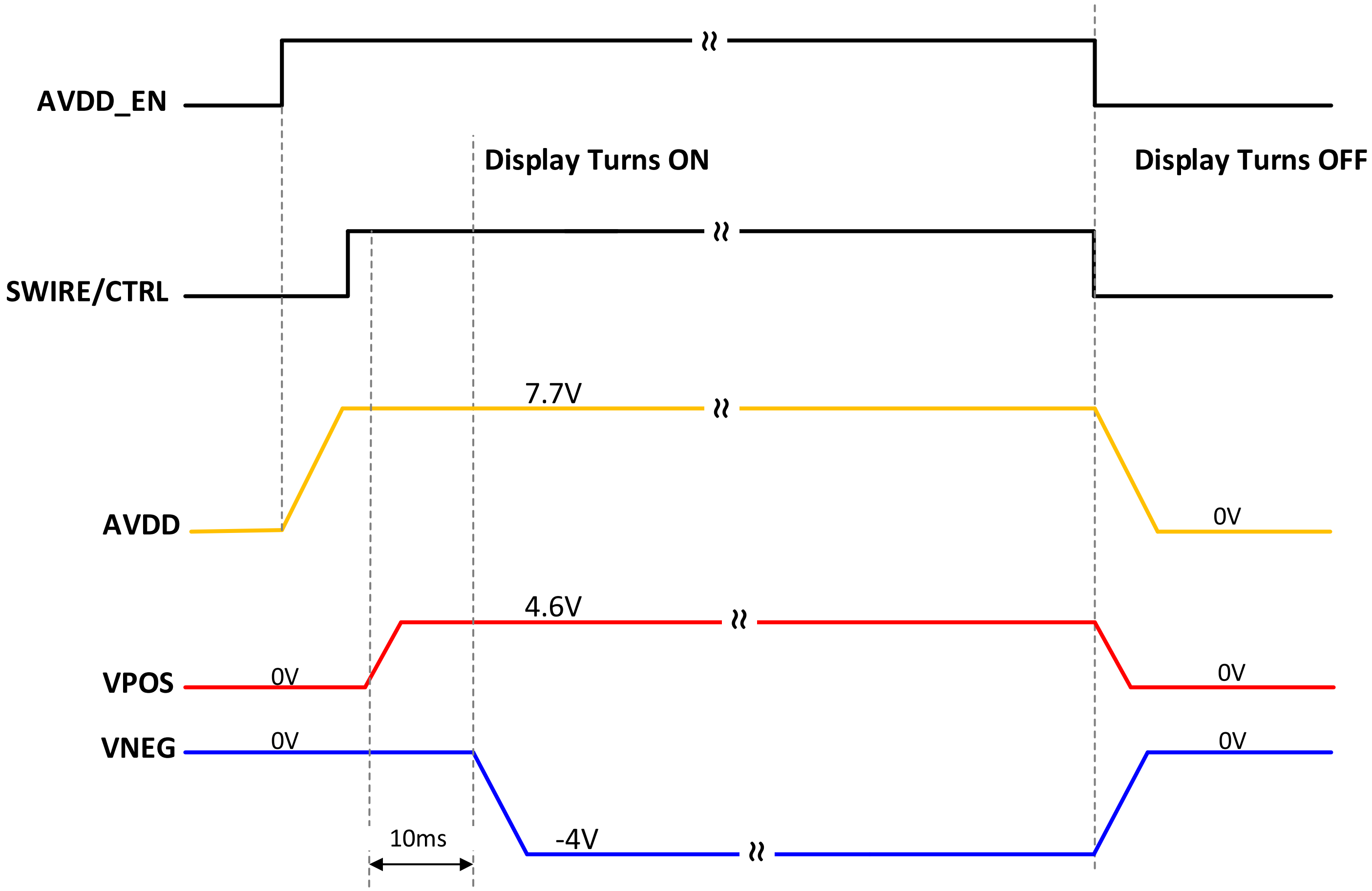
Why Variable VNEG?

- **LED current is varied based on required brightness**
- **Since forward voltage of LED is reduced at lower current, extra voltage between VPOS and VNEG is dropped across current source MP2 hence decreasing the efficiency**
- **VNEG is adjusted to reduce the drop-out across MP2 when brightness is changed**

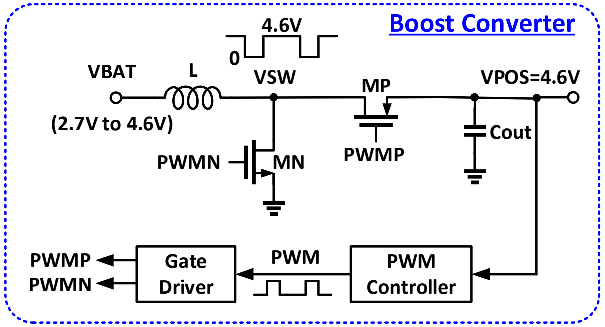


AMOLED Power UP/DOWN Sequencing

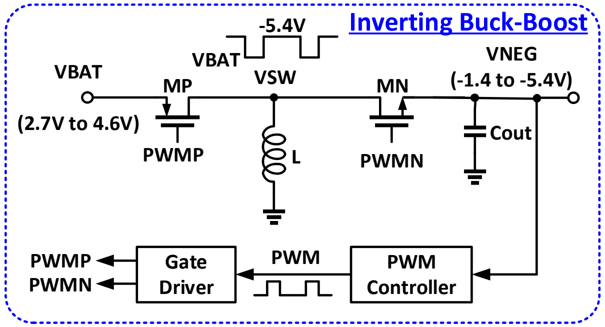
- **AVDD is enabled first then VPOS.**
- **VNEG is enabled after VPOS (~10ms delay)**



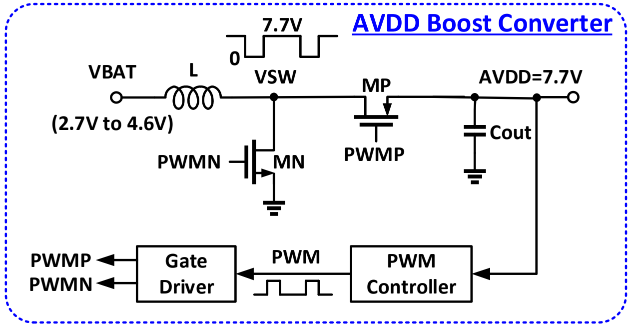
Generating Three Supplies for AMOLED



$$VPOS = \frac{1}{1-D} \cdot VBAT$$



$$VNEG = -\frac{D}{1-D} \cdot VBAT$$

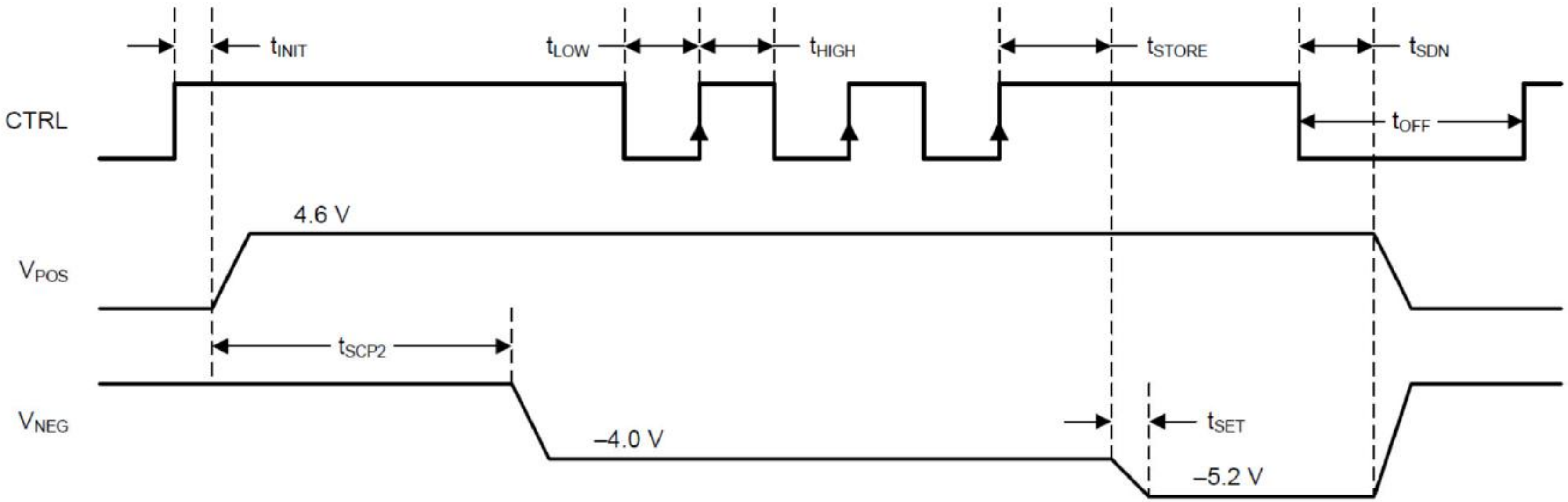


$$AVDD = \frac{1}{1-D} \cdot VBAT$$

VNEG Programming Using SWIRE

- **VPOS is usually fixed at 4.6V**
- **VNEG is varied based on brightness:**

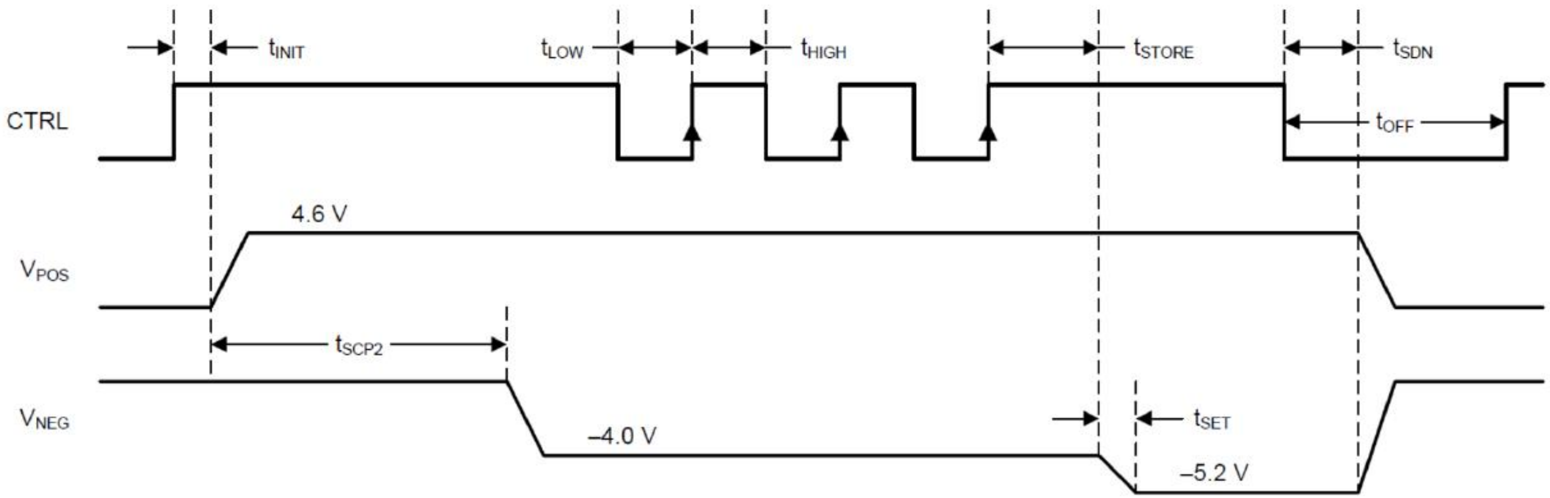
	min	typ	max
t_{INIT}		300µs	400µs
t_{SCP2}		10ms	
t_{LOW}	2µs	10µs	25µ
t_{HIGH}	2µs	10µs	25µ
t_{STORE}	30µs		80µs
t_{SDN}	30µs		80µs
t_{OFF}	200µs		



Source: Texas Instruments

VNEG Programming

- **By default, VNEG turns ON with -4V when SWIRE goes High then programmed by sending pulse.**
- **VNEG is pre-defined at 1 pulse (positive edge) and then reduces by 100mV after every SWIRE pulse (~10uS).**
- **VNEG@1-pulse = 5.4V, VNEG@N-pulses = -(5.4 – (N-1)*100mV).**



Source: Texas Instruments

VNEG Programming Table

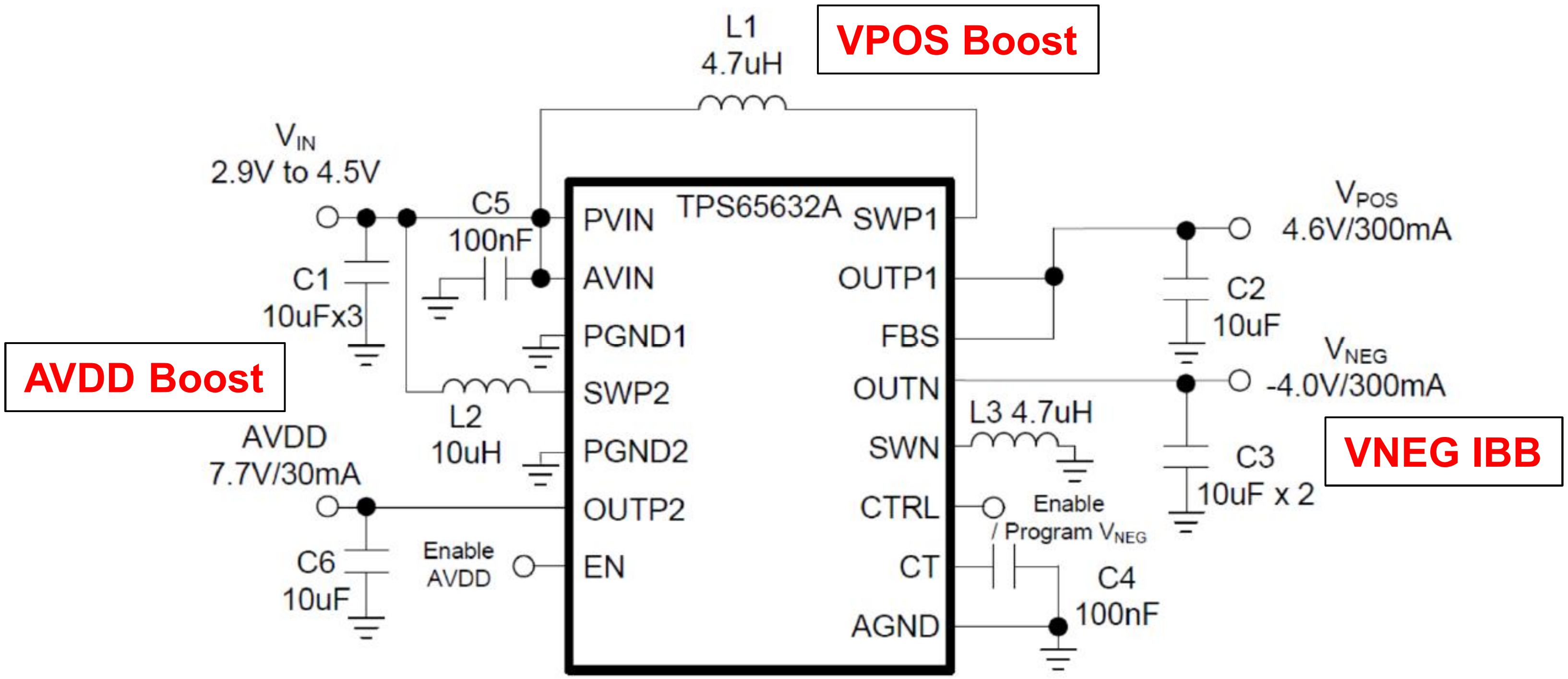
VNEG= -(5.4 – (N-1)*100mV)

Bit / Rising Edges	V_{NEG}	DAC Value	Bit / Rising Edges	V_{NEG}	DAC Value
0 / no pulse	–4.0 V	000000	21	–3.4 V	010101
1	–5.4 V	000001	22	–3.3 V	010110
2	–5.3 V	000010	23	–3.2 V	010111
3	–5.2 V	000011	24	–3.1 V	011000
4	–5.1 V	000100	25	–3.0 V	011001
5	–5.0 V	000101	26	–2.9 V	011010
6	–4.9 V	000110	27	–2.8 V	011011
7	–4.8 V	000111	28	–2.7 V	011100
8	–4.7 V	001000	29	–2.6 V	011101
9	–4.6 V	001001	30	–2.5 V	011110
10	–4.5 V	001010	31	–2.4 V	011111
11	–4.4 V	001011	32	–2.3 V	100000
12	–4.3 V	001100	33	–2.2 V	100001
13	–4.2 V	001101	34	–2.1 V	100010
14	–4.1 V	001110	35	–2.0 V	100011
15	–4.0 V	001111	36	–1.9 V	100100
16	–3.9 V	010000	37	–1.8 V	100101
17	–3.8 V	010001	38	–1.7 V	100110
18	–3.7 V	010010	39	–1.6 V	100111
19	–3.6 V	010011	40	–1.5 V	101000
20	–3.5 V	010100	41	–1.4 V	101001

Source: Texas Instruments

TI AMOLED Display Power Supply – TPS65632

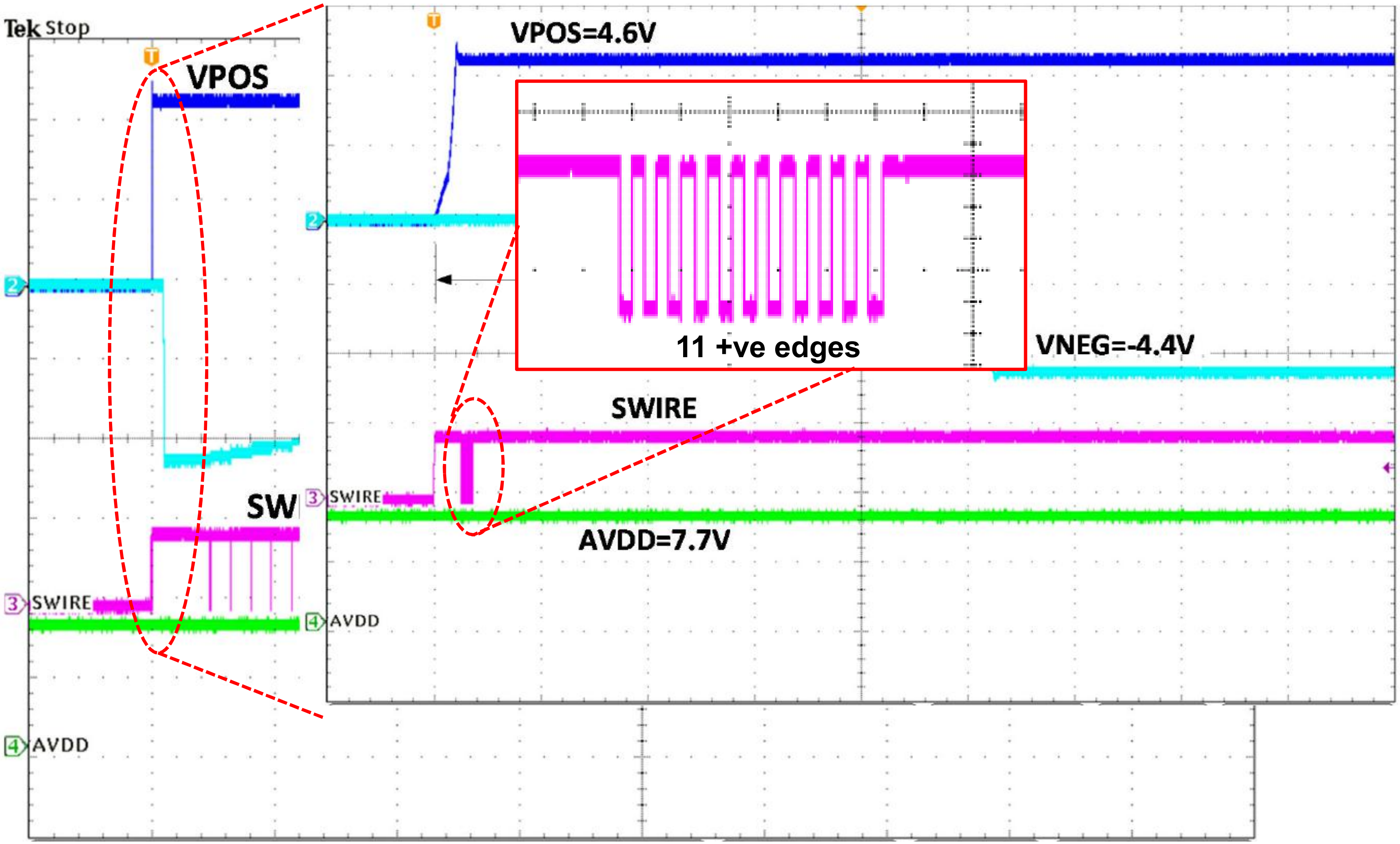
- **Uses boost converter for VPOS (4.6V) and inverting buck-boost for VNEG (programmable through CTRL/SWIRE)**



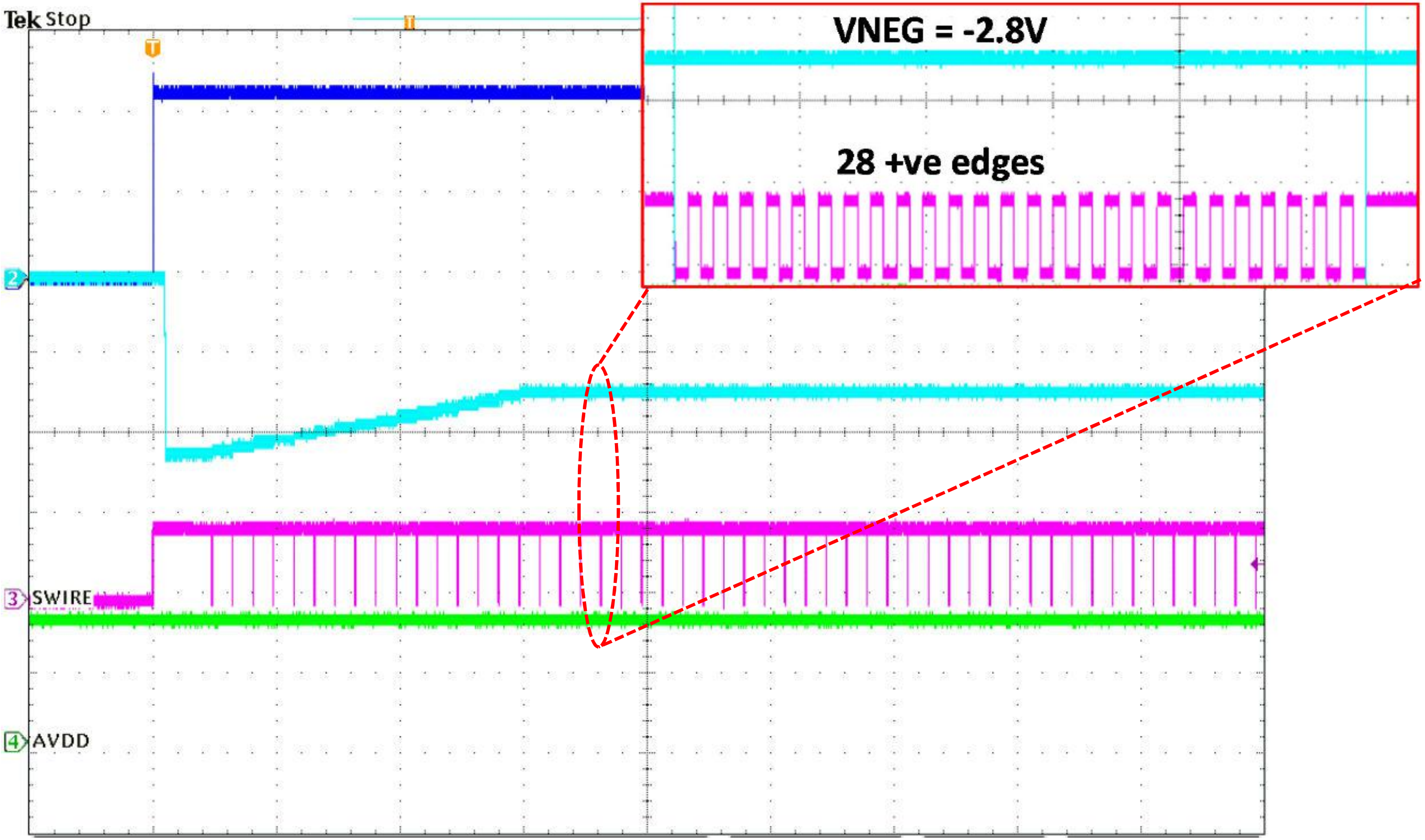
CTRL→ SWIRE

Source: Texas Instruments

Display Power-Up

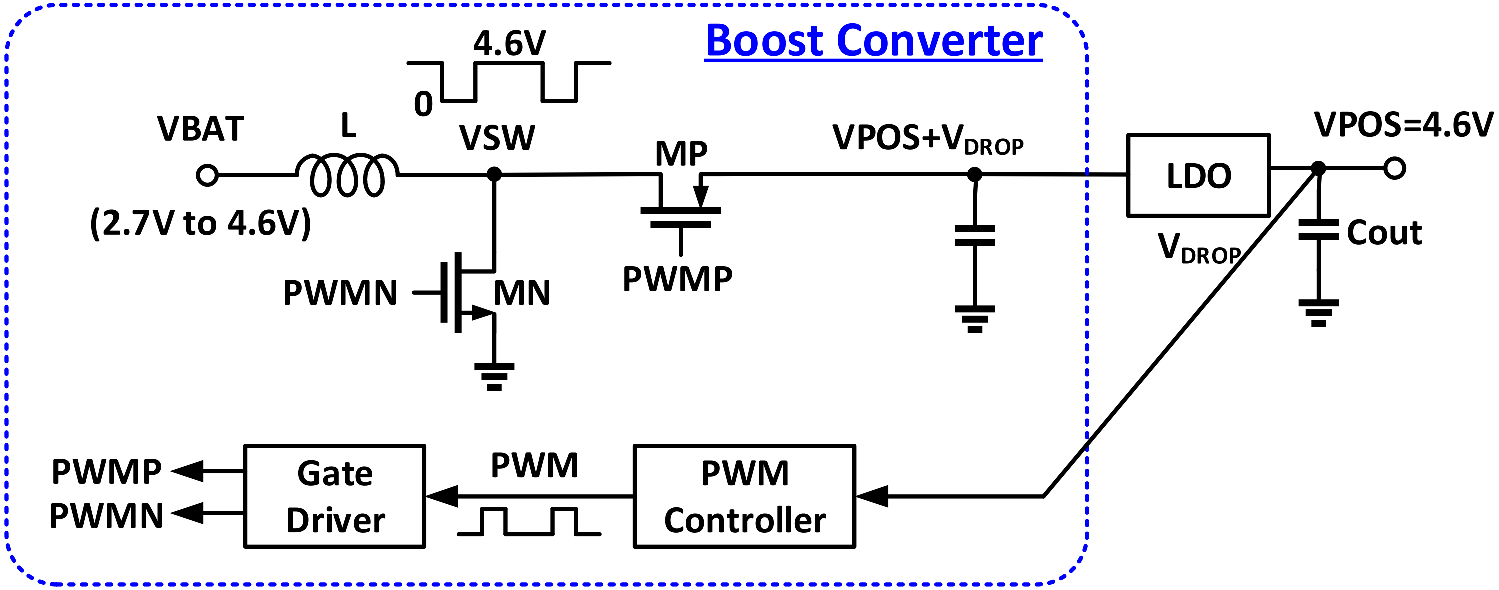


Display Power-Up



Issue with AMOLED Boost Converter

- Battery voltage when fully charged could be as high as 4.6V
- Boost can be regulated to higher voltage and extra voltage can be dropped in LDO to regulate VPOS to 4.6V



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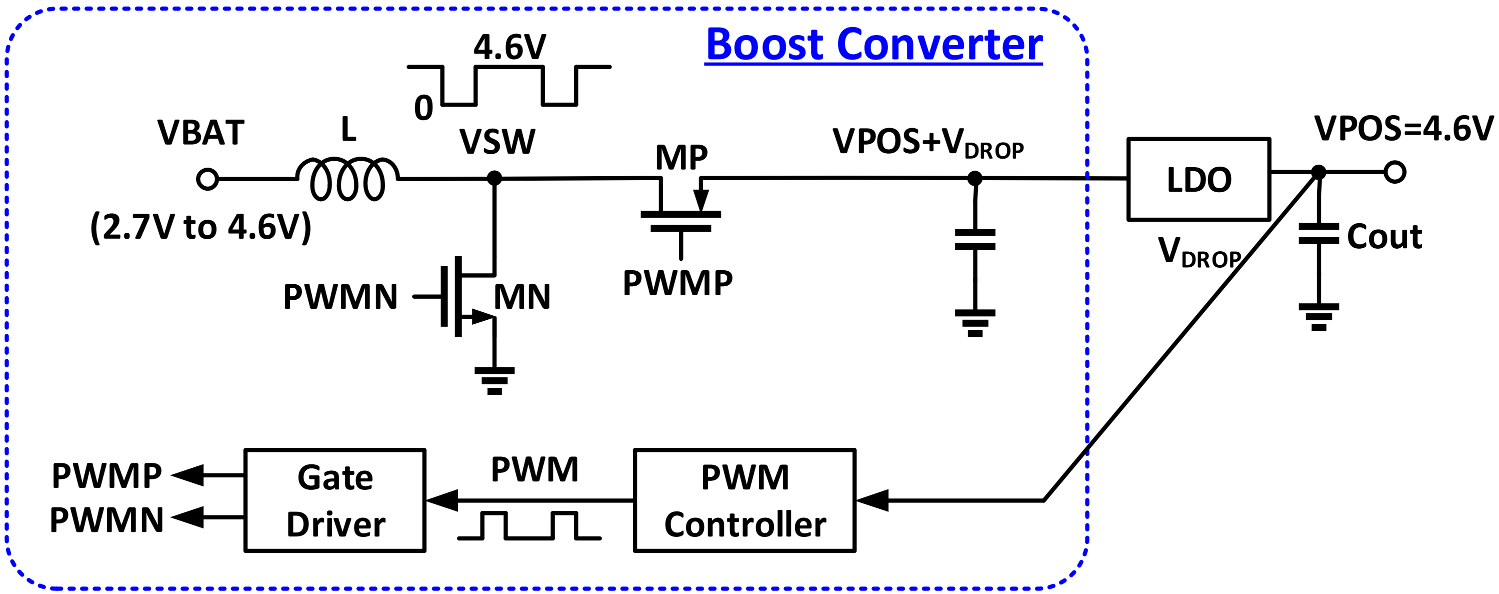
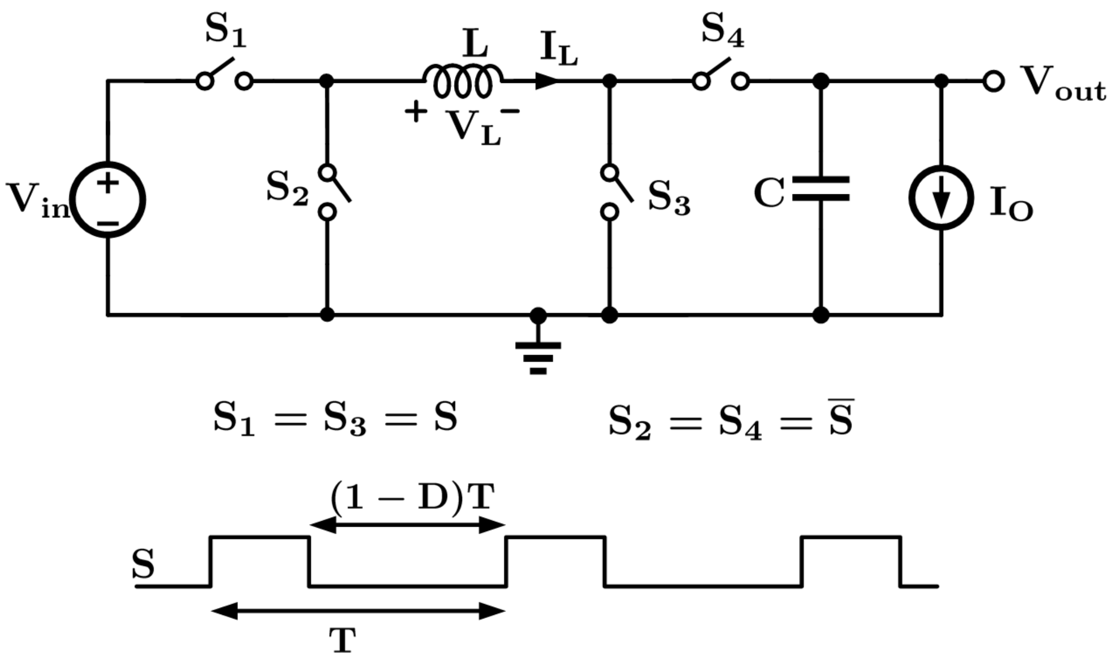


Loss in efficiency due to V_{DROP}

Using Buck-Boost Converter

- **Buck-Boost works for entire range input voltage**

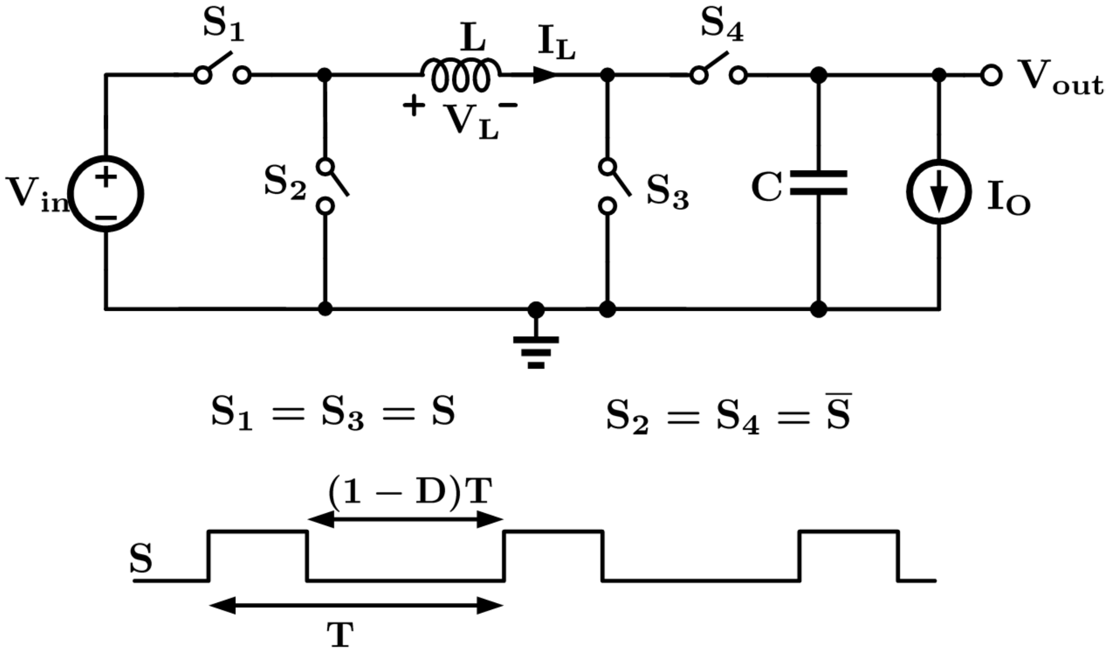


$$V_{out} = \frac{D}{1-D} V_{in} \qquad (1)$$

$$I_L = \frac{1}{1-D} I_o \qquad (2)$$

Vout can be regulated at:
<Vin : D < 0.5
> Vin: D > 0.5
≈ Vin: D ≈ 0.5

Issue with Conventional BB converter

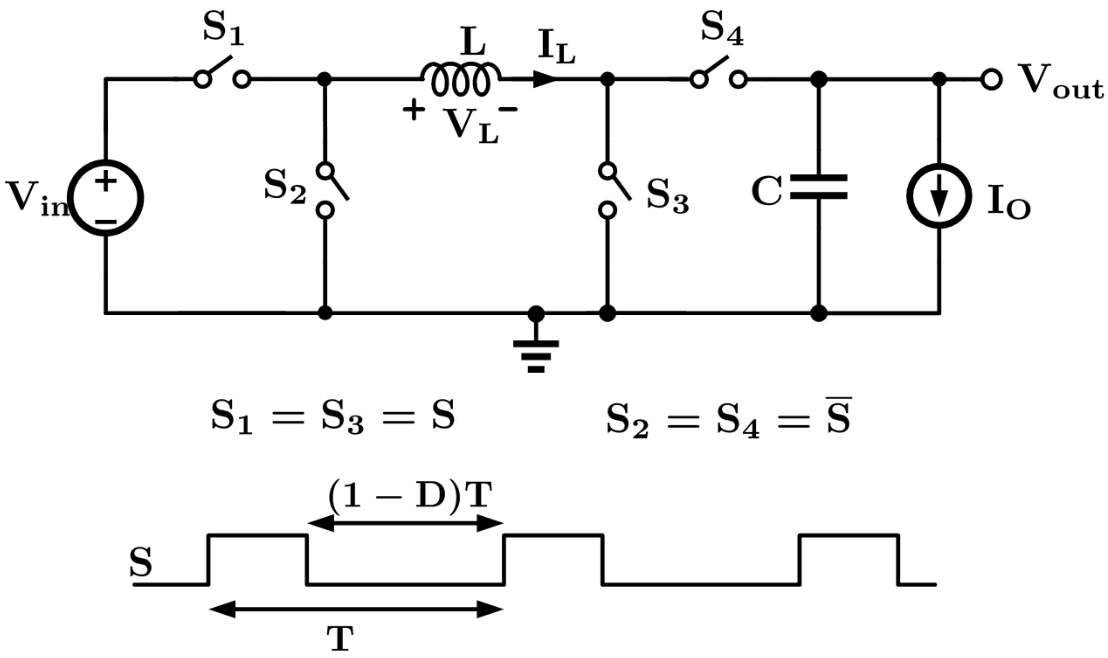


$$V_{out} = \frac{D}{1-D} V_{in} \quad (1)$$

$$I_L = \frac{1}{1-D} I_o \quad (2)$$

- Single Duty cycle, D, controls all the switches
- Switching losses are higher due to simultaneous operation of 4 switches
- Conduction losses are higher due to larger Inductor current (nearly 2x when Vin ≈ Vout.

Issue with Conventional BB converter

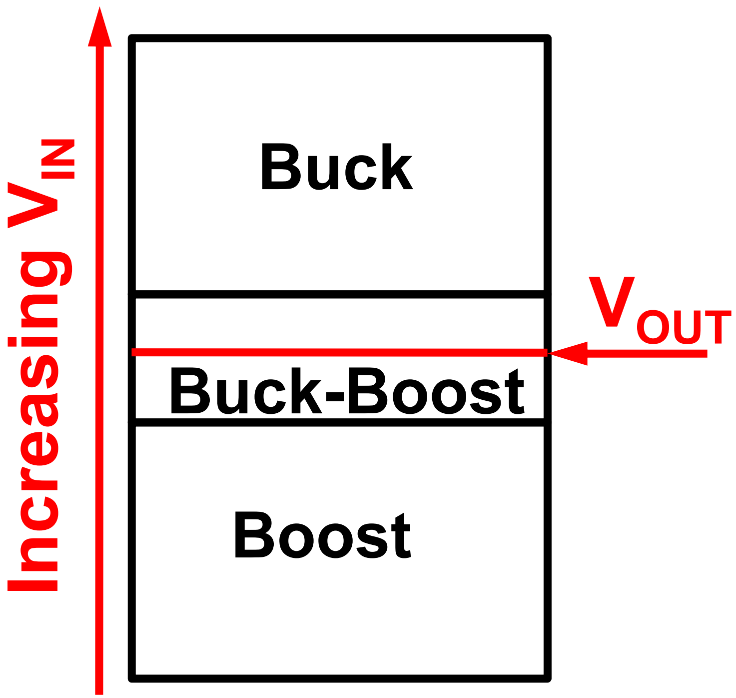


$$V_{out} = \frac{D}{1-D} V_{in} \quad (1)$$

$$I_L = \frac{1}{1-D} I_o \quad (2)$$

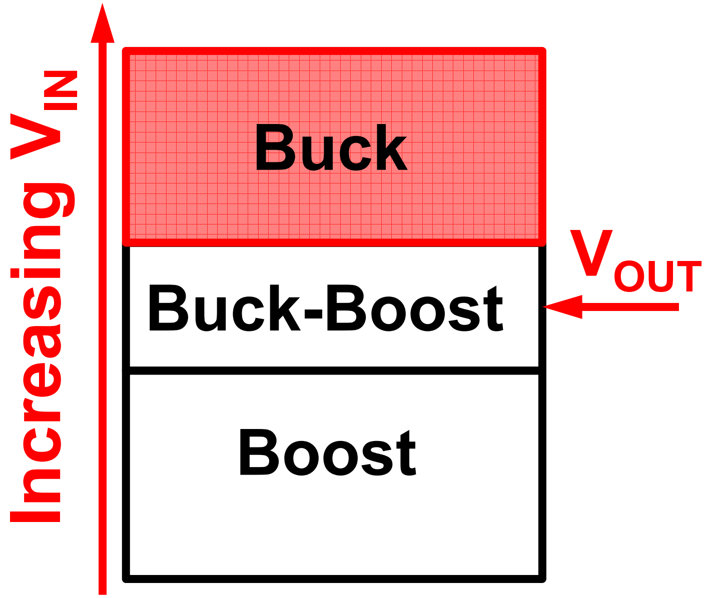
Can we do it in a better way?

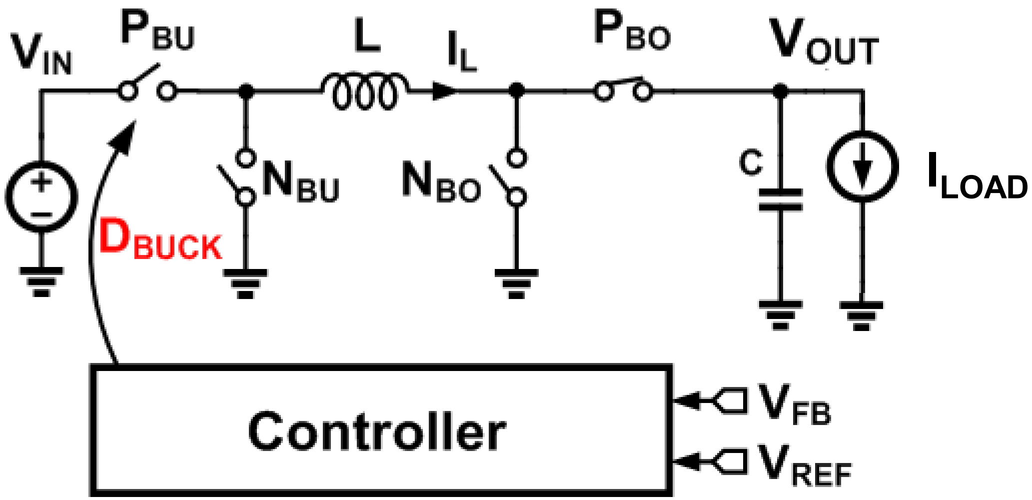
Tri-Mode Operation of BB Converter



- $V_{IN} > V_{OUT}$: **Buck Mode**
- $V_{IN} < V_{OUT}$: **Boost Mode**
- $V_{IN} \sim V_{OUT}$: **Buck-Boost Mode**

Tri-Mode: Buck

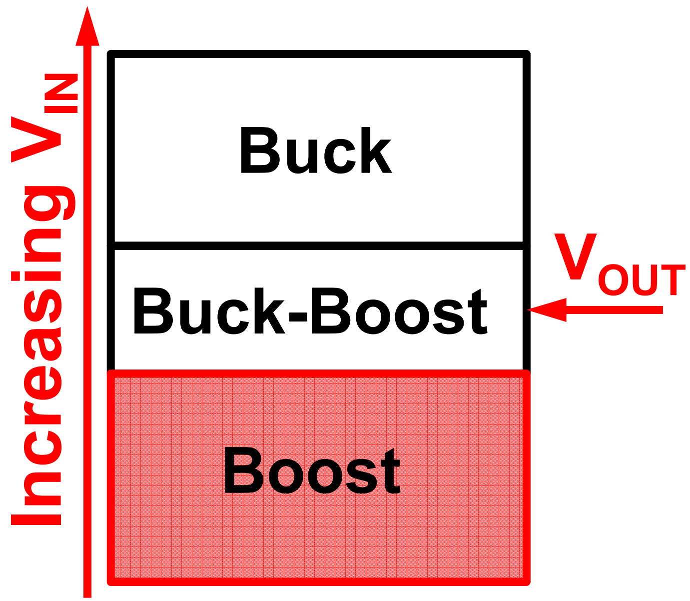


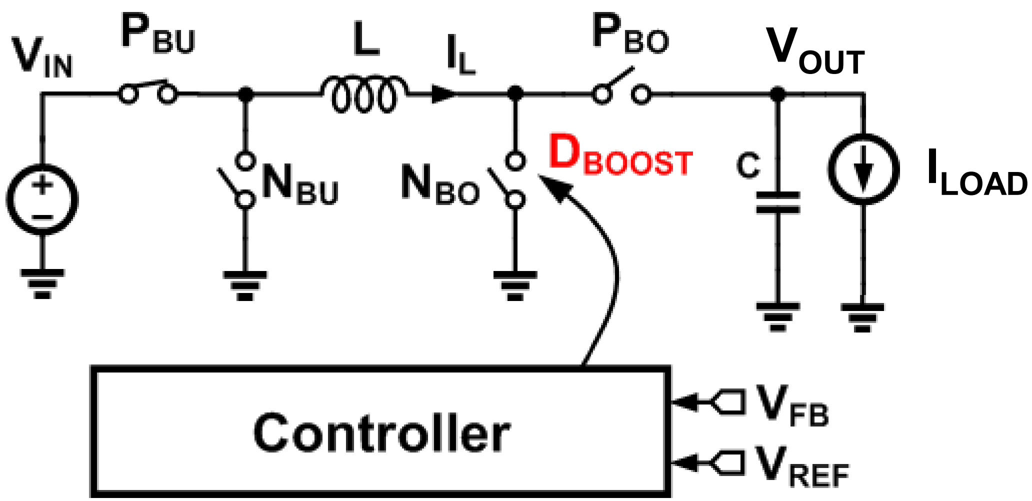


- P_{BO} always ON
- D_{BUCK} controls buck switches

$$\boxed{V_{OUT} \approx (D_{BUCK})V_{IN}} \quad \boxed{I_L = I_{LOAD}}$$

Tri-Mode: Boost



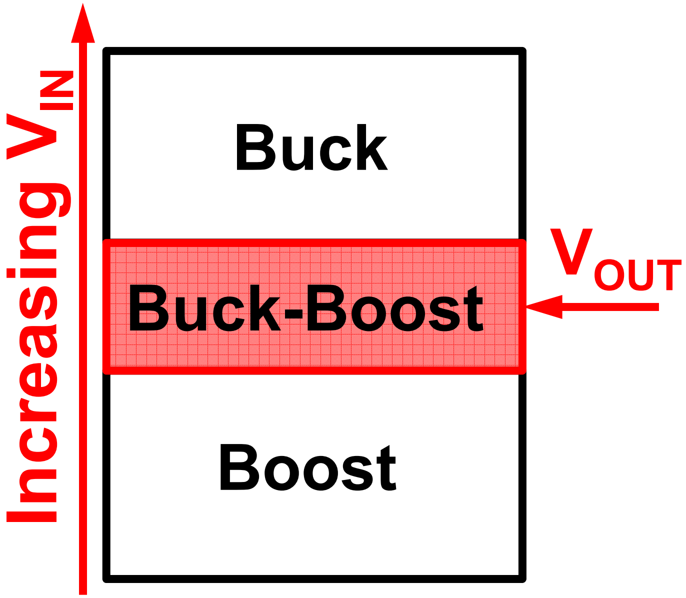


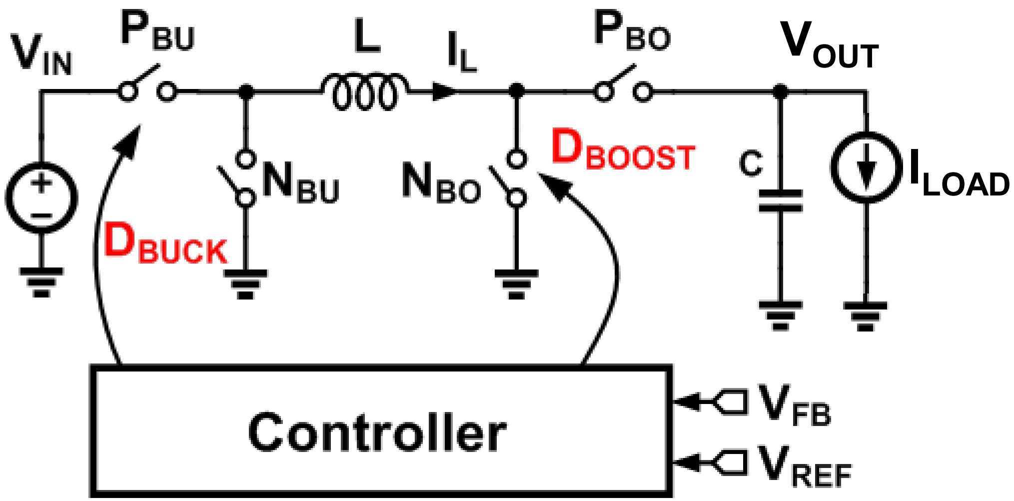
- P_{BU} always ON
- D_{BOOST} controls boost switches

$$V_{OUT} \approx \frac{V_{IN}}{(1 - D_{BOOST})}$$

$$I_L = \frac{I_{LOAD}}{(1 - D_{BOOST})}$$

Tri-Mode: Buck-Boost



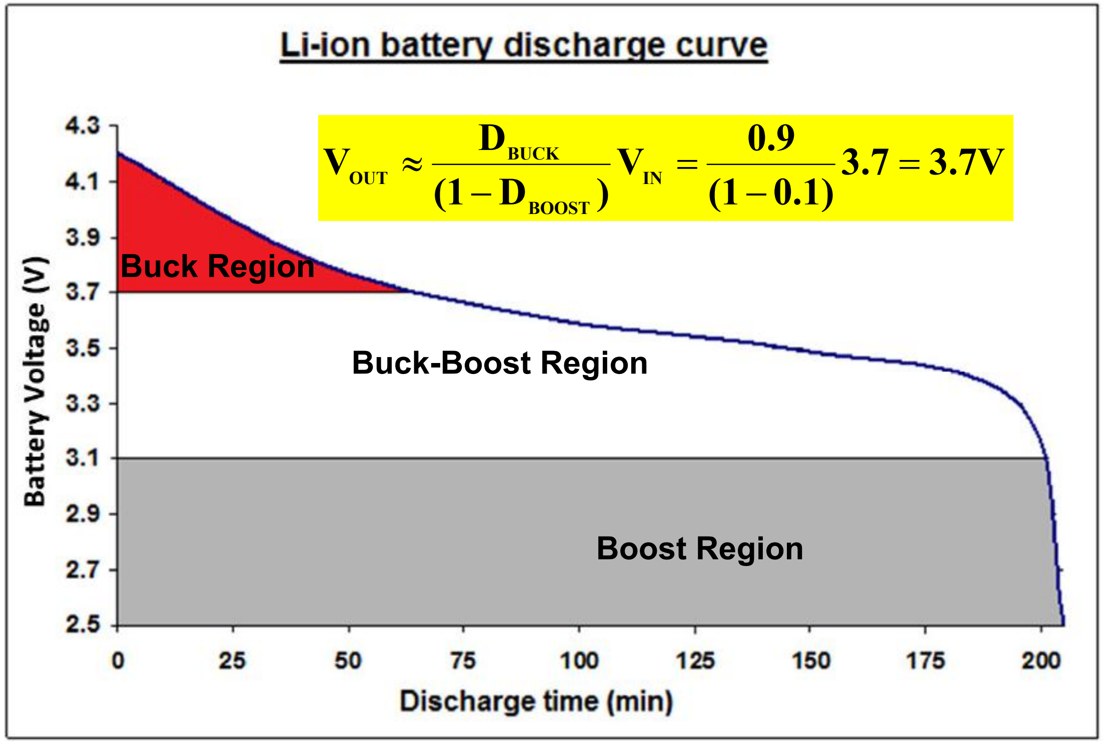


- D_{BUCK} controls buck switches
- D_{BOOST} controls boost switches

$$V_{OUT} \approx \frac{D_{BUCK}}{(1-D_{BOOST})} V_{IN}$$

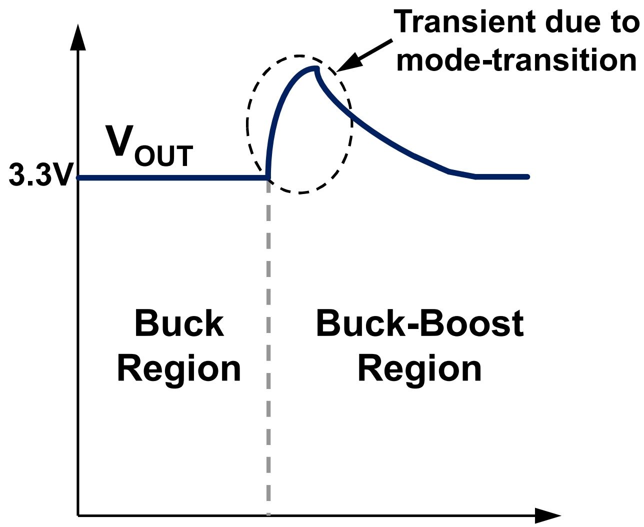
$$I_L = \frac{I_{LOAD}}{1-D_{BOOST}}$$

Issue with Tri-Mode Buck-Boost



$\text{Buck Mode}: D_{BOOST} = 0$

$\text{Boost Mode}: D_{BUCK} = 1$



- **Mode transition causes large voltage transient**
- **Boundary condition must be satisfied**
  - **Varies with load current and losses**

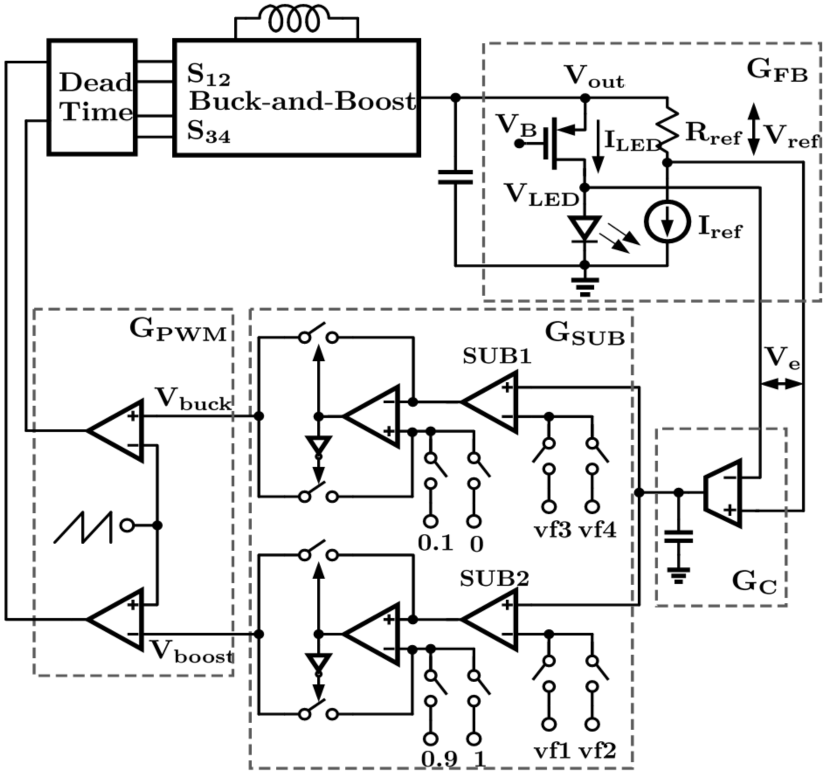
Boundary Condition

$V_{OUT}(\text{buck}) = V_{OUT}(\text{buck-boost})$

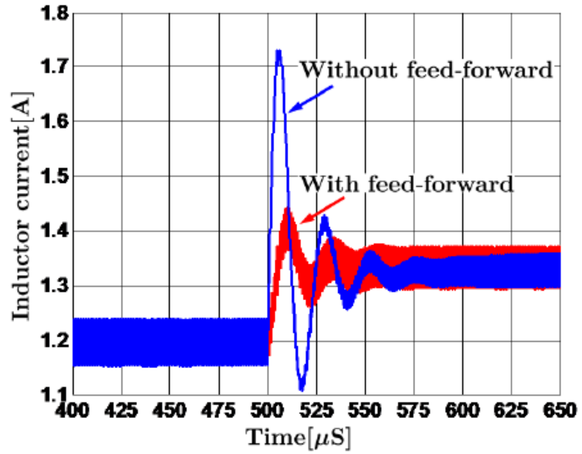
$\rightarrow D_{BUCK\_max} = \frac{D_{BUCK}}{1-D_{BOOST\_min}}$

$\rightarrow D_{BUCK} = D_{BUCK\_max} \cdot (1-D_{BOOST\_min})$

Solution for Mode Transitions



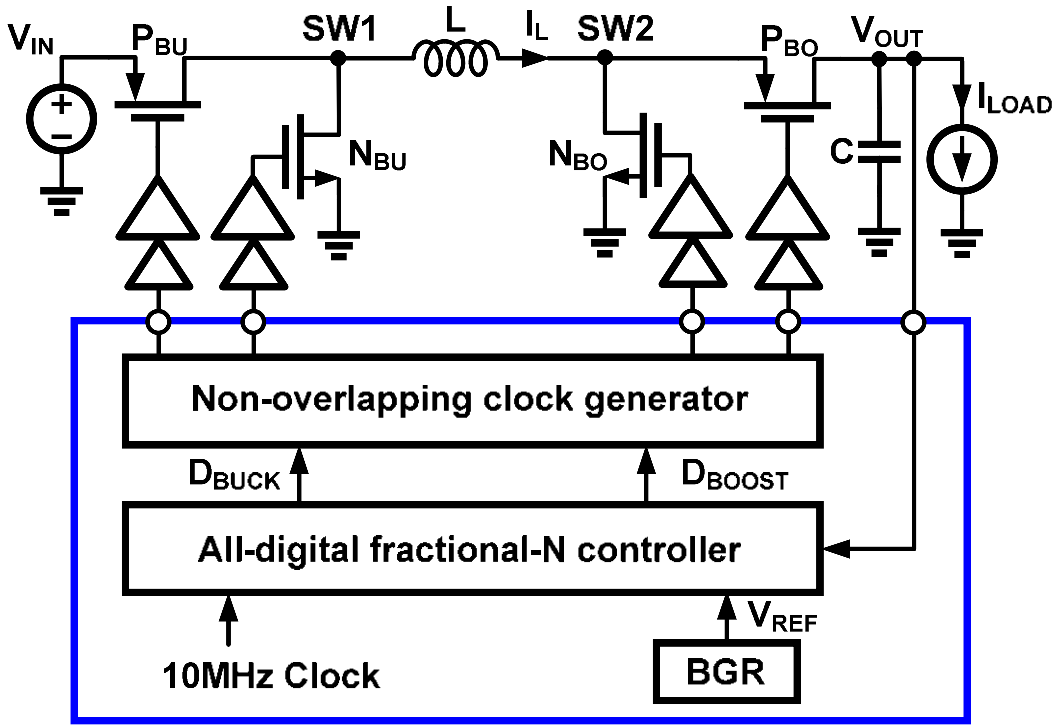
- **Appropriate Feed-forward voltage vf1 - 4 is subtracted to instantaneously change the duty cycles during mode transition.**
- **Analog Implementation makes is susceptible to PVT and requires external compensation capacitor**



S. Bang, D. Swank, A. Rao, W. McIntyre, Q. Khan and P. K. Hanumolu, A 1.2A 2MHz tri-mode Buck-Boost LED driver with feed-forward duty cycle correction, *2010 IEEE Custom Integrated Circuits Conference (CICC)*, pp. 1-4, Sept. 2010.

Digitally Controlled Buck-Boost

- **Uses constant ON/OFF technique**
- **Enables High Switching Frequency Operation**
- **All digital implementation eliminates the need of external compensation capacitor**



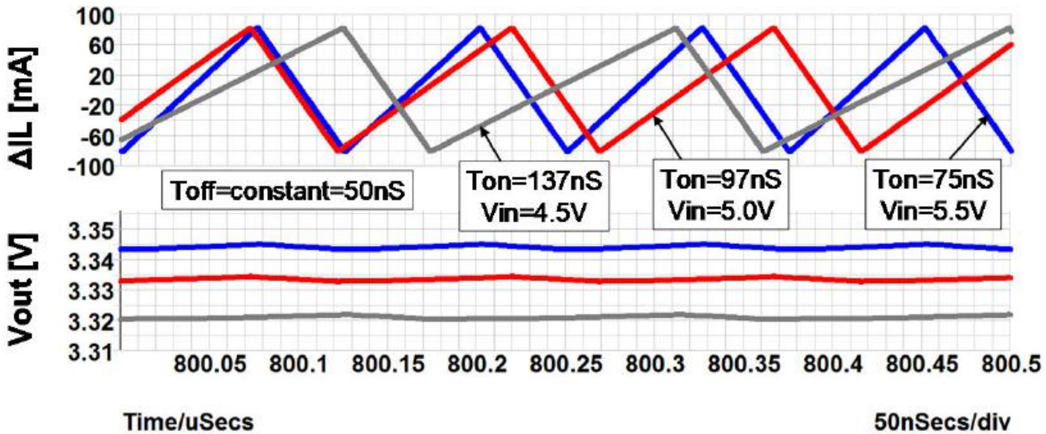
Q. Khan, S. Rao, D. Swank, A. Rao, W. McIntyre, S. Bang, P.K. Hanumolu, "A 3.3V 500mA Digital Buck-Boost Converter with 92% Peak Efficiency Using Constant ON/OFF Time Delta-Sigma Fractional-N Control," *37th European Solid-State Circuits Conference (ESSCIRC)*, 12-16 Sept. 2011, Helsinki, Finland.

Constant ON/OFF Time Operation

$$\text{Inductor ripple current, } \Delta I_L = \frac{V_{IN} - V_{OUT}}{L} T_{ON} \qquad (1)$$

$$T_{ON} = D \cdot T \qquad T_{OFF} = (1 - D) \cdot T$$

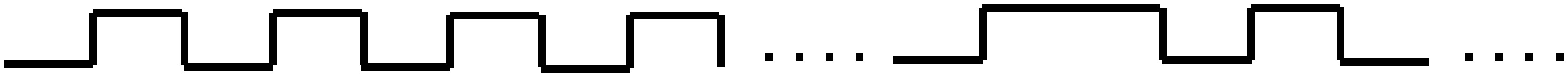
- **Max ripple occurs at D=0.5 (Ton = Toff)**
  - **The converter can be operated at high switching frequency when D=0.5**
- **From eq. 1, D increases with Vin**
  - **Fixing OFF time and making ON time function of Vin does not affect the inductor ripple**
  - **Causes variable switching frequency**



Fractional-N Control

Buck Mode:

N cycles of 50% Buck : 1 cycle of 100% Buck

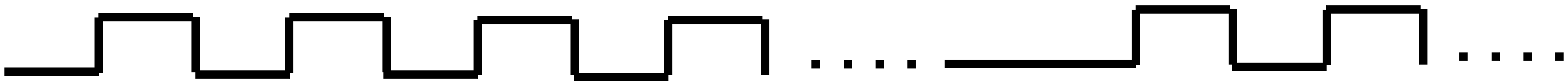


Buck-Boost Mode:

1 cycle of 50% Buck : 1 cycle of 50% Boost

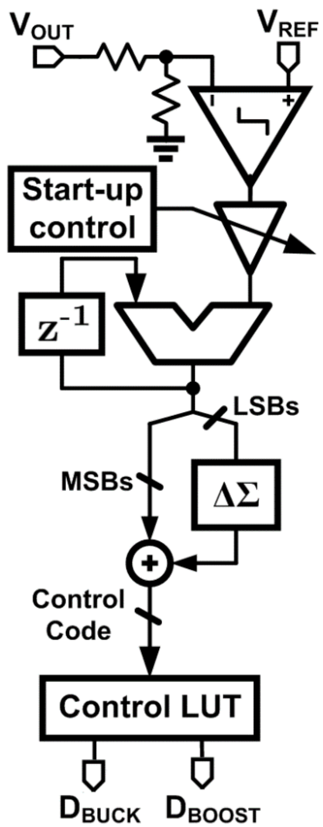
Boost Mode:

N cycle of 50% Boost : 1 cycle of 0% Boost



Fractional-N Control Logic

- Predefined states are stored in the lookup table providing the coarse voltages
- Uses 18-bit acc for integrating the error (4 MSBs, 7 LSBs, 7 dropped bits.
- Any intermediate states are resolved by ΔΣ Modulator



Mode	Operating States	Control Code	Fraction N:1
			50%Buck:100%Buck
Buck Mode	ST1	0001	5:1
	ST2	0010	4:1
	ST3	0011	3:1
	ST4	0100	2:1
	ST5	0101	1:1
			50%Buck:50%Boost
Buck-Boost Mode	ST6	0110	1:1
			50%Boost:0%Boost
Boost Mode	ST7	0111	1:1
	ST8	1000	2:1
	ST9	1001	3:1
	ST10	1010	4:1
	ST11	1011	5:1

5.5V

Decreasing V_{IN}

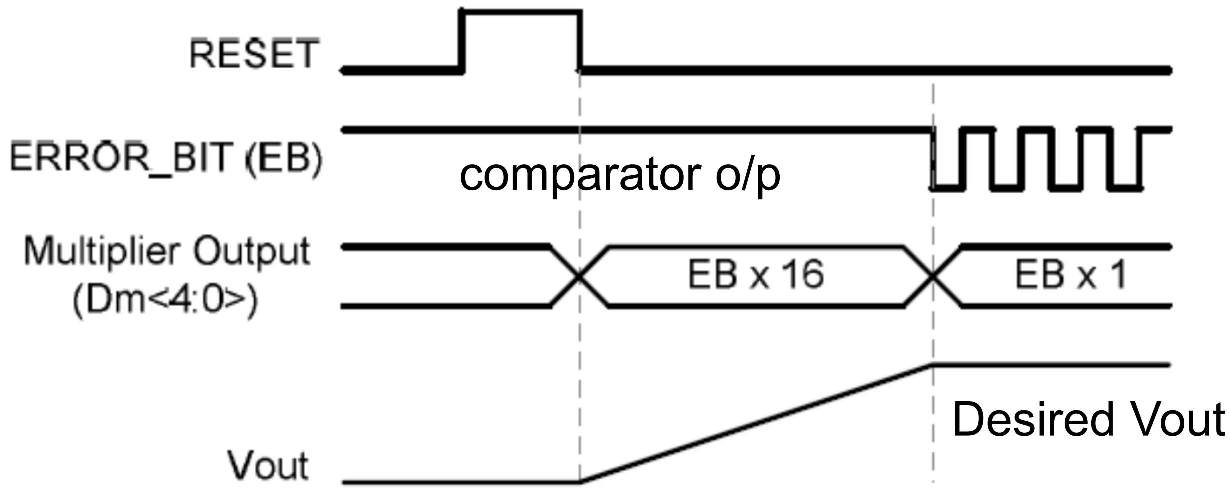
2.7V

Start-up Control

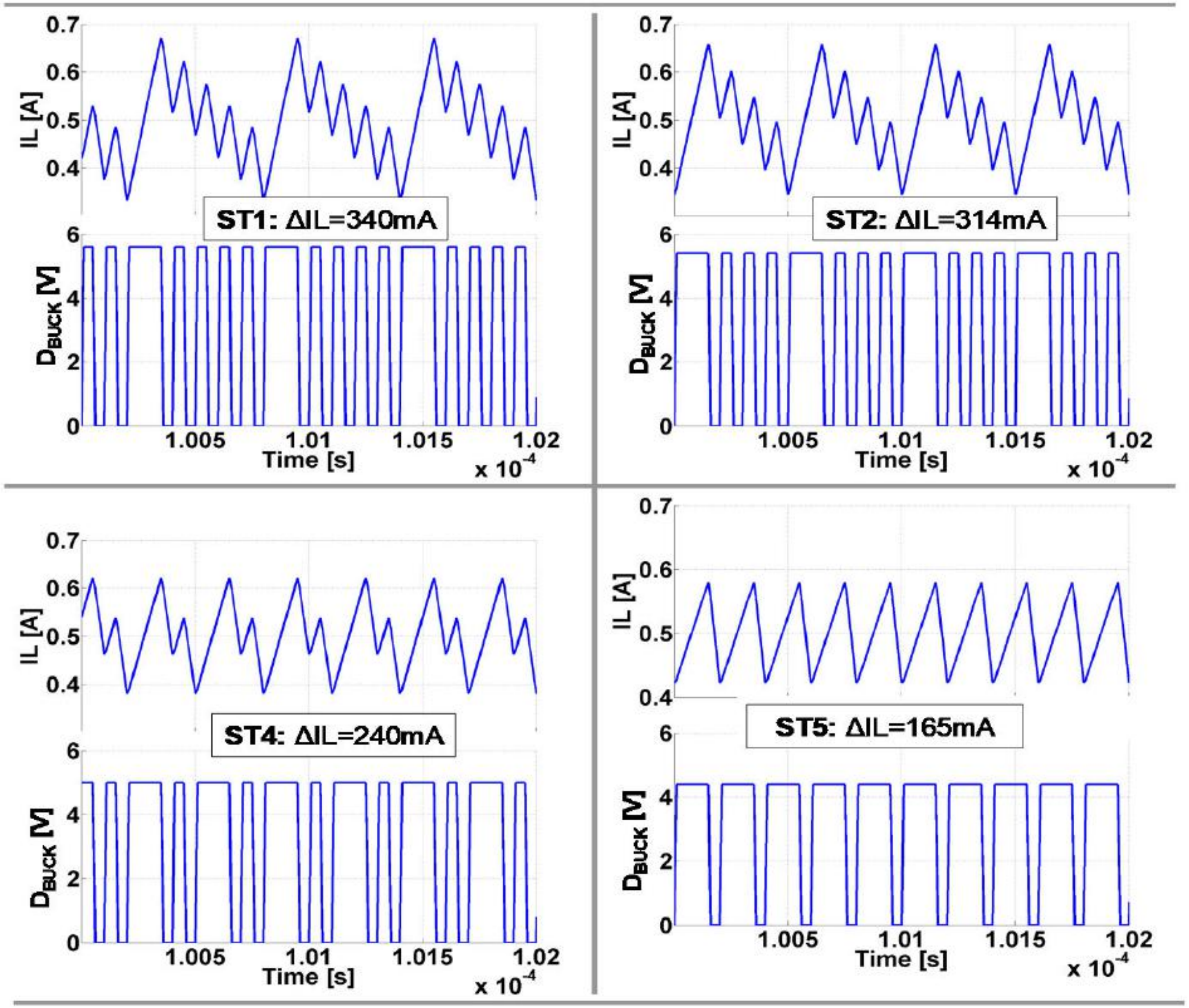
- **Startup time is the function of no. of bits dropped in the accumulator and converter resolution**

- **No. of ACC bits dropped = 7**
  - → **The startup time may be more than 10ms**

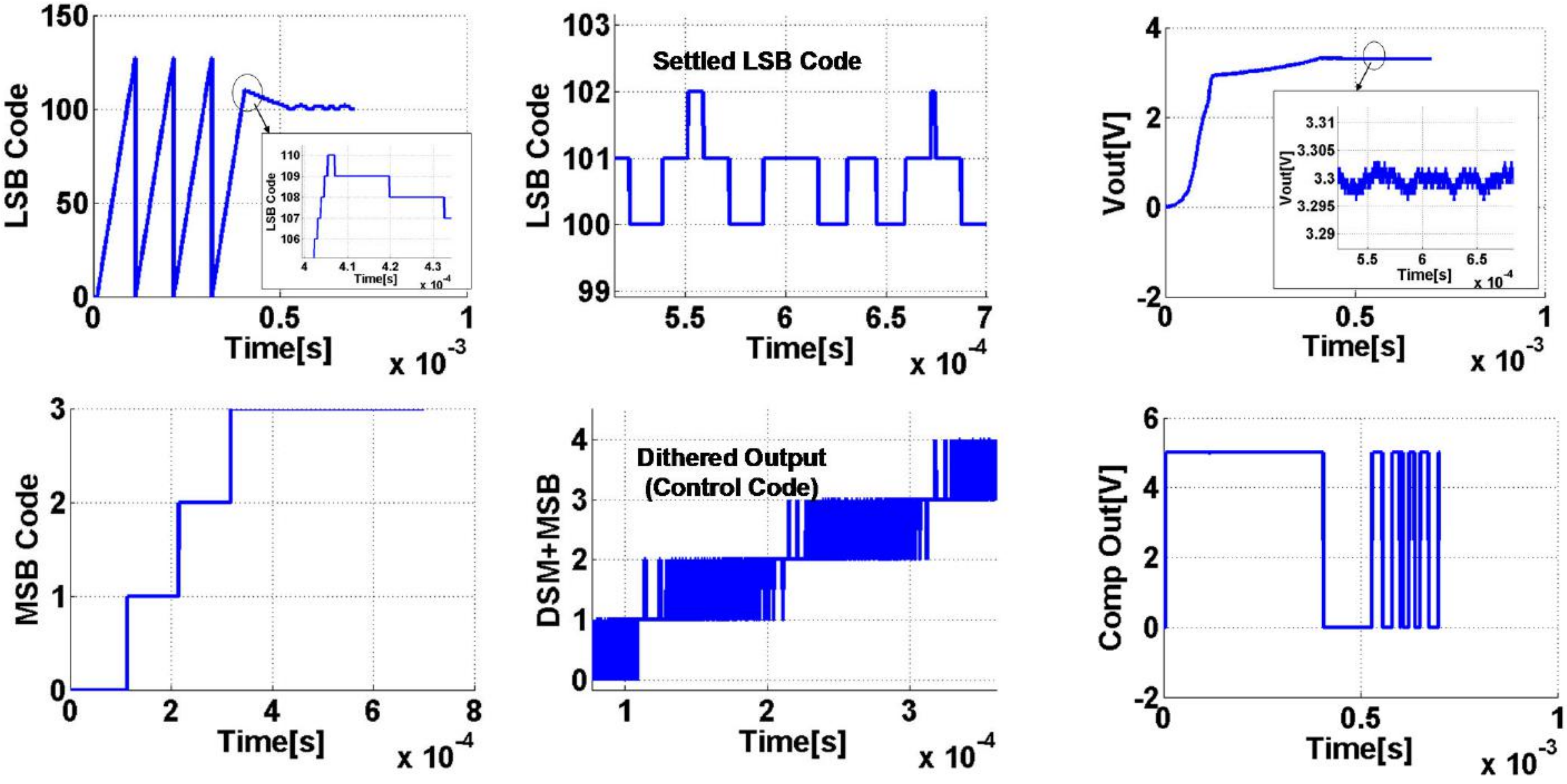
- **Speeded up by dropping only 3 bits in accumulator and switch to 7 bits once the output settles**



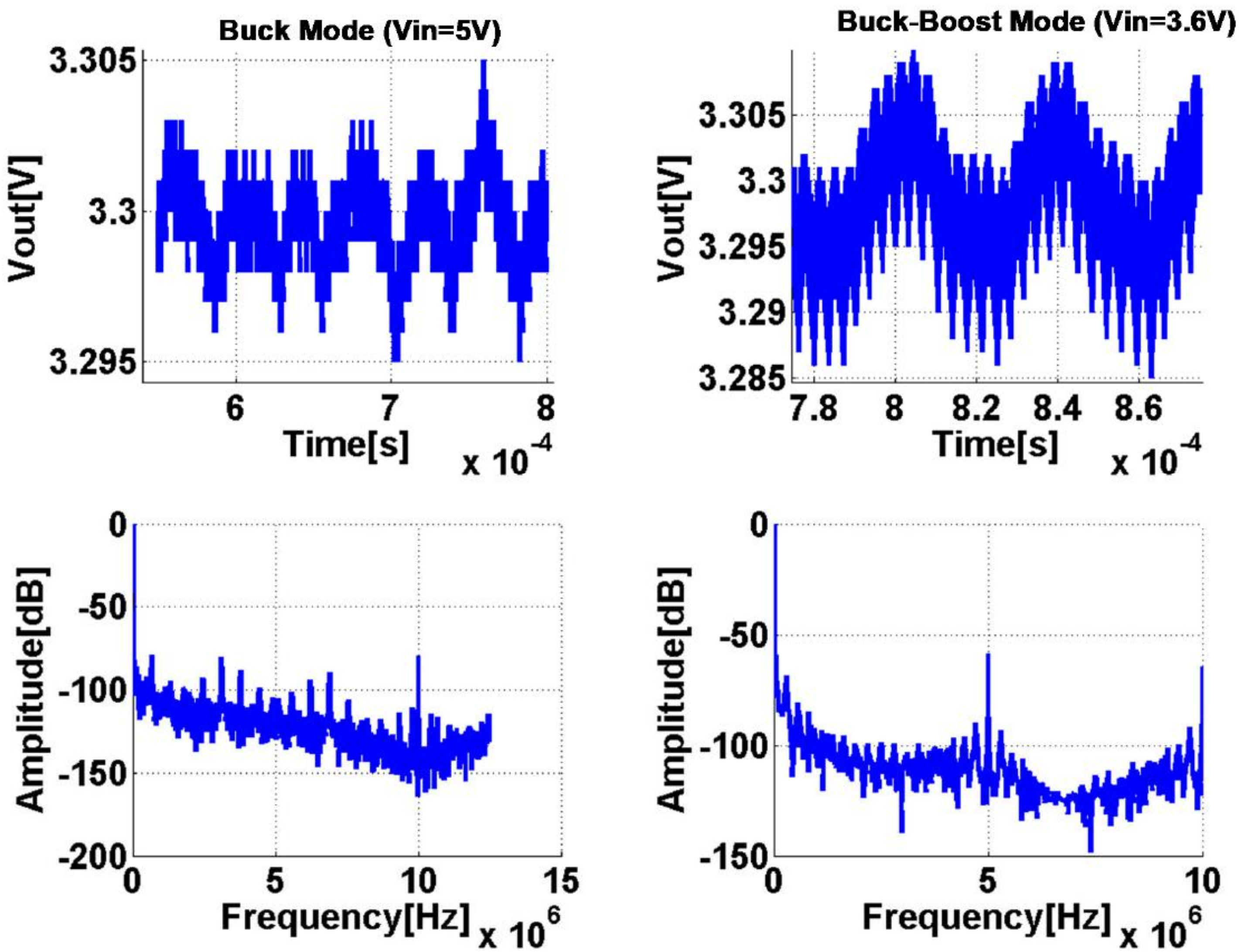
Inductor Current Profile



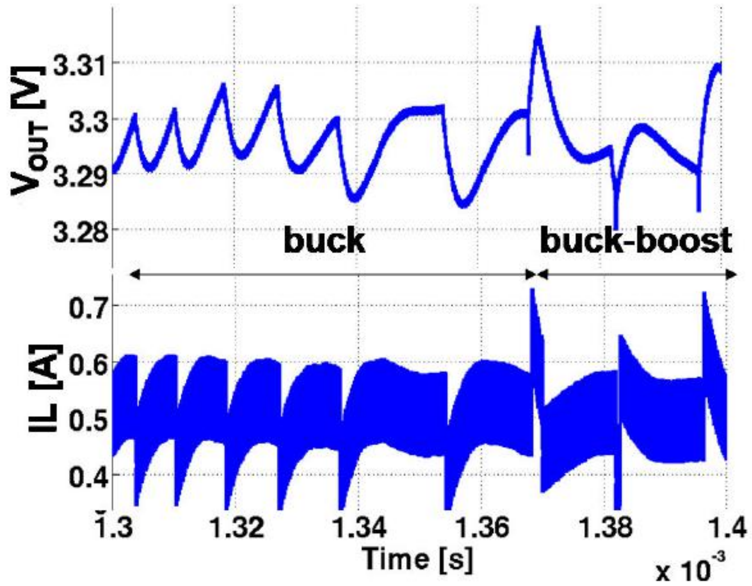
Controller Response

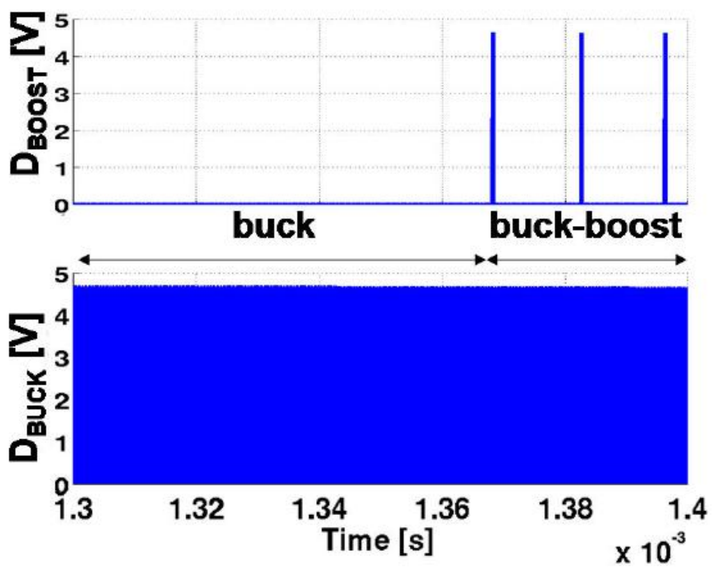


Output Voltage Ripple



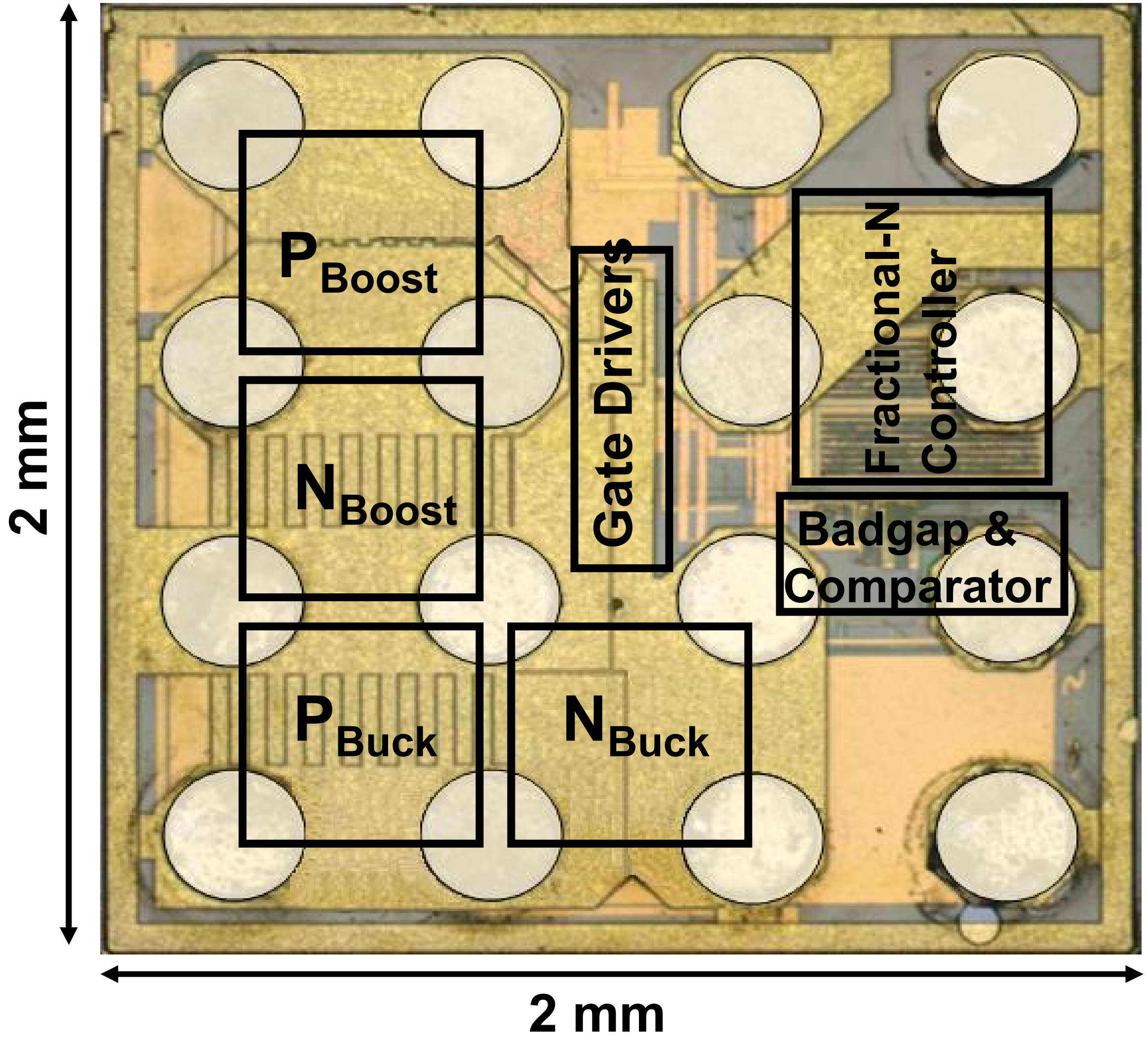
Mode Transition





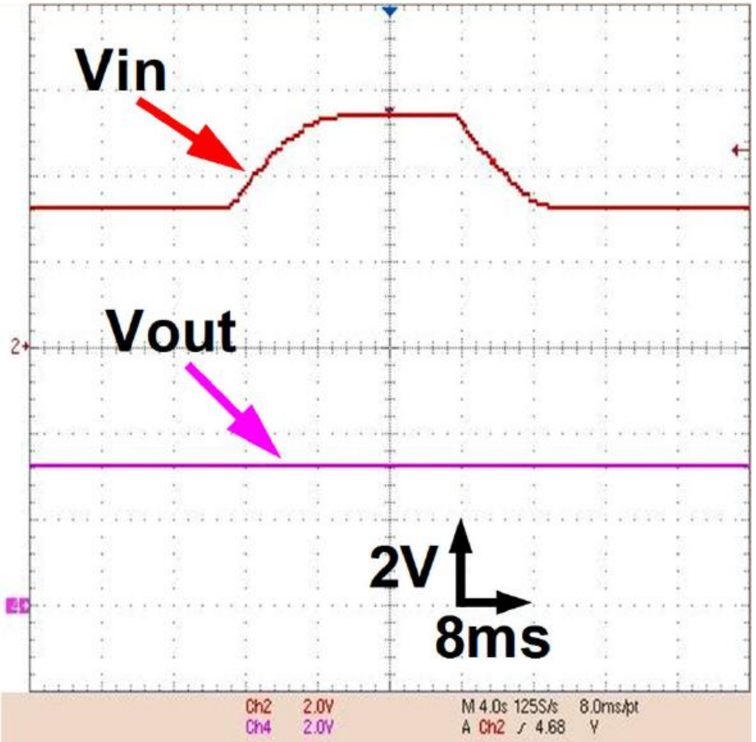
Performance Table and Die Photo

Technology	0.5um CMOS
L	1uH
C	10uF
ESR in C	10mΩ
ESR in L	50mΩ - 100mΩ
Vout	3.3V
Vin	3.3V to 5.5V
Load Current	500mA
Efficiency	85% - 92%
Area Digital Total	 0.24 mm^2 4 mm^2
Power FETs	On-chip

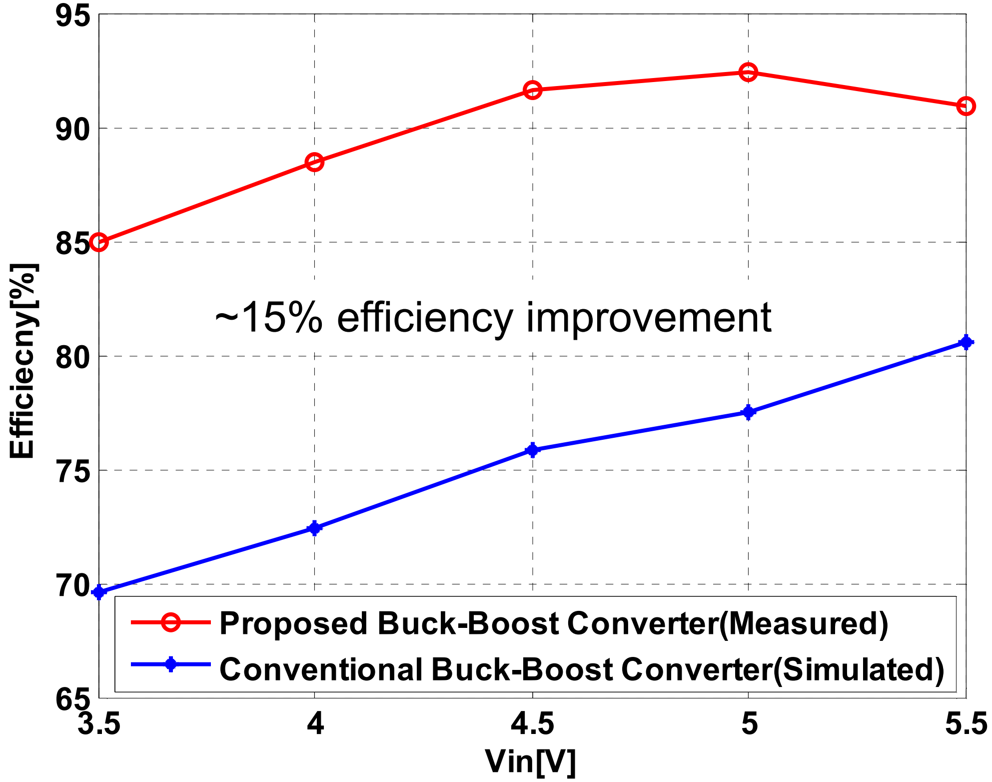


Measurement Results

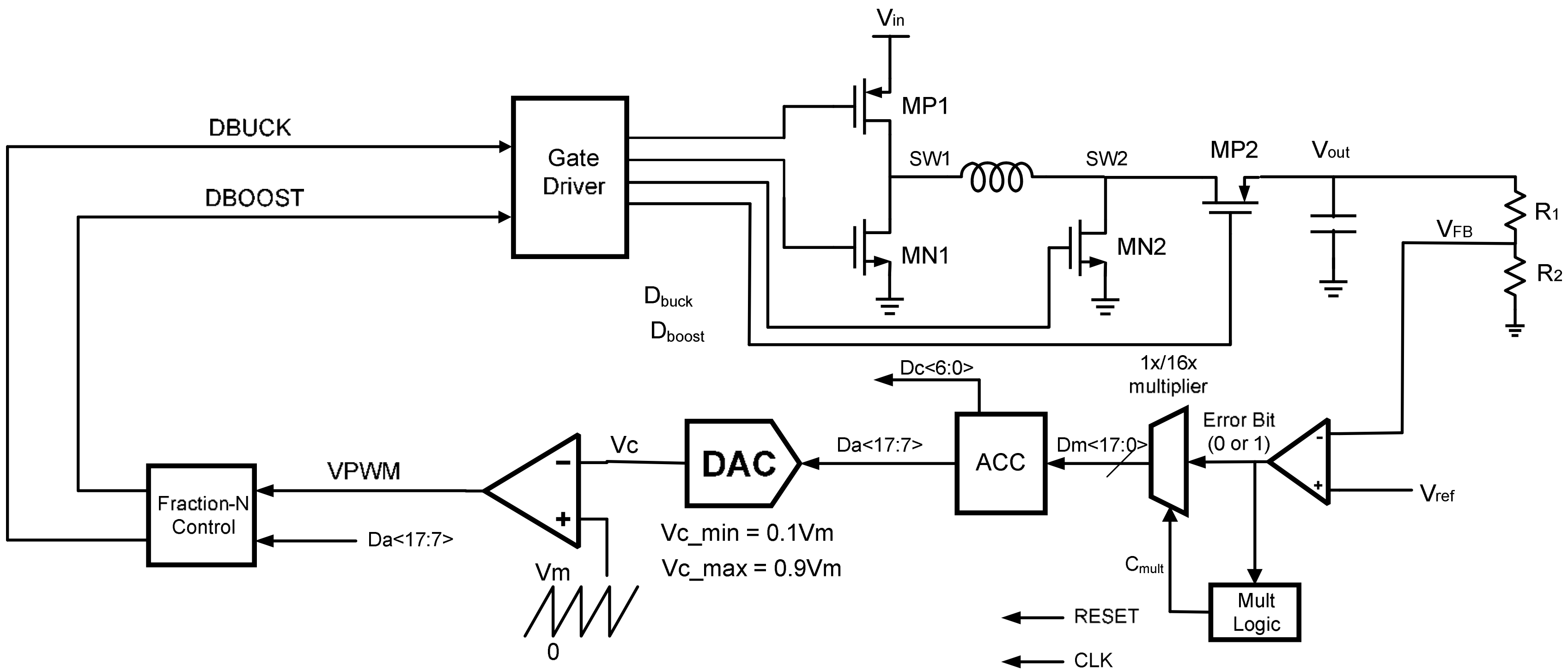
Vin & Vout



Efficiency



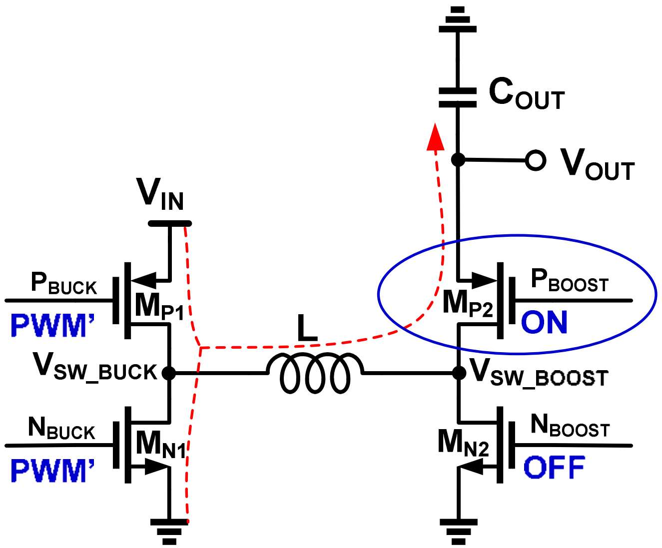
Hybrid Analog-Digital PWM Fractional-N Control



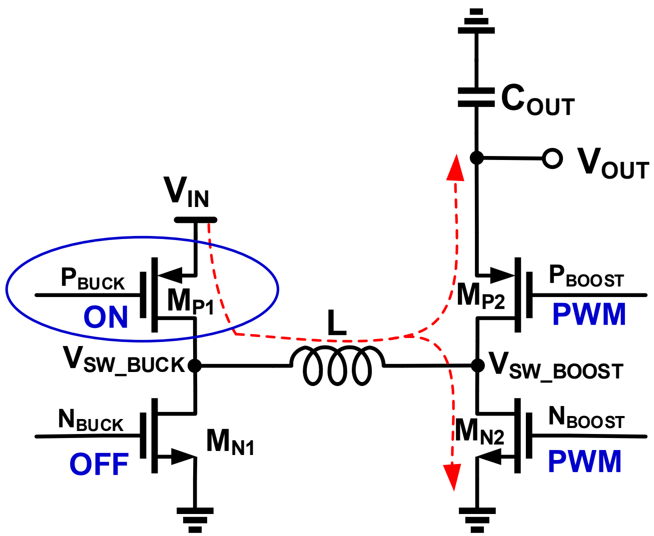
Buck Mode	Buck-Boost Mode	Boost Mode
DBOOST = 1 DBUCK = VPWM	90%Buck:100%Buck 90%Buck:10%Boost 10%Boost:0%Boost	DBOOST = VPWM DBUCK = 1

Losses in Tri-Mode Buck-Boost

- **Buck Mode with equivalent loss model**
  - Additional conduction loss due to M_{P2}

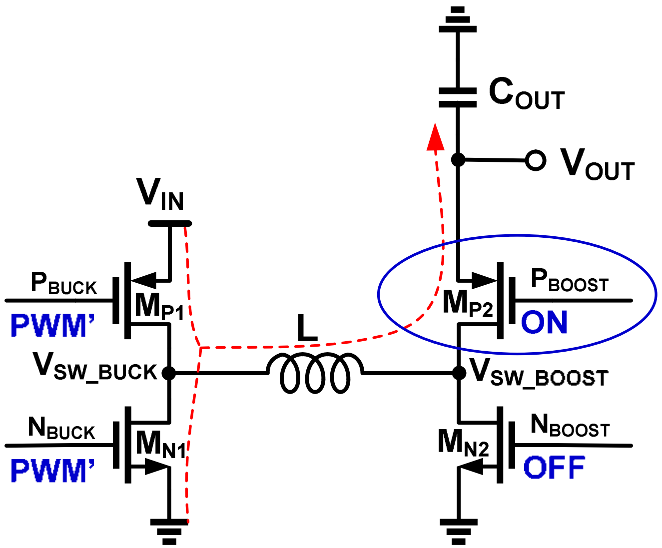


- **Boost Mode with equivalent loss model**
  - Additional loss due to M_{P1}
  - Loss increases due to boosted current Iout/(1-D)

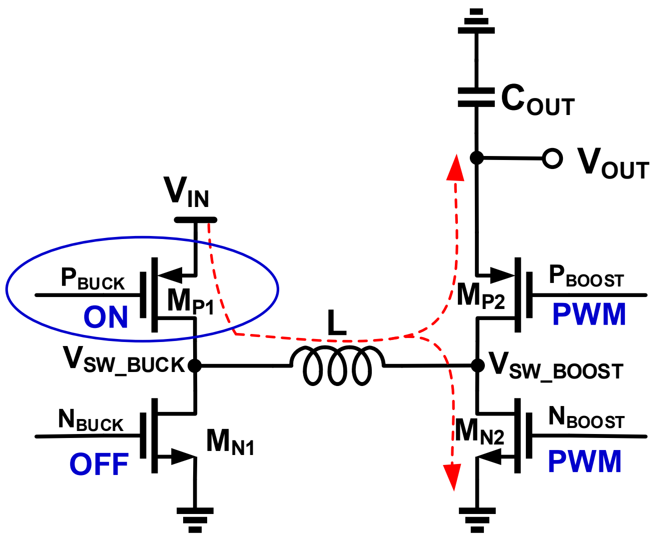


Losses in Tri-Mode Buck-Boost

- **Buck Mode with equivalent loss model**
  - Additional conduction loss due to M_{P2}



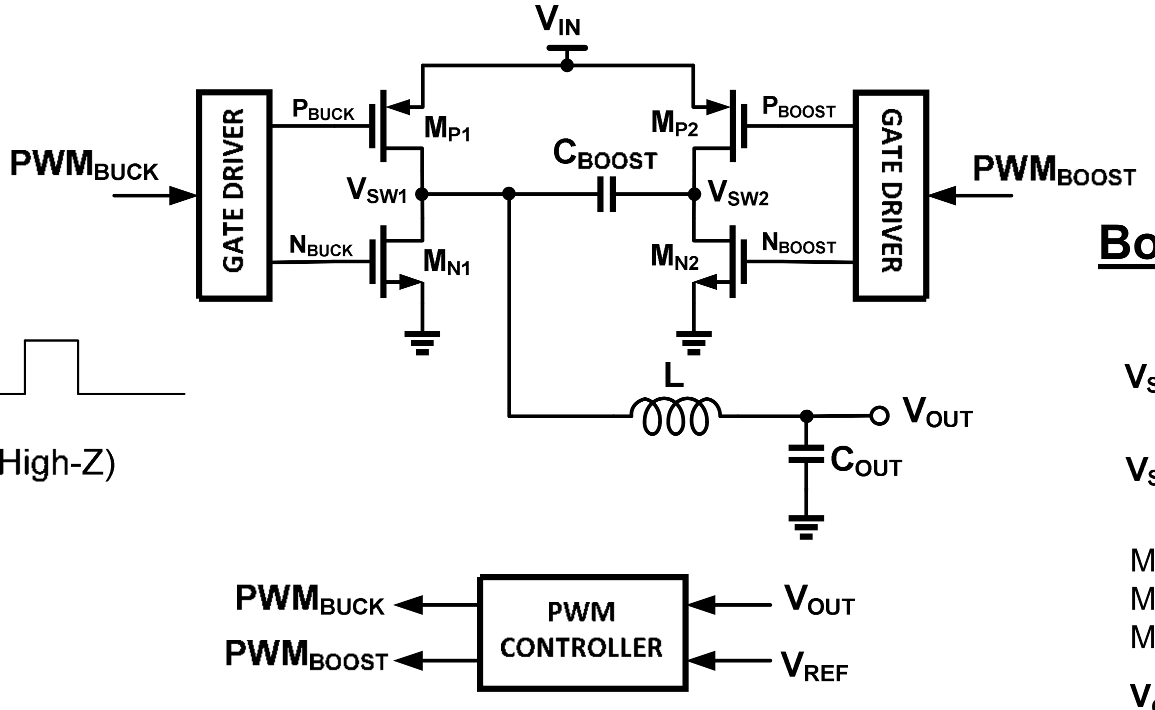
- **Boost Mode with equivalent loss model**
  - Additional loss due to M_{P1}
  - Loss increases due to boosted current Iout/(1-D)



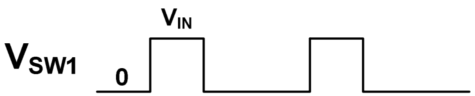
Can we improve?

Hybrid Buck-Boost

- **Uses Hybrid Switched Capacitor and Inductor where Capacitive stage is used to boost the voltage at 2x and Inductive stage is used for regulation**
- **Since Switched Capacitor is isolated from Inductor current path, it incurs less conduction losses**
- **Inductive buck stage has no right half plane zero hence provides better transient response**



Buck Mode

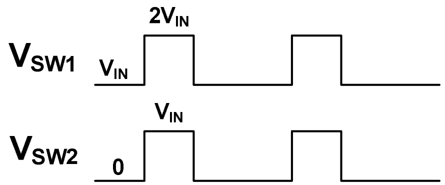


V_{SW2} → Floating (High-Z)

M_{P2}/M_{N2} → OFF
M_{P1}/M_{N1} → PWM

$V_{OUT}=D.V_{IN}$

Boost Mode

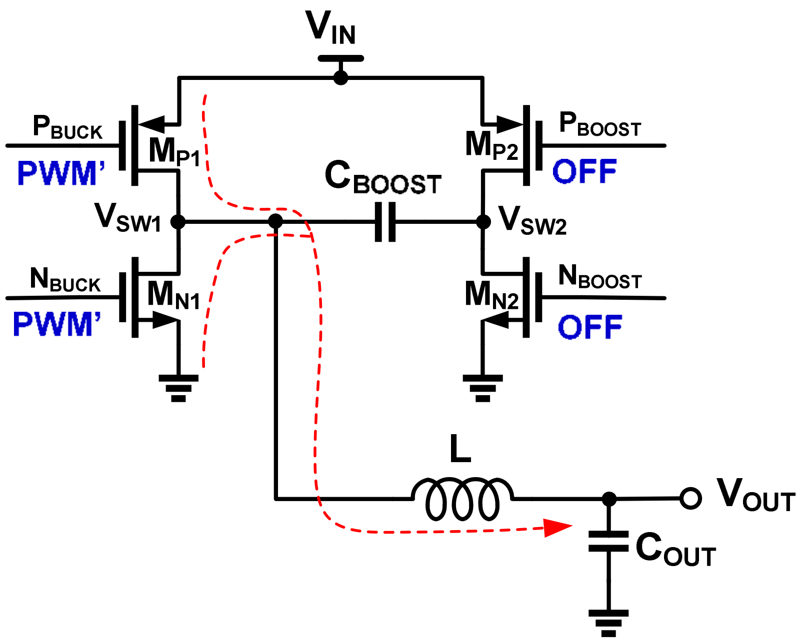


M_{P2}/M_{N2} → PWM
M_{P1} → PWM
M_{N1} → OFF

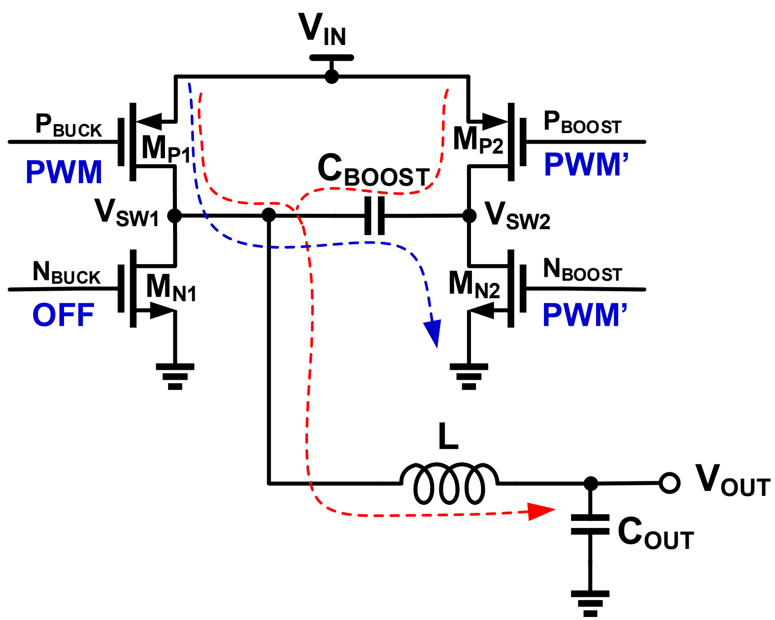
$V_{OUT}=(1+D).V_{IN}$

Hybrid Buck-Boost(Contd.)

- **Buck Mode with equitant loss model**
  - **No additional conduction loss due to MP2**



- **Boost Mode with equivalent loss model**
  - **Reduces loss as inductor current remains same as load current**



Conventional Vs. Hybrid BB (Buck Mode)

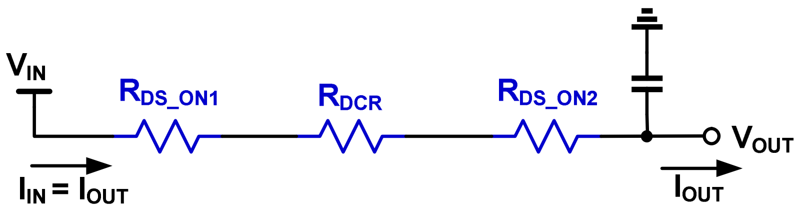
Conventional

- **Additional conduction loss due to MP2**
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100m\Omega$, $I_{OUT} = 1A$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DS\_ON2} + R_{DCR})$

  $= 300mW$



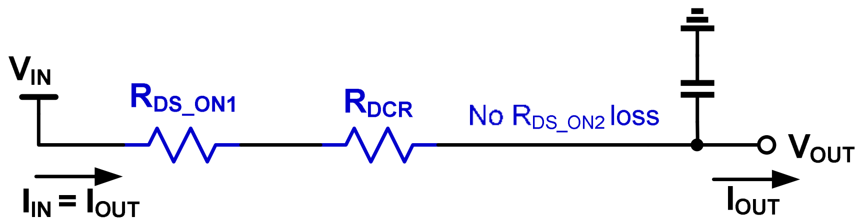
Hybrid

- **No additional conduction loss due to MP2**
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR} = 100m\Omega$, $I_{OUT} = 1A$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DCR})$

  $= 200mW \rightarrow$ 100mW saving in loss



Conventional Vs. Hybrid BB (Boost Mode)

Conventional

- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR}=100m\Omega$, $I_{OUT}=1A$. $V_{OUT}=1.5xV_{IN}$

  Total conduction loss will be:

  $P_{LOSS} = \{I_{OUT}/(1-D)\}^2(R_{DS\_ON1} + R_{DS\_ON2} + R_{DCR})$

  = 675mW

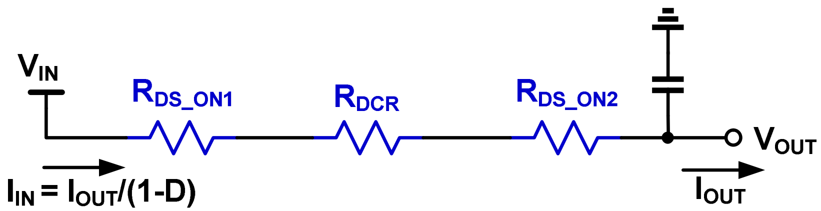
Hybrid

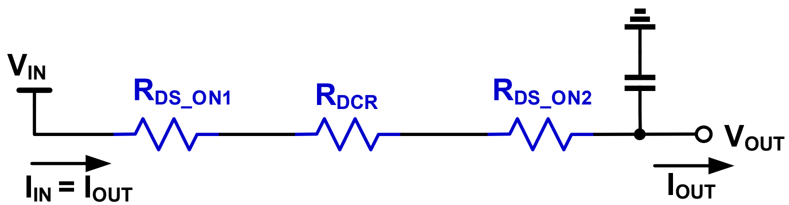
- **Assuming:**
  - $R_{DS\_ON1} = R_{DS\_ON2} = R_{DCR}=100m\Omega$, $I_{OUT}=1A$, $V_{OUT}=1.5xV_{IN}$

  Total conduction loss will be:

  $P_{LOSS} = I_{OUT}^2(R_{DS\_ON1} + R_{DCR} + R_{DS\_ON2})$

  = 300mW → 375mW saving in loss



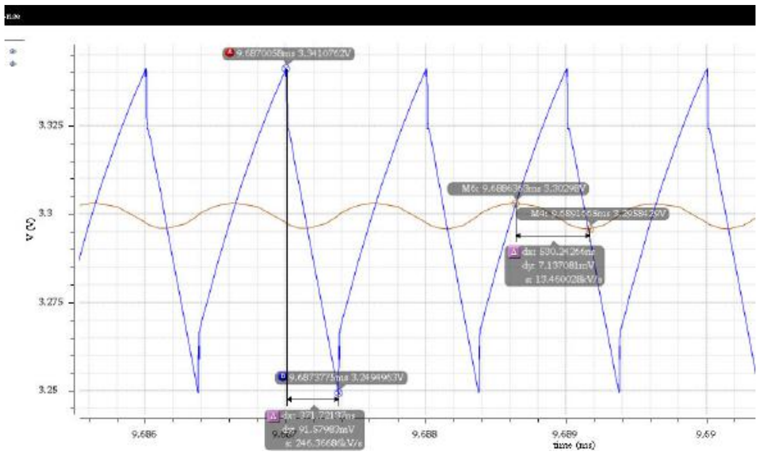


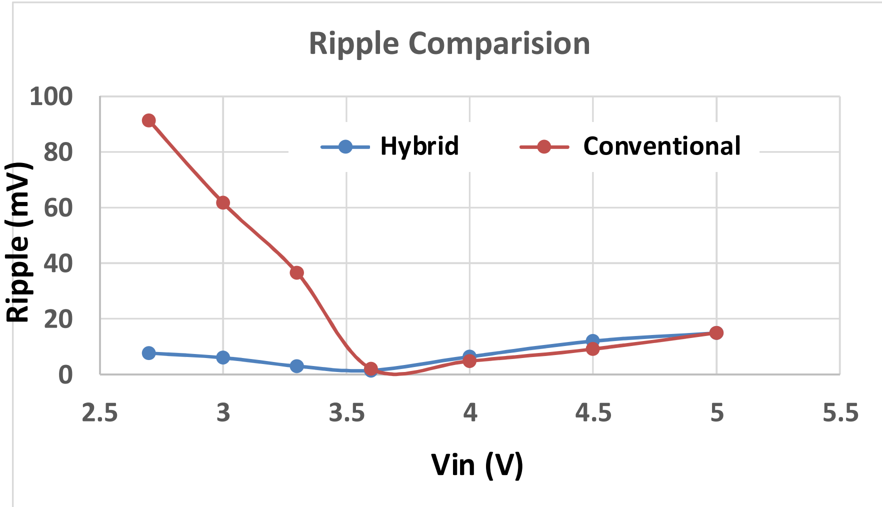
Simulation Results – Ripple Comparison

Boost Mode
Vin = 2.7V, Vout = 3.3V, Iout=1A
Fsw = 1MHz, L = 2.2uH, Cout = 4.7uF

Hybrid→ 7mV Vs. Conventional → 91mV

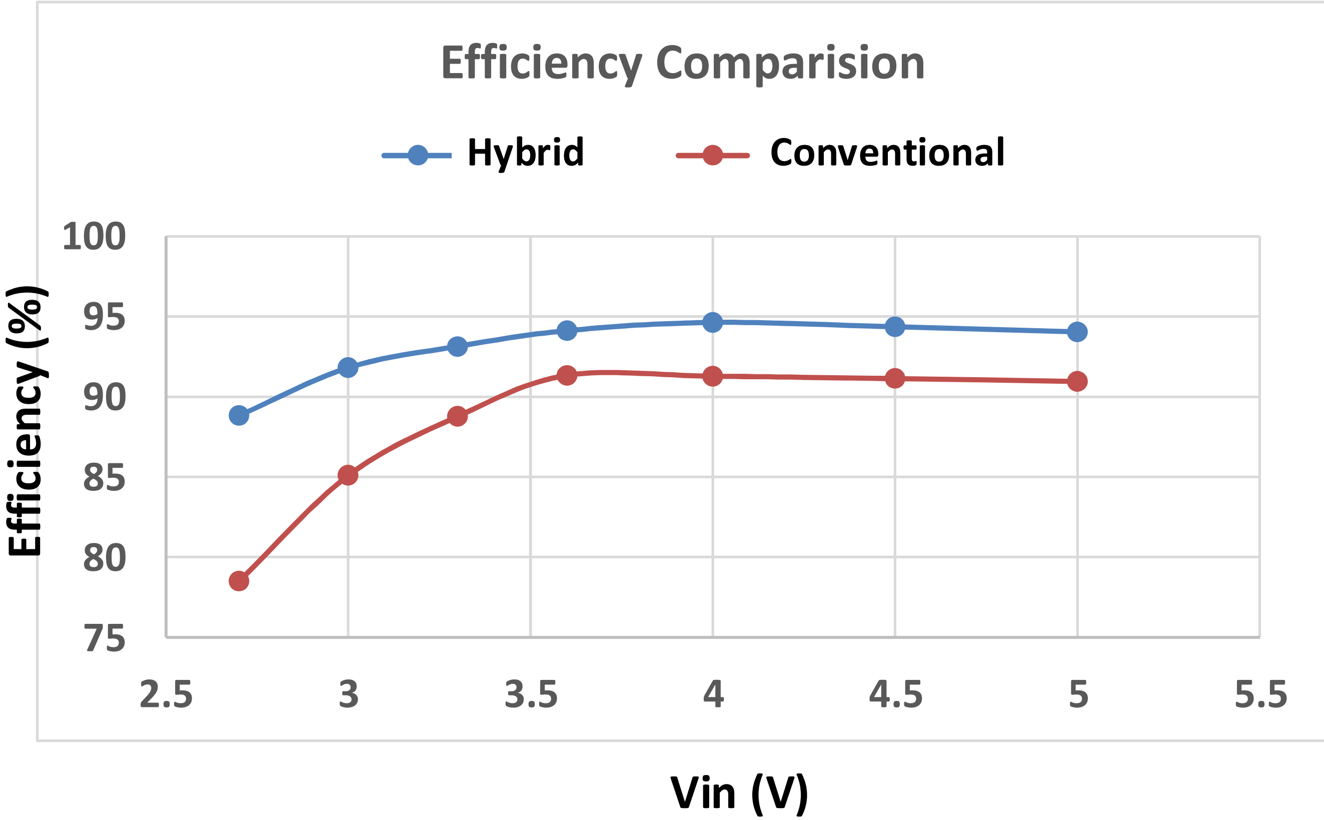
More than 10x reduction in output ripple voltage → Highly suitable for noise sensitive applications





Efficiency Comparison

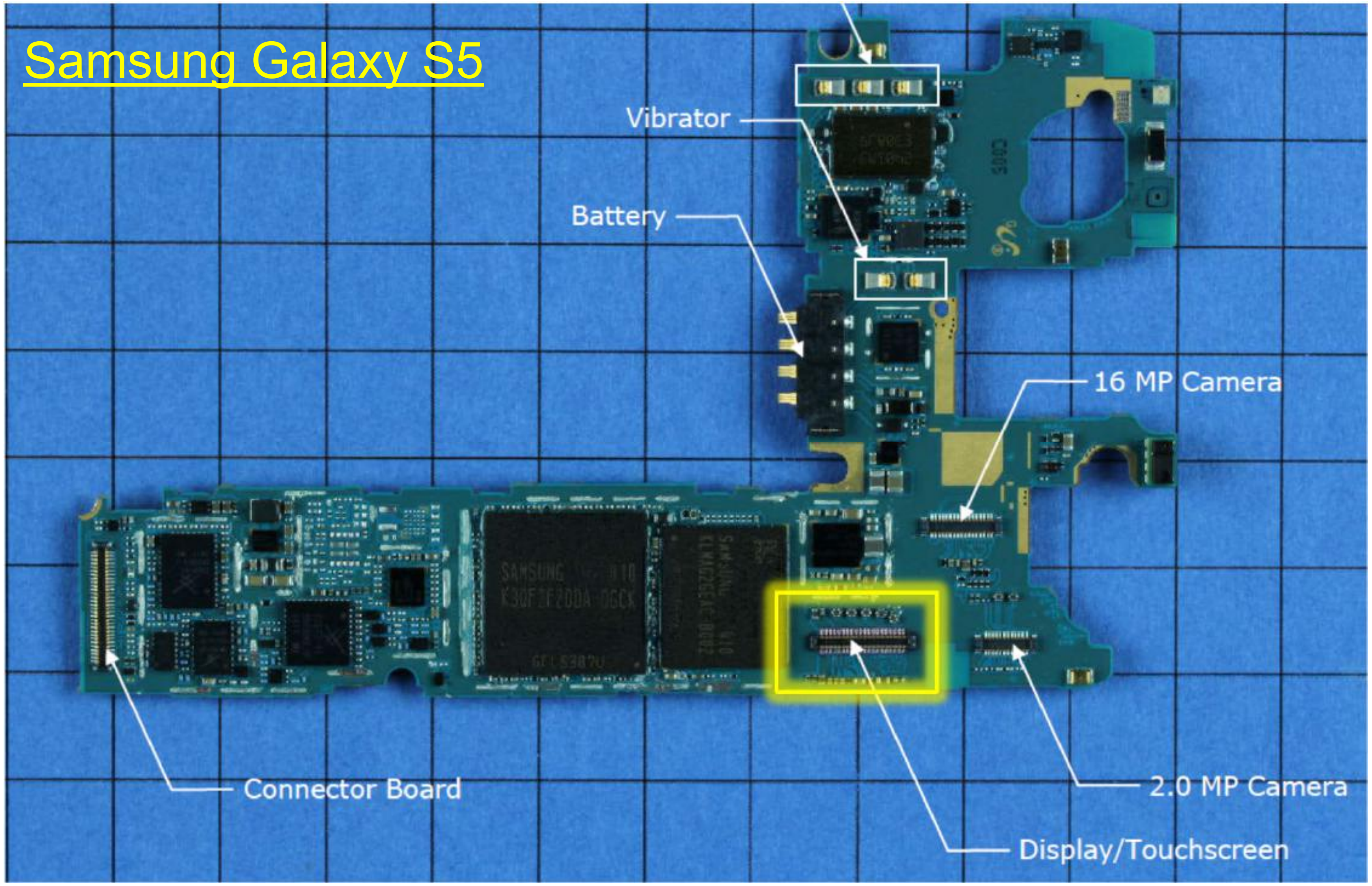
- **Hybrid solution provides ~10% improvement in efficiency in Boost mode and ~3% improvement in Buck mode**



Board Level Design Guidelines

Placement of Display Supply Driver

PCB top view

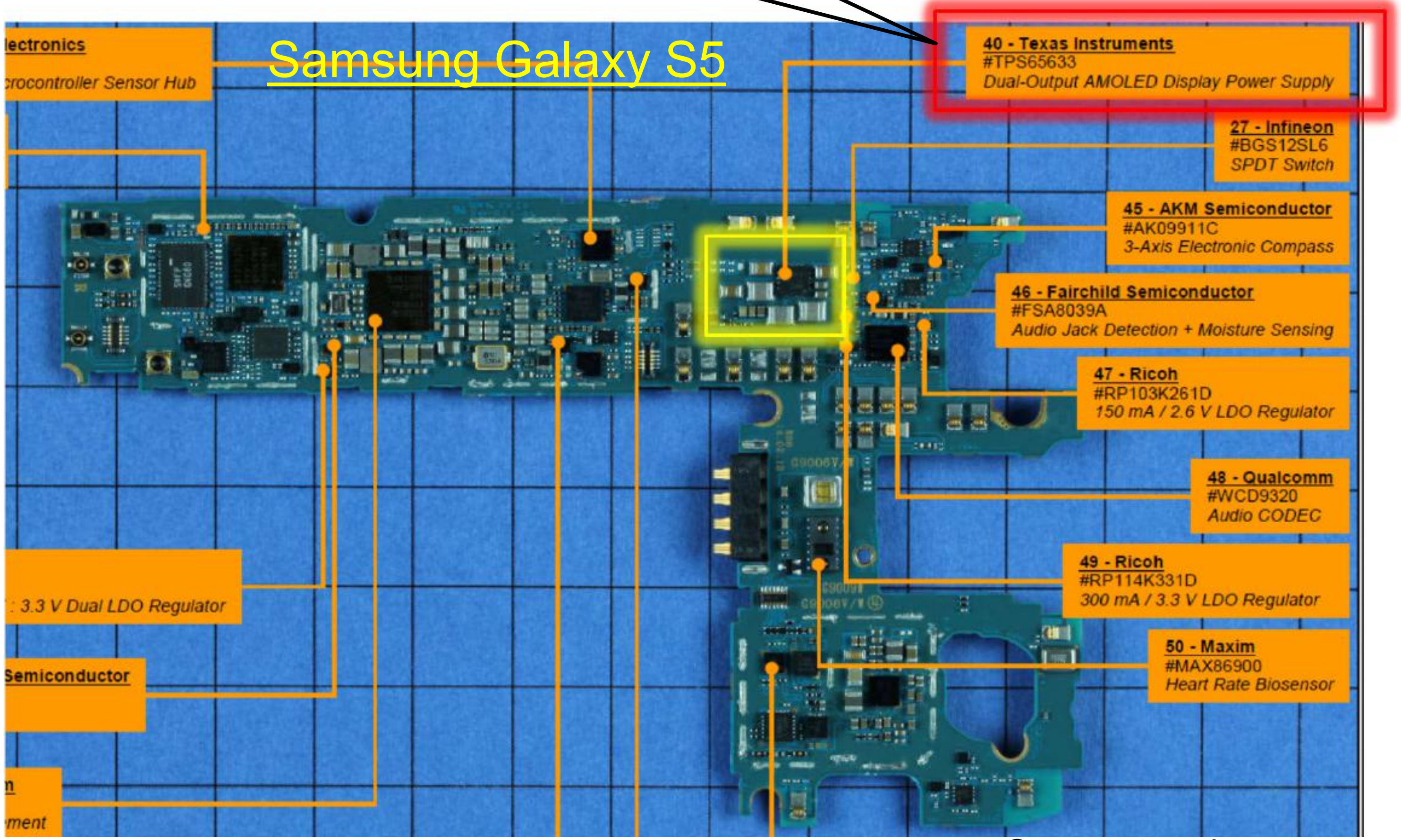


Source: teardown.com

Placement of Display Supply Driver

TI's TPS65633 AMOLED Supply placed right under the display connector

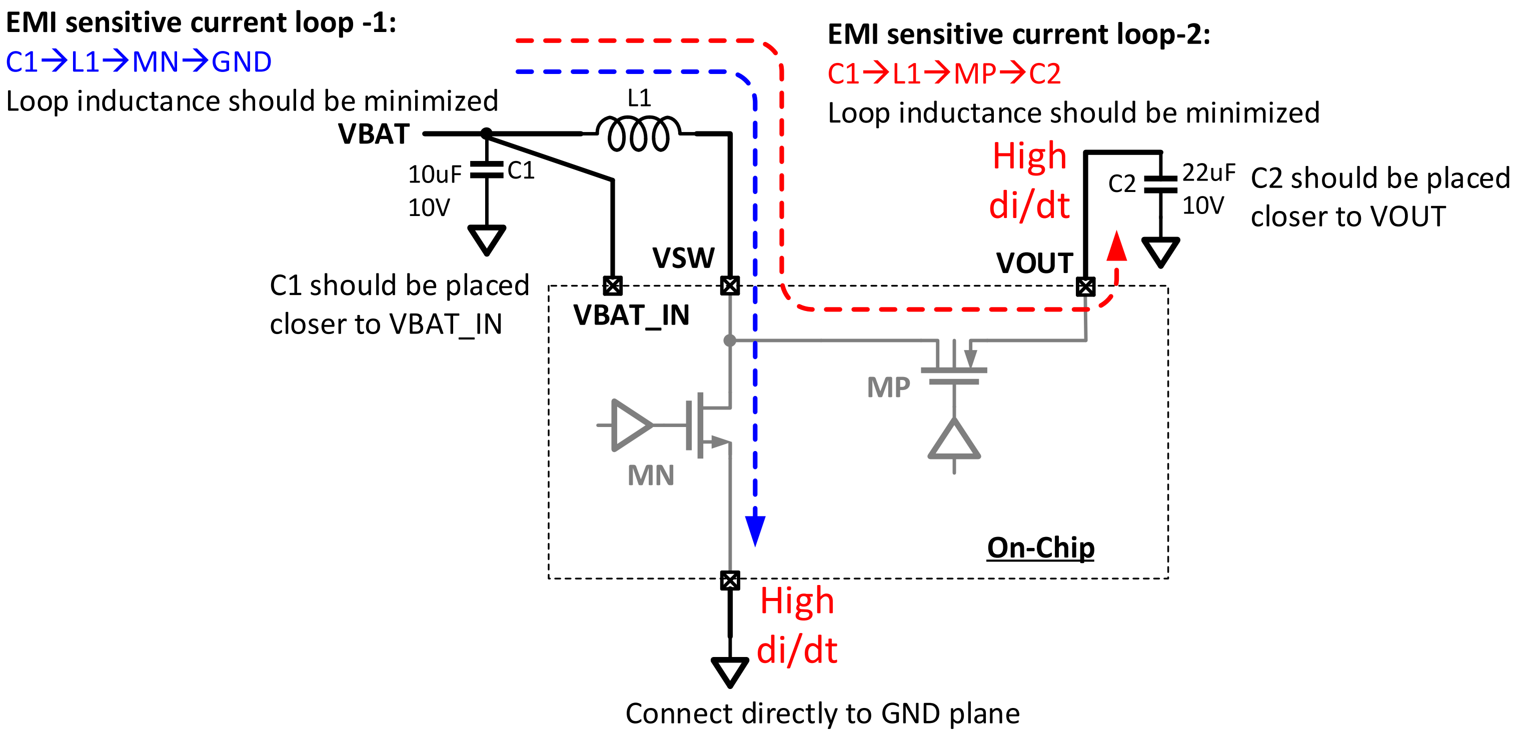
PCB bottom view



Source: teardown.com

EMI Guidelines

- Parasitic Inductance of all traces carrying high switching current (high di/dt) should be minimized
- Capacitors on all voltage switching pins (high dv/dt) should placed closer to the pin



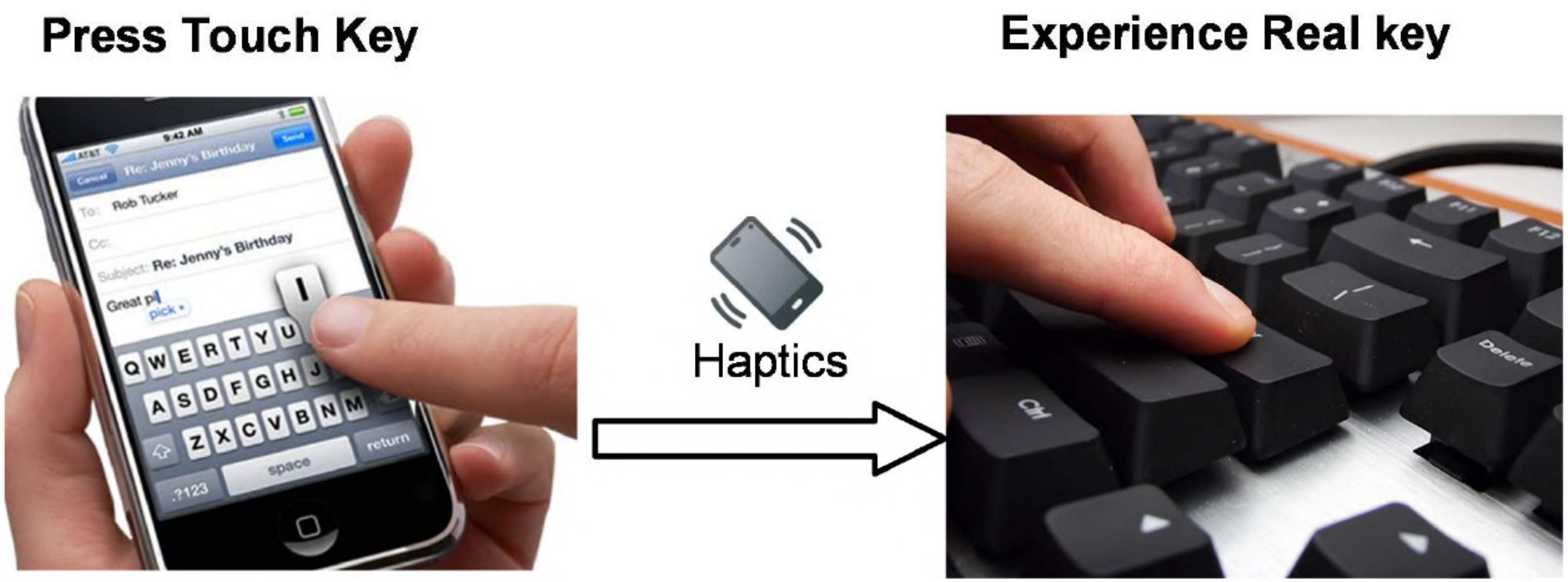
Summary

- Power management techniques for LCD and AMOLED panels were presented
- System level techniques such as RGBW and CABC offer significant power savings
- Hybrid dimming of backlight can be used to reduce the risk of flicker due to noise
- Hybrid Buck-Boost converter for AMOLED positive supply offers better performance compared to conventional boost or buck-boost
- Proper placement of power supply driver and passive components mitigates the effect of EMI

Haptic Driver for Mobile Application

What is Haptics?

- *Haptic* is a sense of touch which provides a feedback through vibration to simulate an event or action.
- Gives user a more enhanced computing experience by simulating 3 dimensional effect on touch screen



Haptic Applications – Medical

- Robotic surgery for remotely located patients
- Surgical training

Haptic Applications – Gaming Consoles

- **Enhanced gaming experience**

Haptic Applications – Automotive

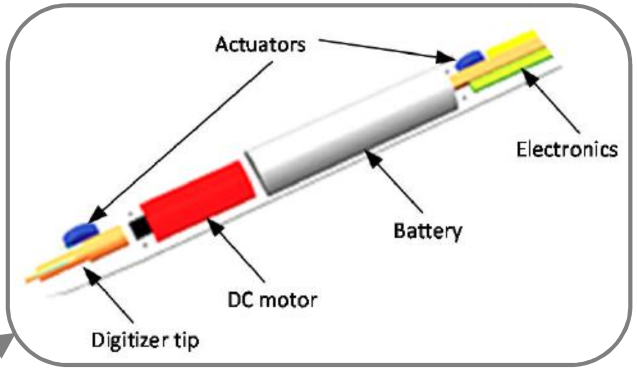
- **Safety alters and dashboard control for ADAS**

Haptic Applications – Tablets and PCs

- **Touchscreens**
- **Touchpads and keyboards**

Haptic Applications – Stylus

- **Vibration is created to provide the feeling of writing on a real paper**



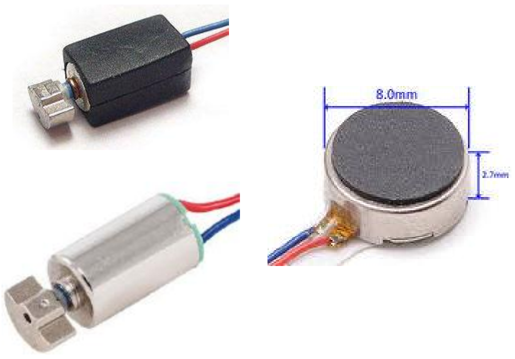
Haptic Applications – Smartphones and Wearables

- Touchscreens
- Touchpads
- Vibration Alerts

Types of Haptic Actuators

- **Three most commonly used actuators for haptic**

ERM – Eccentric Rotating Mass



Brushed or brushless DC motor

Comes in various shapes

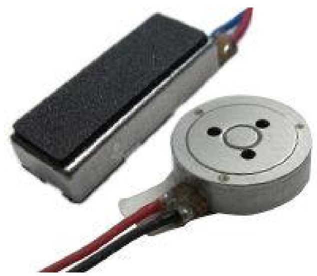
Operating voltage: up to 1V-3.6V

Slow response time : 50m-100ms

Variable vibration frequency: 1-300 Hz

Drive Signal : DC

LRA – Linear Resonant Actuator



Resonant vibrator

Rectangular and circular shapes

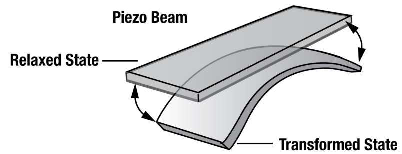
Operating voltage : 2Vrms

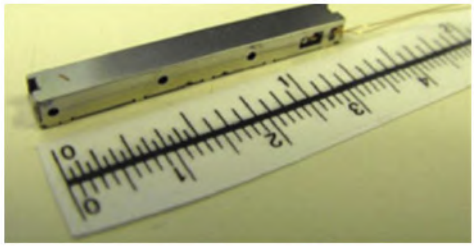
Faster response time : 20-30ms

Fixed vibration frequency: 150-200 Hz

Drive Signal : AC

Piezo





Piezo beam

Rectangular shape, large size

Operating voltage : 50-200V

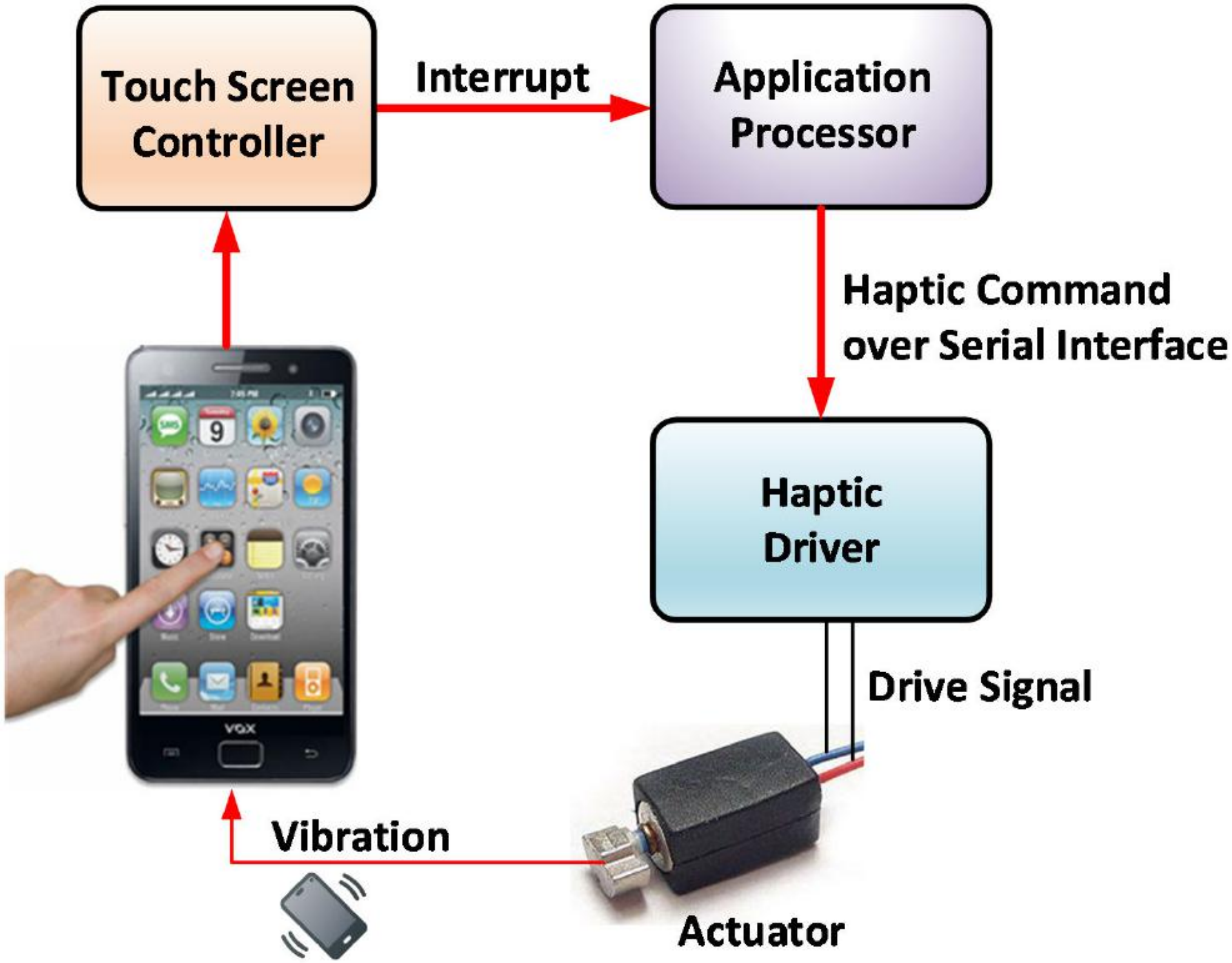
Fastest response time : < 1ms

Fixed vibration frequency: 150-200 Hz

Mostly used in tablets and not suitable for mobiles phones due to large for factor

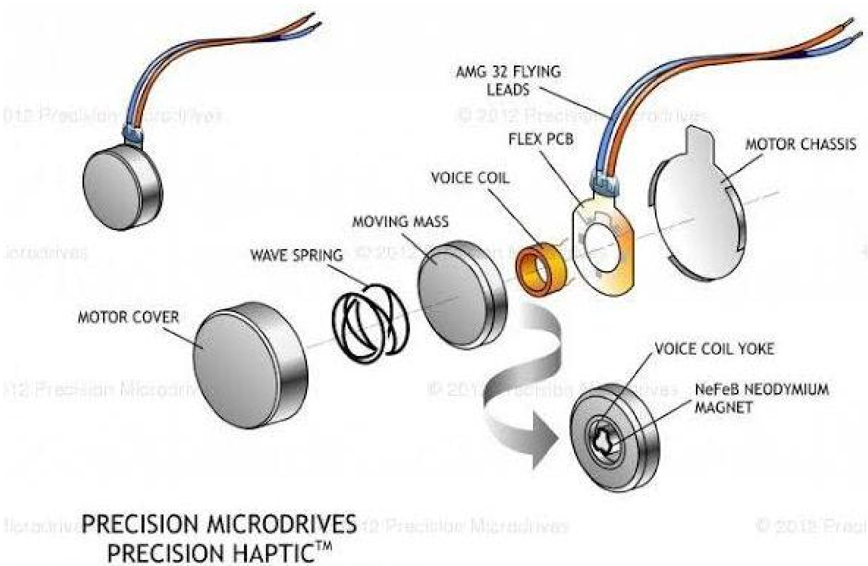
Sources: Texas Instruments, Precision Microdrives, EEtimes

How Haptic System Works

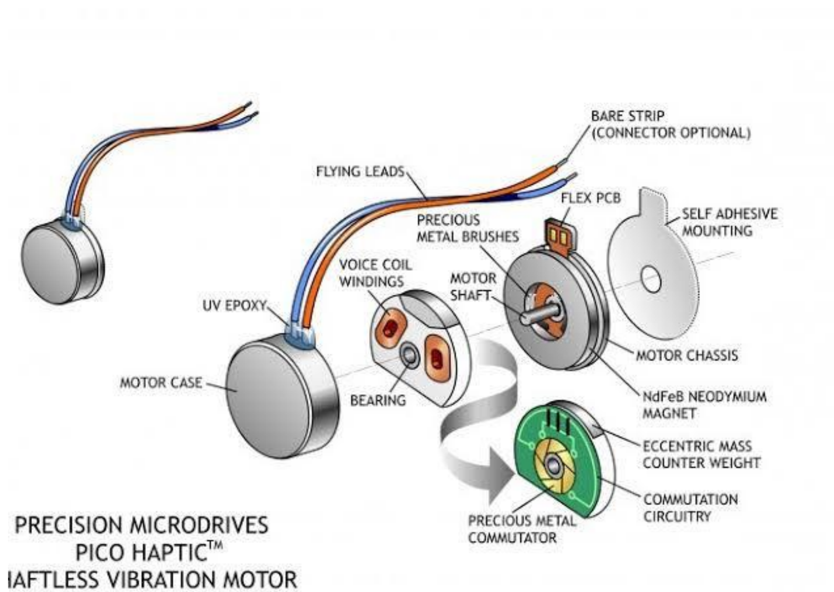


Inside ERM and LRA

LRA



ERM

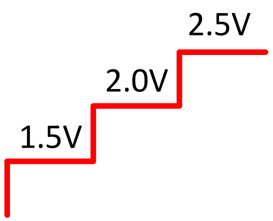


Sources: Precision Microdrives

Driving ERM and LRA

ERM (Eccentric Rotating Mass)

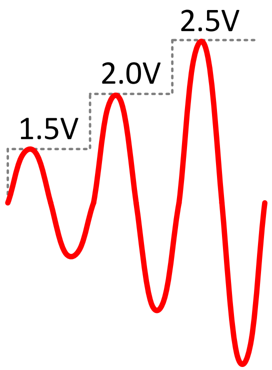
- Based on dc motor with off centered mass
- Uses DC voltage drive
- Operating voltage up to 3.6V dc
- Vibration strength is proportional to dc voltage
- Slow start/stop (50ms-100ms)
- Overdrive is used to start faster and reverse braking is used to stop it faster



DC Drive Signal

LRA (Linear Resonant Actuator

- Based on fixed voice coil and moving magnet
- Uses AC drive signal and operate at fixed resonance frequency (~200Hz).
- Operating voltage up to 2.0V rms
- Vibration strength is proportional to AC signal amplitude
- Fast start (15-20ms) but slow stop (~100-200ms) due to spring action
- Reverse braking is used to stop it faster



AC Drive Signal

ERM consumes ~2x more power compared to LRA

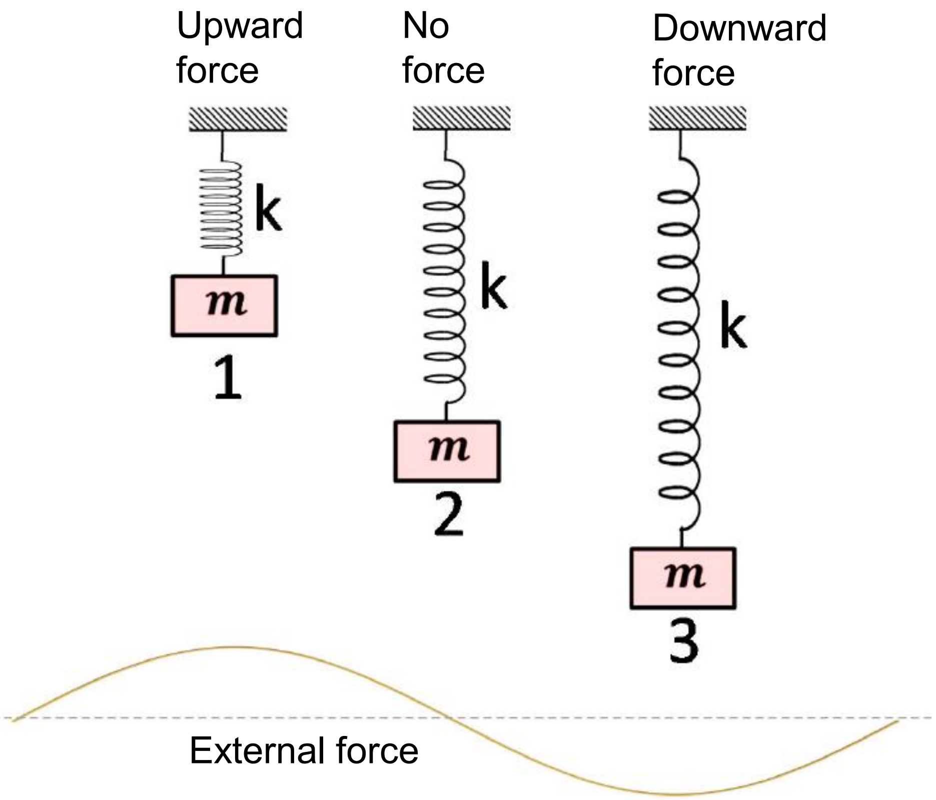
How Does It Work

- **A hanging spring with one end fixed and other end attached to a moving mass will resonate if an external force is applied.**
- **The resonance frequency is given by:**

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Where k=spring constant, m=mass

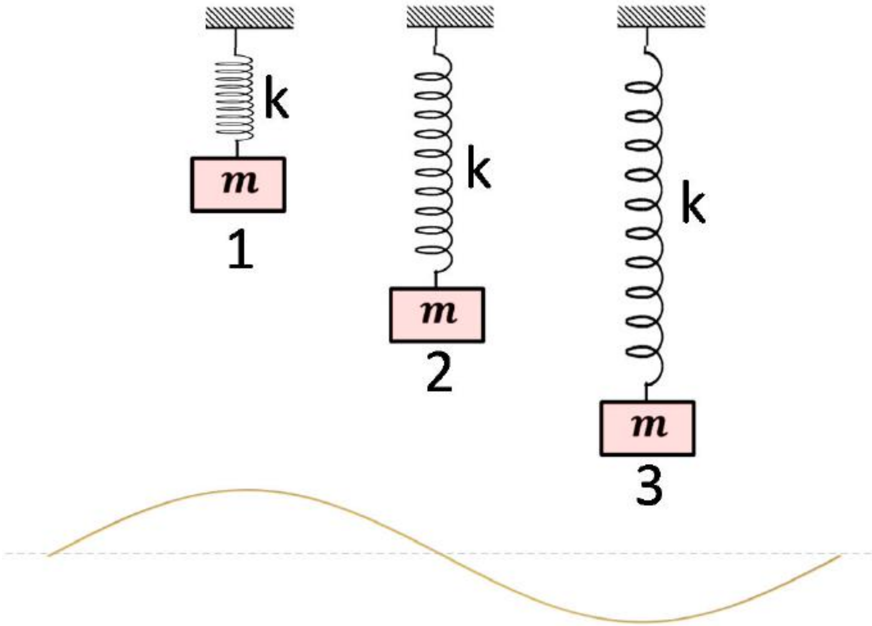
- **Since spring is a high-Q resonant system, it generates maximum force when driven at it's natural frequency, f_o.**
- **A driving force with frequency ≠ f_o will tend to oppose the reactive force generated by spring due to phase shift and reduces the vibration amplitude.**

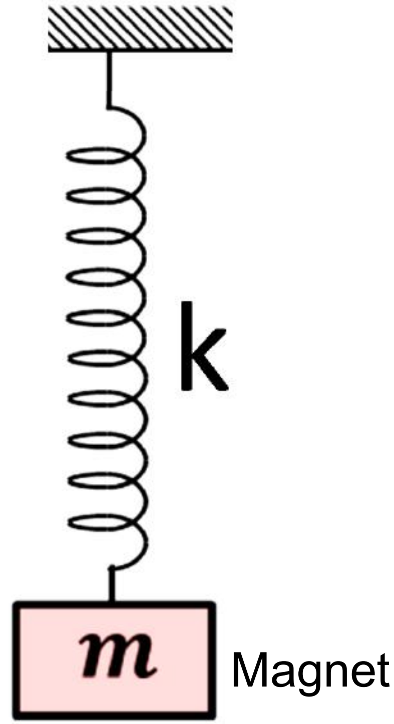


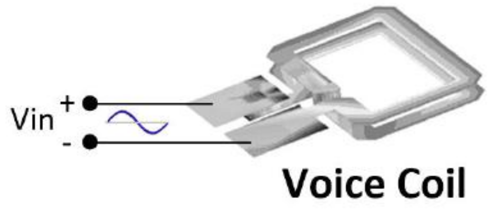
Generating External Force

- If the moving mass is replaced with a magnet then a voice coil, which acts as electromagnet, placed close the magnet can excite the spring if an electrical AC signal with frequency=f_o applied across the voice coil.

- Mass of the magnet is selected such that spring is in equilibrium when no electrical signal is applied across the voice coil.



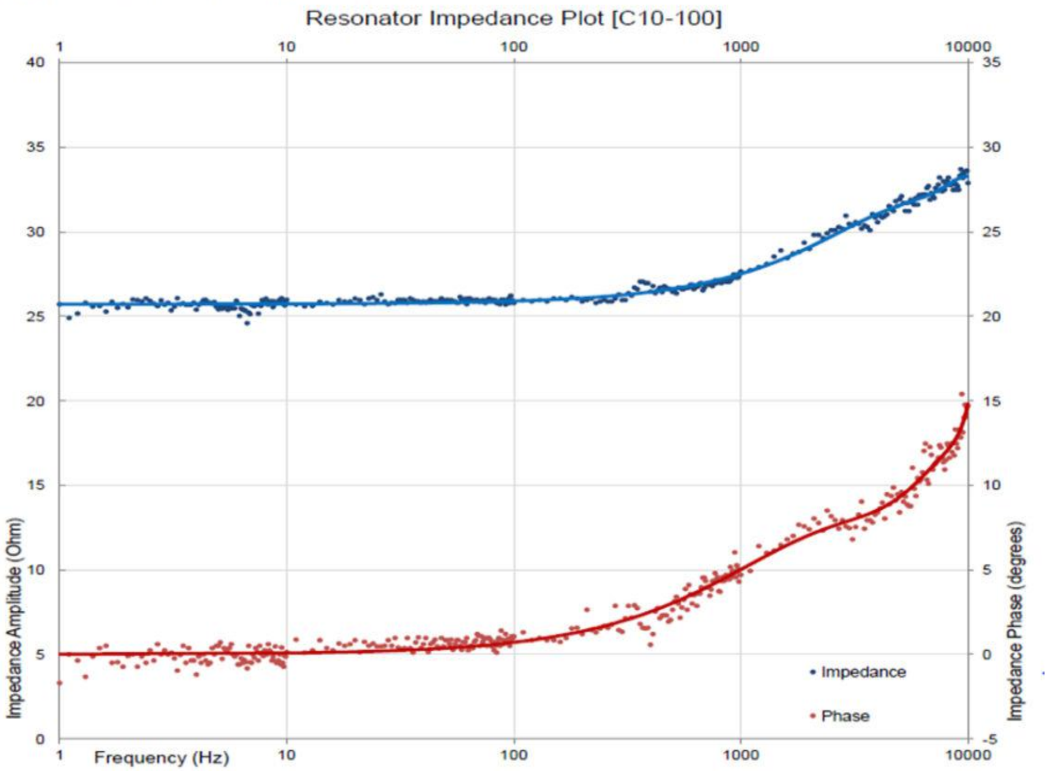




LRA Electrical Model

- **LRA manufactures datasheet usually show input impedance plot which doesn't model the resonance**
- **Since electrical coupling of LRA is through voice coil which has only R and L so it's only a LPF**

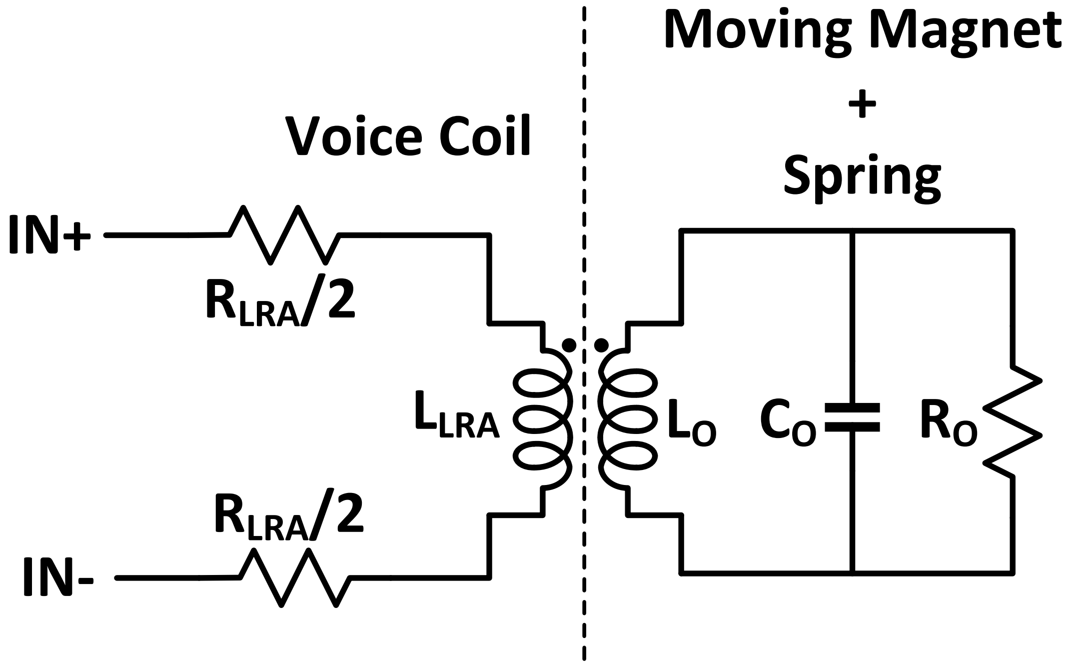
Typical Resonator Impedance Plot



Sources: Precision Microdrives

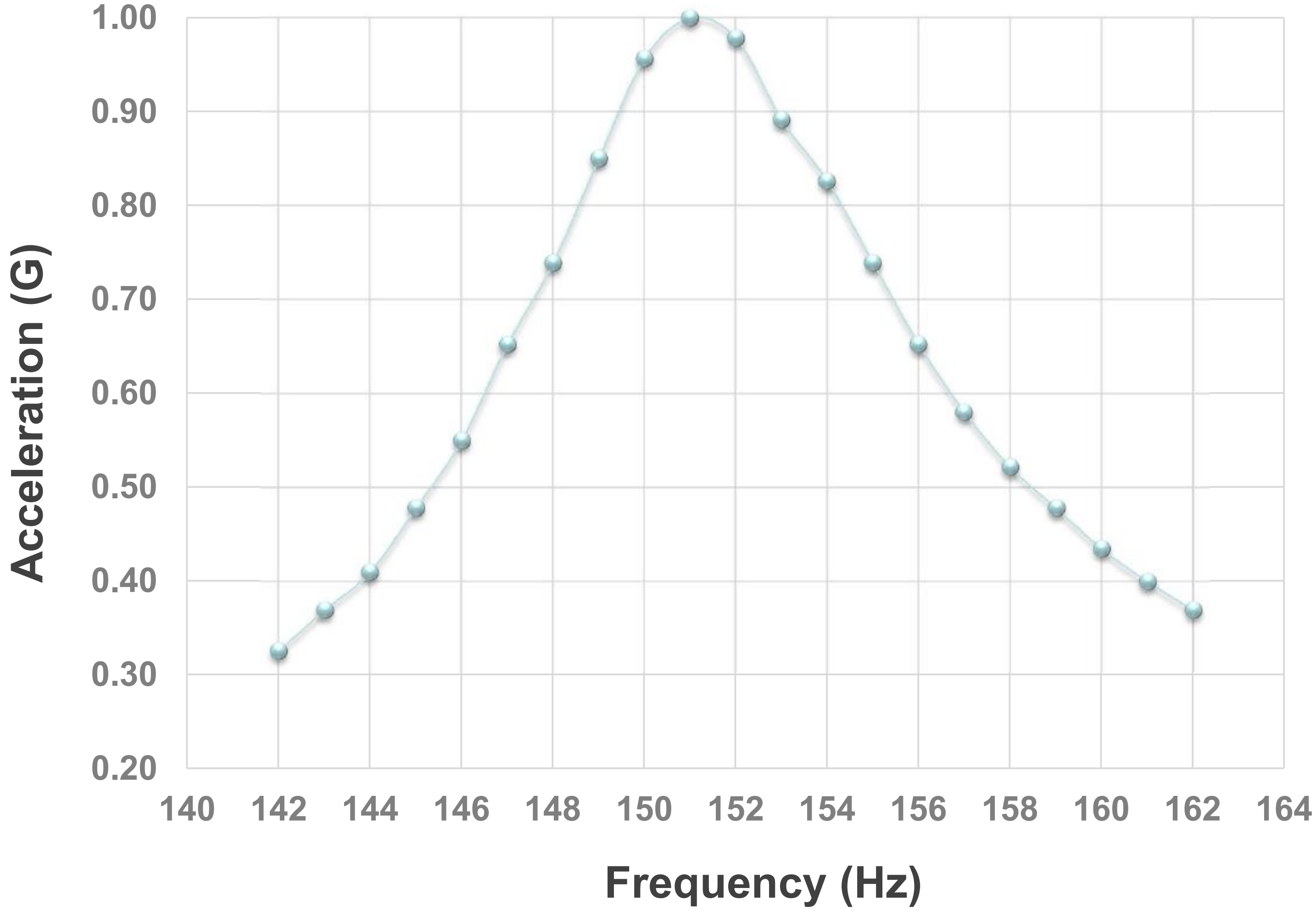
Improved Electrical Model of LRA

- There is only magnetic between voice coil and resonating spring.
- The electrical model can be approximated as series L-R (voice coil) with magnetically coupled LC tank (spring + magnet).



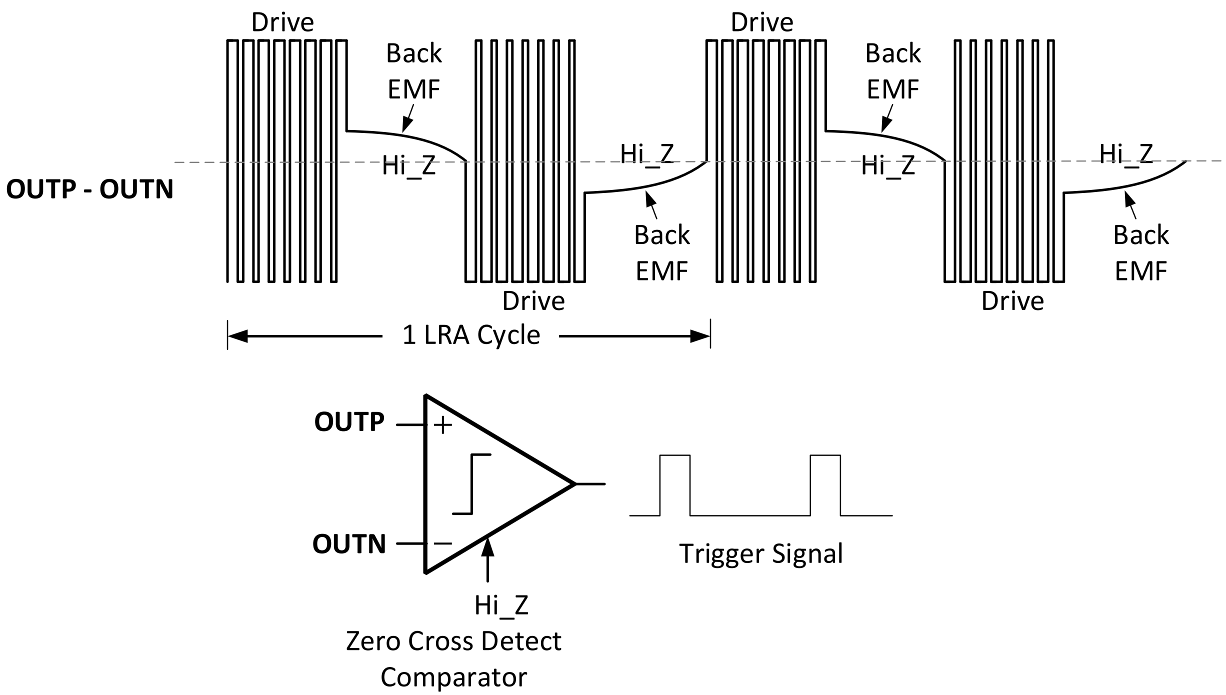
Q. Khan et al, Circuits and Methods for Driving Resonant Actuators, US 9,344,022 B2, May 17, 2016.

Frequency Response of LRA



Detecting LRA Resonance Frequency using Back EMF

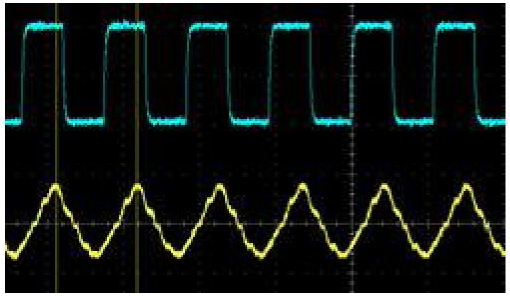
- **LRA is driven for partial cycle and left in high-z mode to read the back EMF**
- **During high-z phase, ZXD comparator generates next trigger edge when back EMF at OUTP and OUTN cross**



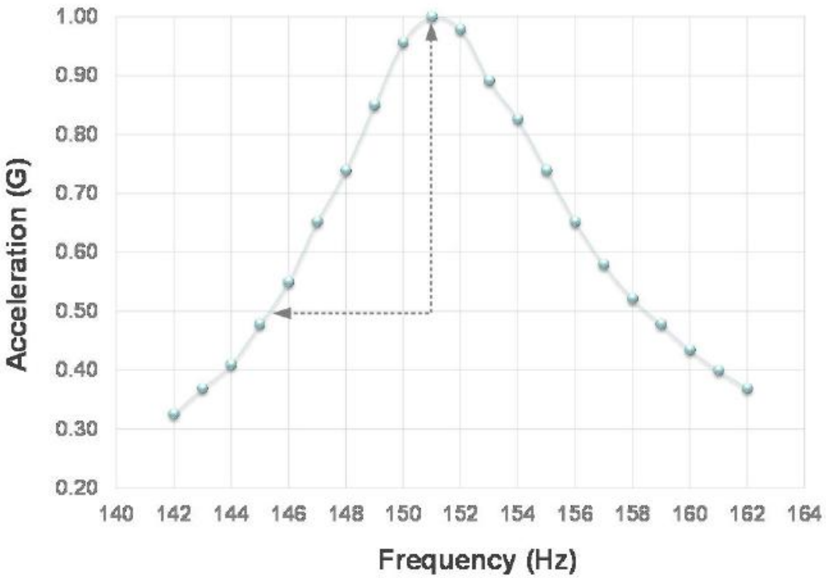
Q. Khan et al, Circuits and Methods for Driving Resonant Actuators, US 9,344,022 B2, May 17, 2016.

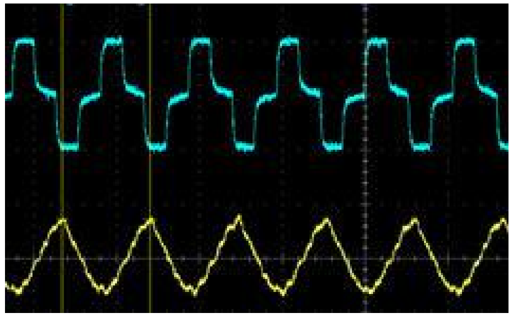
Auto Resonance for LRA

- **LRA is a high Q system, a small drift in the resonance frequency may cause significant drop in the vibration strength.**
- **Auto resonance detection to correct any drifts in the frequency and ensures optimum driver strength across varying operating conditions.**



Without Auto resonance
Power consumption = 200mW/g

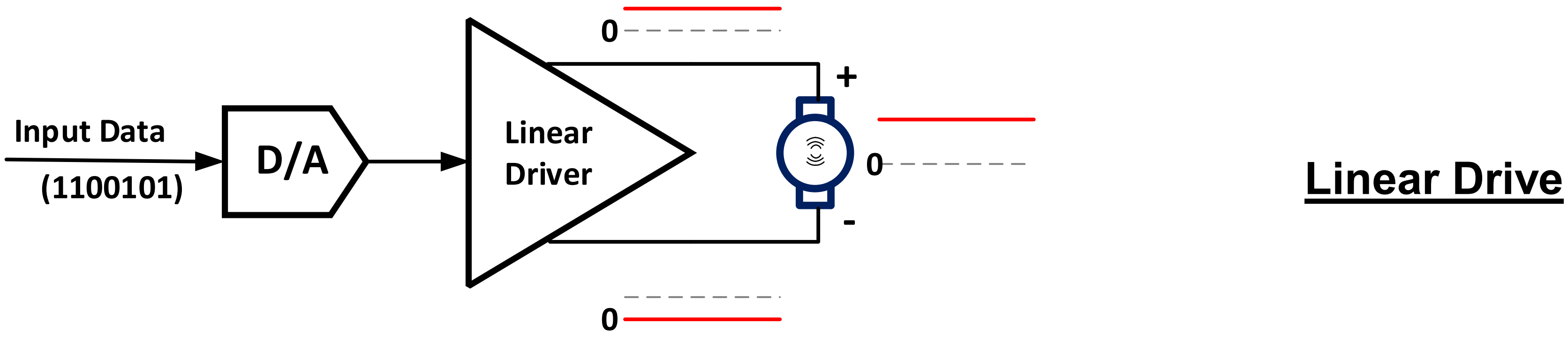


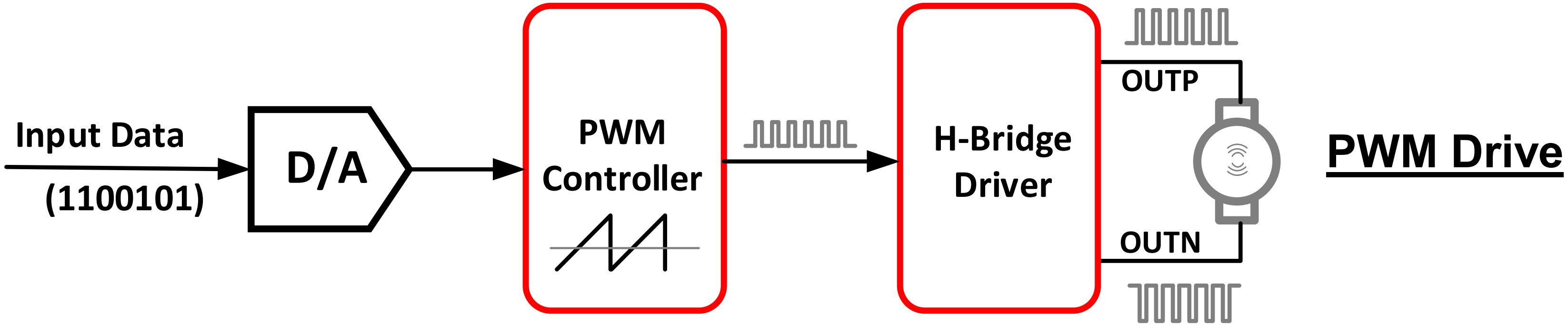


Without Auto resonance
Power consumption = 100mW/g

Drive Methods

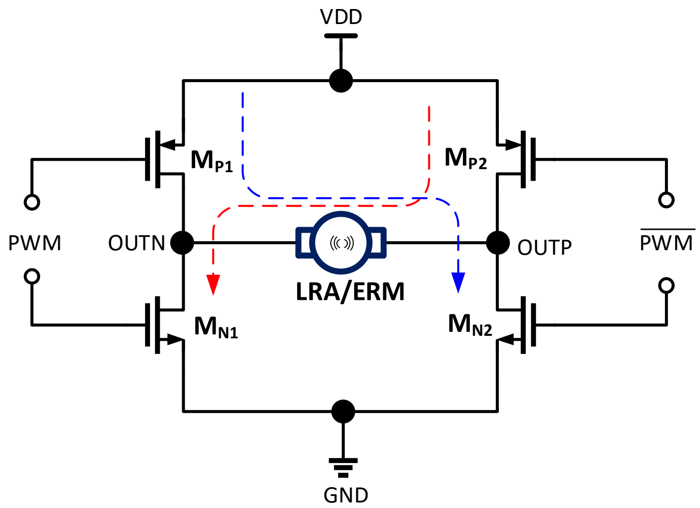
- **Fully differential driver is used to support both DC (for ERM) and AC (for LRA) as well as active braking (reverse drive)**

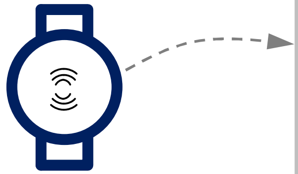


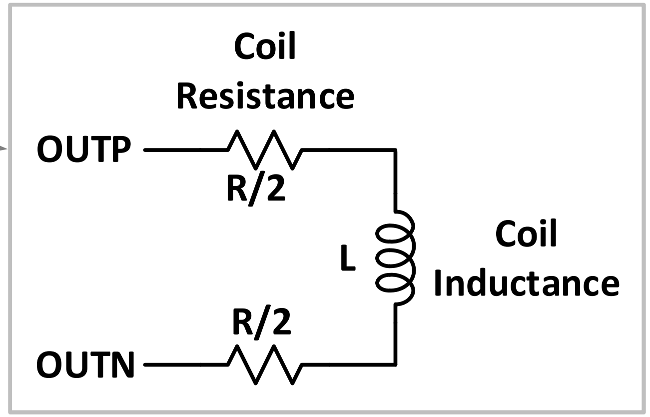


Differential PWM Drive

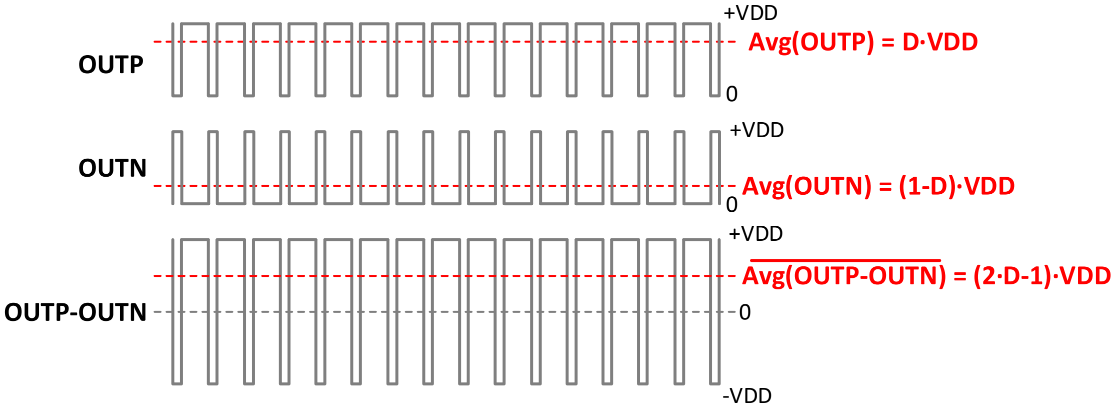
- **H-Bridge driver is used**
- **High value of actuator inductance (100uH-1mH) converts**







Actuator model



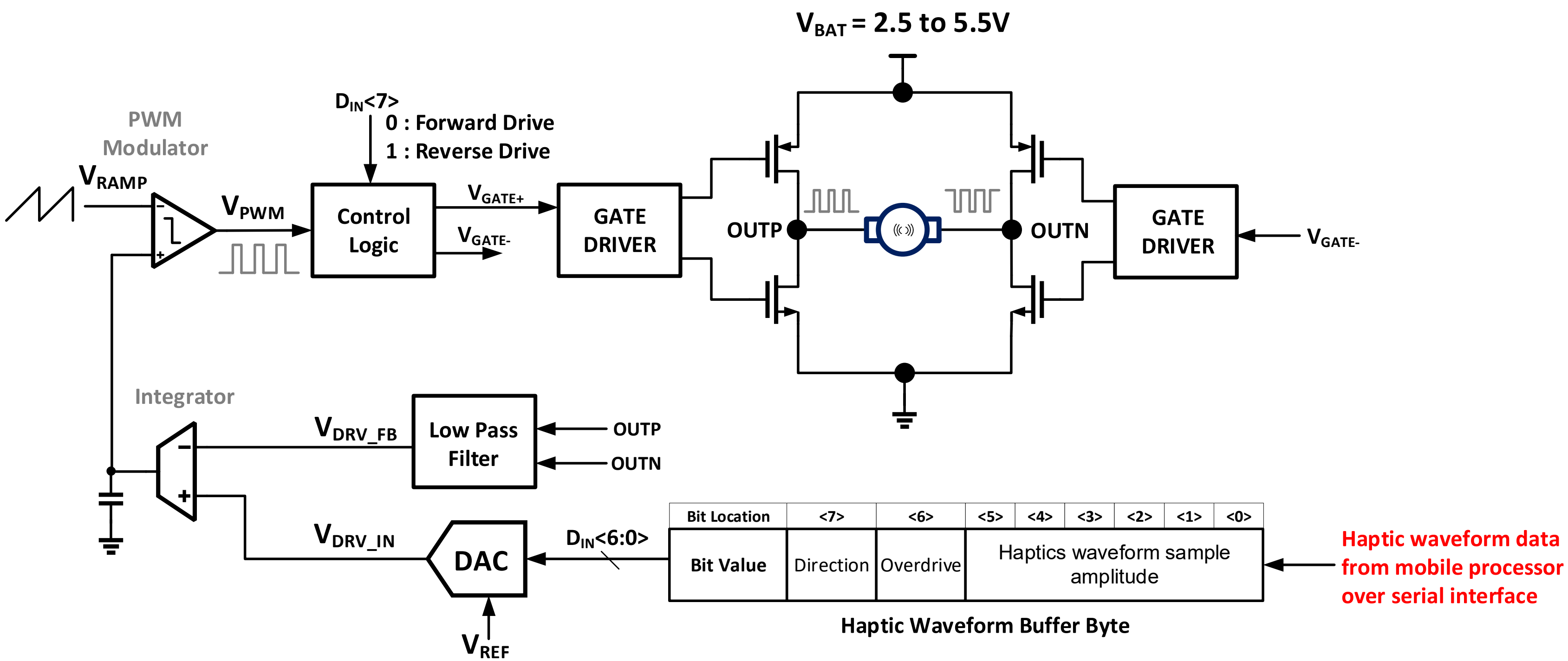
D > 0.5 : Positive or Forward Drive

D = 0.5 : No Drive

D < 0.5 : Negative or Reverse Drive

Closed Loop Control

- **Closed loop control is needed to compensate for variation in input supply voltage (V_{BAT}) and IR drop across MOSFET switches**

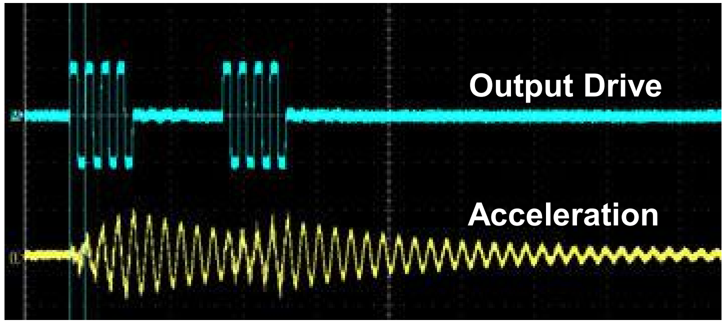


Bit Location	<7>	<6>	<5>	<4>	<3>	<2>	<1>	<0>
Bit Value	Direction	Overdrive	Haptics waveform sample amplitude					

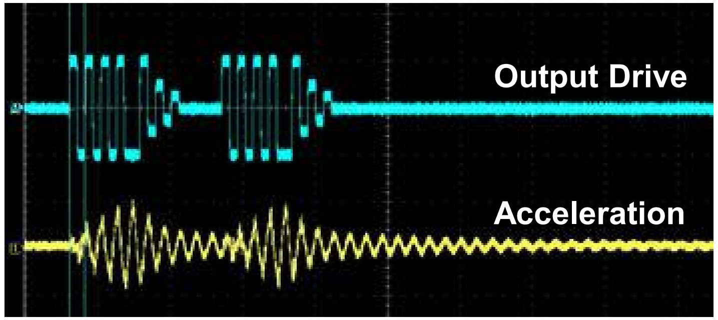
Haptic Waveform Buffer Byte

Active Braking

- **Since LRAs can't stop quickly due to resonance, users can hardly differentiate between quick key press**
- **Driving LRA in reverse direction (active braking) helps in stopping it faster**



Without Active Braking



With Active Braking

Types of Patterns

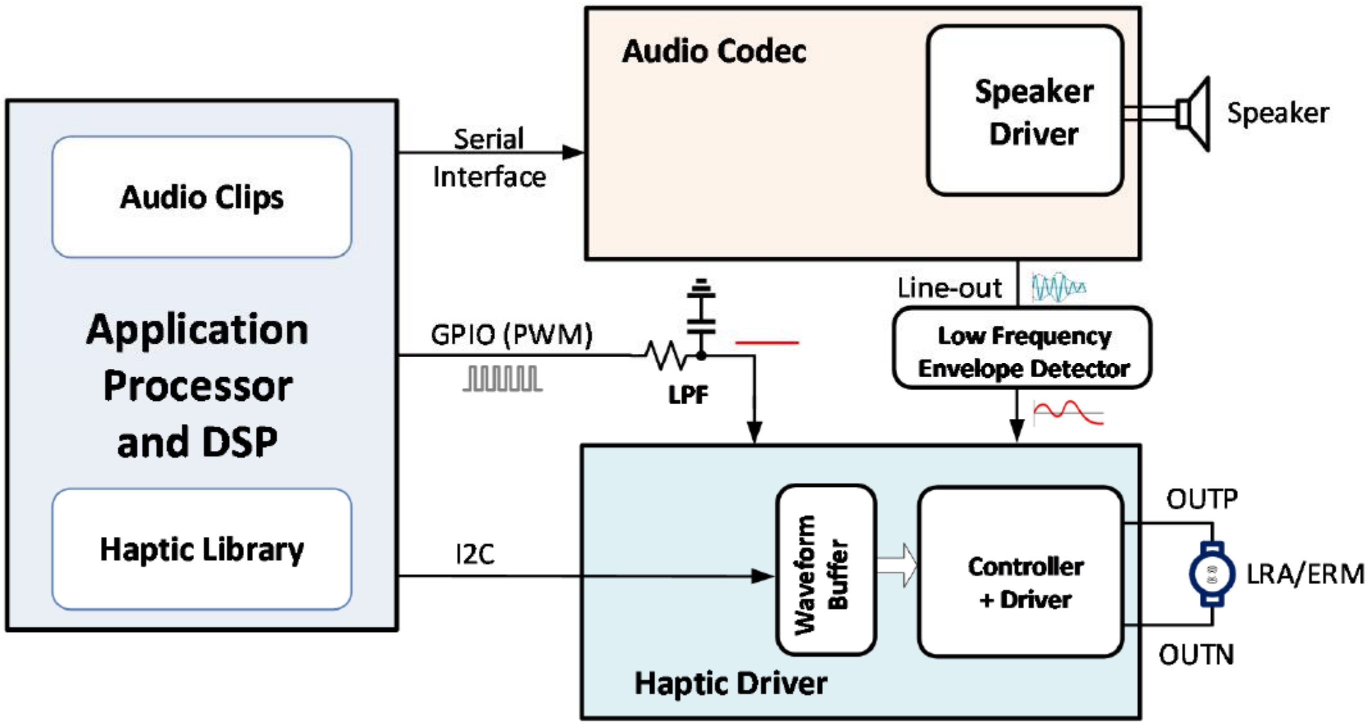
- **Short Patterns**
  - Used in typing for generating press/bump
  - Message alert
- **Long Patterns**
  - Scrolling
  - Call alerts
- **Complex Patterns**
  - Typing with synchronized press/bump and click sound
  - Synchronized ringtone with vibration
  - Setting different vibration patterns for different callers
  - Full audio-visual gaming with haptics added as another dimension

Haptics-Audio Interfacing

- **Can play the sound pattern through haptics for enhanced gaming and computing experience**
- **Ringtones or audio clips can be used as vibration pattern in silent mode**

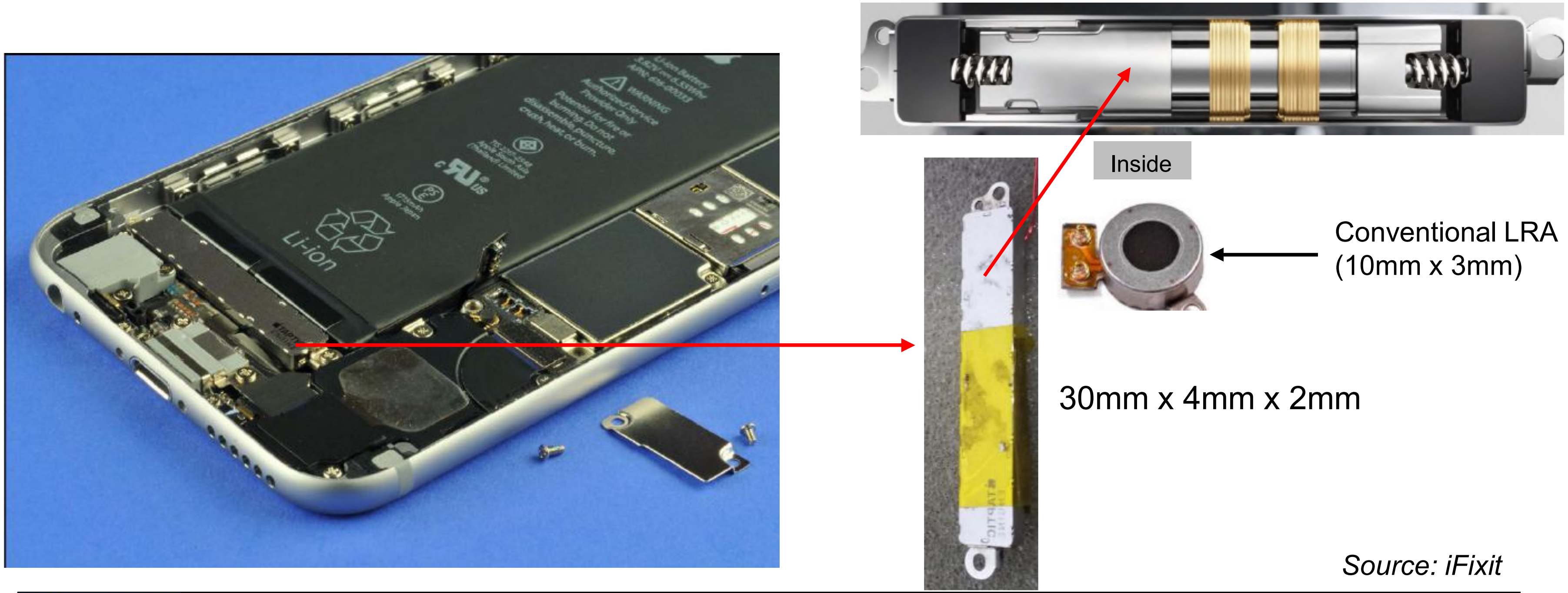
Playing Waveforms

- **Haptic waveforms can be played from three sources**
  - Serial interface by buffering the data in waveform buffer
  - External PWM sent over general purpose IO (GPIO)
  - Audio Line-out from codec



Iphone Haptics Module

- **The Haptics driver inside iphone 6S is called Taptic engine, integrated with TS module**
- **Larger in size (comparable to piezo) and supports much higher voltage (10-12V)**
- **Lower Q so doesn't require auto resonance detection**



Source: iFixit

Thank You