Power Management Integrated Circuits
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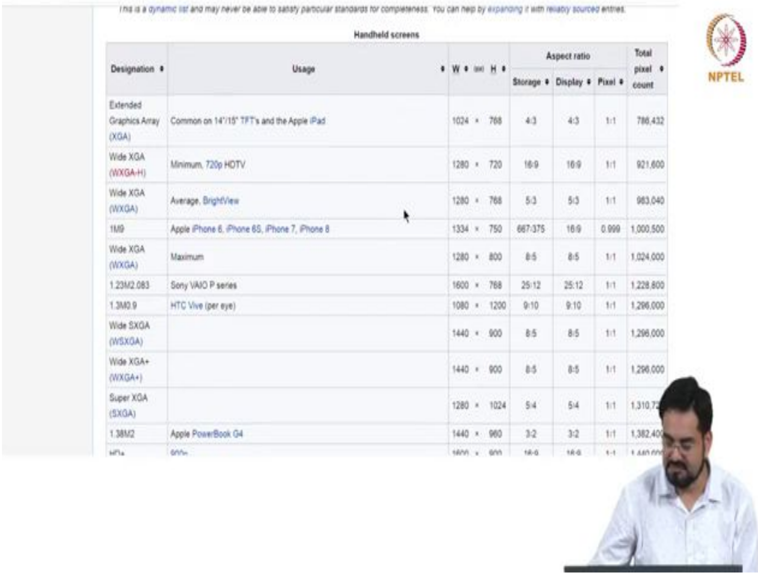
Lecture – 99
LCD/AMOLED Display Drivers – Part 2



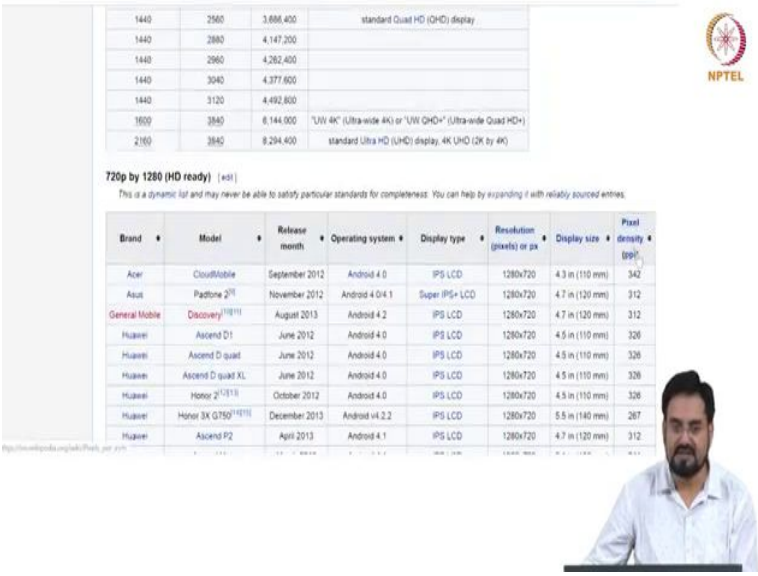
Width over length will give you the aspect ratio and it depends on the shape of the display also. I mean square or rectangular or width is more than height or height is more than width. So, that gives you an aspect ratio. So, you can get a different pixel size in the x and y direction.

This is a dynamic list and may never be able to satisfy particular standards for completeness. You can help by expanding it with reliably sourced entries.

Display size row	Display size col	Total Pixels	Note
768	1024	786,432	
720	1280	921,600	standard high density (HD ready) display
736	1280	942,080	
752	1280	962,560	
768	1280	983,040	
750	1334	1,000,500	Apple phones only
800	1280	1,024,000	
1080	1920	2,073,600	standard Full HD (FHD) display
1080	2160	2,332,800	
1080	2340	2,527,200	
1125	2436	2,740,500	Apple phones only
1440	2560	3,686,400	standard Quad HD (QHD) display
1440	2880	4,147,200	
1440	2960	4,262,400	
1440	3040	4,377,600	
1440	3120	4,492,800	
1600	3840	6,144,000	"UW 4K" (Ultra-wide 4K) or "UW QHD+" (Ultra-wide Quad HD+)
2160	3840	8,294,400	standard Ultra HD (UHD) display, 4K UHD (2K by 4K)

720p by 1280 (HD ready) [edit]

So, this is your row and column display size. So, you have a different number of pixels on x and y.



Display size row	Display size col	Total Pixels	Note
1440	2560	3,686,400	standard Quad HD (QHD) display
1440	2880	4,147,200	
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720p by 1280 (HD ready) [edit]

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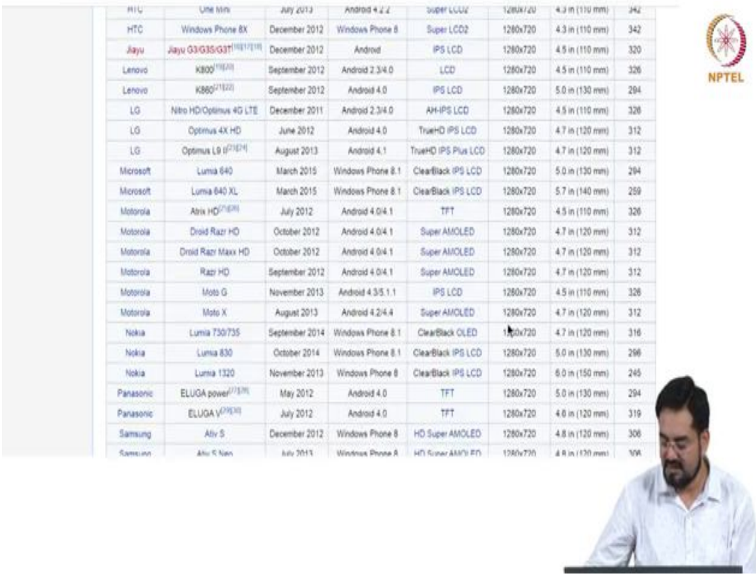
Brand	Model	Release month	Operating system	Display type	Resolution (pixels) or px	Display size	Pixel density (ppi)
Acer	CloudMobile	September 2012	Android 4.0	IPS LCD	1280x720	4.3 in (110 mm)	342
Asus	Padfone 2[9]	November 2012	Android 4.0/4.1	Super IPS+ LCD	1280x720	4.7 in (120 mm)	312
General Mobile	Discovery[10][11]	August 2013	Android 4.2	IPS LCD	1280x720	4.7 in (120 mm)	312
Huawei	Ascend D1	June 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
Huawei	Ascend D quad	June 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
Huawei	Ascend D quad XL	June 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
Huawei	Honor 2[12][13]	October 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
Huawei	Honor 3X G750[14][15]	December 2013	Android v4.2.2	IPS LCD	1280x720	5.5 in (140 mm)	267
Huawei	Ascend P2	April 2013	Android 4.1	IPS LCD	1280x720	4.7 in (120 mm)	312

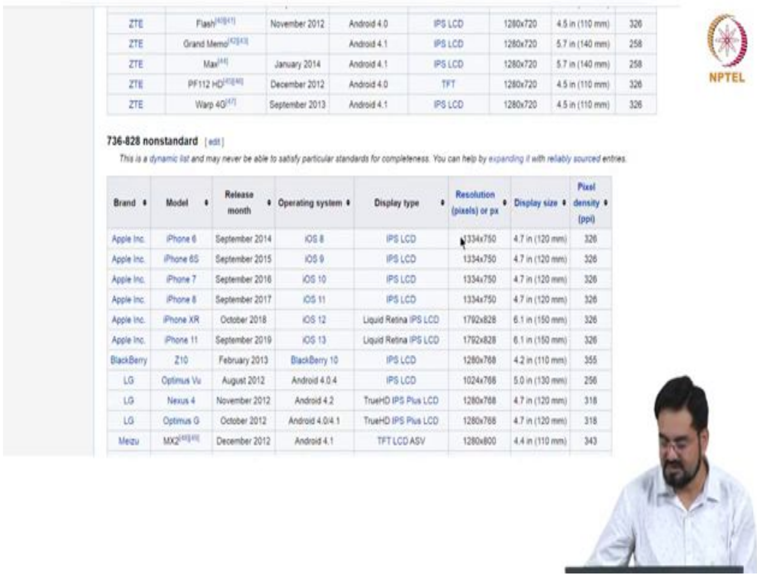
And then so, the resolution is mostly measured in terms of pixel density which is PPI. Let us say we have 1280 by 720 which is for a 4.3-inch display.



HTC	One Mini	July 2013	Android 4.2.2	Super LCD2	1280x720	4.3 in (110 mm)	342
HTC	Windows Phone 8X	December 2012	Windows Phone 8	Super LCD2	1280x720	4.3 in (110 mm)	342
Jiayu	Jiayu G3/G3S/G3T	December 2012	Android	IPS LCD	1280x720	4.5 in (110 mm)	320
Lenovo	K800	September 2012	Android 2.3/4.0	LCD	1280x720	4.5 in (110 mm)	326
Lenovo	K860	September 2012	Android 4.0	IPS LCD	1280x720	5.0 in (130 mm)	294
LG	Nitro HD/Optimus 4G LTE	December 2011	Android 2.3/4.0	AH-IPS LCD	1280x720	4.5 in (110 mm)	326
LG	Optimus 4X HD	June 2012	Android 4.0	TrueHD IPS LCD	1280x720	4.7 in (120 mm)	312
LG	Optimus L9 II	August 2013	Android 4.1	TrueHD IPS Plus LCD	1280x720	4.7 in (120 mm)	312
Microsoft	Lumia 640	March 2015	Windows Phone 8.1	ClearBlack IPS LCD	1280x720	5.0 in (130 mm)	294
Microsoft	Lumia 640 XL	March 2015	Windows Phone 8.1	ClearBlack IPS LCD	1280x720	5.7 in (140 mm)	259
Motorola	Atrix HD	July 2012	Android 4.0/4.1	TFT	1280x720	4.5 in (110 mm)	326
Motorola	Droid Razr HD	October 2012	Android 4.0/4.1	Super AMOLED	1280x720	4.7 in (120 mm)	312
Motorola	Droid Razr Maxx HD	October 2012	Android 4.0/4.1	Super AMOLED	1280x720	4.7 in (120 mm)	312
Motorola	Razr HD	September 2012	Android 4.0/4.1	Super AMOLED	1280x720	4.7 in (120 mm)	312
Motorola	Moto G	November 2013	Android 4.3/5.1.1	IPS LCD	1280x720	4.5 in (110 mm)	326
Motorola	Moto X	August 2013	Android 4.2/4.4	Super AMOLED	1280x720	4.7 in (120 mm)	312
Nokia	Lumia 730/735	September 2014	Windows Phone 8.1	ClearBlack OLED	1280x720	4.7 in (120 mm)	316
Nokia	Lumia 830	October 2014	Windows Phone 8.1	ClearBlack IPS LCD	1280x720	5.0 in (130 mm)	296
Nokia	Lumia 1320	November 2013	Windows Phone 8	ClearBlack IPS LCD	1280x720	6.0 in (150 mm)	245
Panasonic	ELUGA power	May 2012	Android 4.0	TFT	1280x720	5.0 in (130 mm)	294
Panasonic	ELUGA V	July 2012	Android 4.0	TFT	1280x720	4.6 in (120 mm)	319
Samsung	Ativ S	December 2012	Windows Phone 8	HD Super AMOLED	1280x720	4.8 in (120 mm)	306
Samsung	Ativ S Neo	July 2013	Windows Phone 8	HD Super AMOLED	1280x720	4.8 in (120 mm)	306

So; obviously, the number of pixels per inch will be more compared to 4.7 inches, if you have the same total number of pixels. So, when your display gets bigger in order to get a better picture quality you have to increase the number of pixels.

Samsung	Galaxy Premier	November 2012	Android 4.1	HD Super AMOLED	1280x720	4.65 in (118 mm)	319
Samsung	Galaxy Mega 6.3	June 2013	Android 4.1	TFT	1280x720	6.29 in (160 mm)	234
Sony	Xperia acro HD	September 2012	Android 2.3/4.0	TFT	1280x720	4.3 in (110 mm)	342
Sony	Xperia acro S	August 2012	Android 4.0	TFT	1280x720	4.3 in (110 mm)	342
Sony	Xperia ion	June 2012	Android 2.3/4.0	TFT	1280x720	4.55 in (116 mm)	323
Sony	Xperia S/SL	February 2012	Android 2.3/4.0	TFT	1280x720	4.3 in (110 mm)	342
Sony	Xperia V	October 2012	Android 4.0/4.1	TFT	1280x720	4.3 in (110 mm)	342
Sony	Xperia T/TX	October 2012	Android 4.0/4.1	TFT	1280x720	4.55 in (116 mm)	323
Sony	Xperia SP	October 2012	Android 4.1/4.2	TFT	1280x720	4.6 in (120 mm)	320
Sony	Xperia XA	June 2016	Android 6.0.1	IPS LCD	1280x720	5.0 in (130 mm)	294
Sony	Xperia X Compact	September 2016	Android 6.0.1/7.0	IPS LCD	1280x720	4.6 in (120 mm)	319
Xiaomi	Mi-Two	November 2012	Android 4.1	IPS LCD	1280x720	4.3 in (110 mm)	342
Xiaomi	Mi-2S	April 2013	Android 4.1	IPS LCD	1280x720	4.3 in (110 mm)	342
ZTE	Flash	November 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
ZTE	Grand Memo		Android 4.1	IPS LCD	1280x720	5.7 in (140 mm)	258
ZTE	Max	January 2014	Android 4.1	IPS LCD	1280x720	5.7 in (140 mm)	258
ZTE	PF112 HD	December 2012	Android 4.0	TFT	1280x720	4.5 in (110 mm)	326
ZTE	Warp 4G	September 2013	Android 4.1	IPS LCD	1280x720	4.5 in (110 mm)	326



ZTE	Flash[40][41]	November 2012	Android 4.0	IPS LCD	1280x720	4.5 in (110 mm)	326
ZTE	Grand Memo[42][43]		Android 4.1	IPS LCD	1280x720	5.7 in (140 mm)	258
ZTE	Mai[44]	January 2014	Android 4.1	IPS LCD	1280x720	5.7 in (140 mm)	258
ZTE	PF112 HD[45][46]	December 2012	Android 4.0	TFT	1280x720	4.5 in (110 mm)	326
ZTE	Warp 4G[47]	September 2013	Android 4.1	IPS LCD	1280x720	4.5 in (110 mm)	326

736-828 nonstandard [edit]

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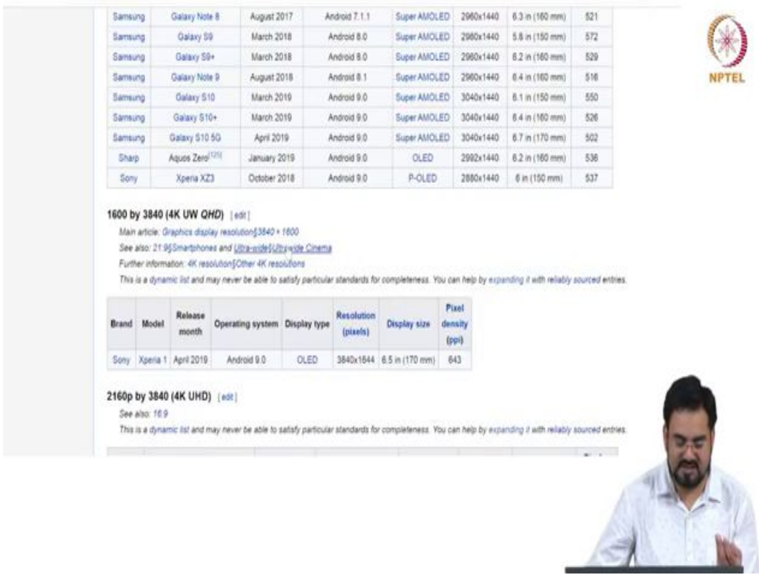
Brand	Model	Release month	Operating system	Display type	Resolution (pixels) or px	Display size	Pixel density (ppi)
Apple Inc.	iPhone 6	September 2014	iOS 8	IPS LCD	1334x750	4.7 in (120 mm)	326
Apple Inc.	iPhone 6S	September 2015	iOS 9	IPS LCD	1334x750	4.7 in (120 mm)	326
Apple Inc.	iPhone 7	September 2016	iOS 10	IPS LCD	1334x750	4.7 in (120 mm)	326
Apple Inc.	iPhone 8	September 2017	iOS 11	IPS LCD	1334x750	4.7 in (120 mm)	326
Apple Inc.	iPhone XR	October 2018	iOS 12	Liquid Retina IPS LCD	1792x828	6.1 in (150 mm)	326
Apple Inc.	iPhone 11	September 2019	iOS 13	Liquid Retina IPS LCD	1792x828	6.1 in (150 mm)	326
BlackBerry	Z10	February 2013	BlackBerry 10	IPS LCD	1280x768	4.2 in (110 mm)	355
LG	Optimus Vu	August 2012	Android 4.0.4	IPS LCD	1024x768	5.0 in (130 mm)	256
LG	Nexus 4	November 2012	Android 4.2	TrueHD IPS Plus LCD	1280x768	4.7 in (120 mm)	318
LG	Optimus G	October 2012	Android 4.0/4.1	TrueHD IPS Plus LCD	1280x768	4.7 in (120 mm)	318
Meizu	MX2[48][49]	December 2012	Android 4.1	TFT LCD ASV	1280x800	4.4 in (110 mm)	343

And then eventually you may have to move to let us say from 1280 by 720 to 1334 by 750. So, your pixel density has increased now. So, that is how resolution increases, or you can say pixel density keeps on increasing.



Samsung	Galaxy Note 8	August 2017	Android 7.1.1	Super AMOLED	2960x1440	6.3 in (160 mm)	521
Samsung	Galaxy S9	March 2018	Android 8.0	Super AMOLED	2960x1440	5.8 in (150 mm)	572
Samsung	Galaxy S9+	March 2018	Android 8.0	Super AMOLED	2960x1440	6.2 in (160 mm)	529
Samsung	Galaxy Note 9	August 2018	Android 8.1	Super AMOLED	2960x1440	6.4 in (160 mm)	516
Samsung	Galaxy S10	March 2019	Android 9.0	Super AMOLED	3040x1440	6.1 in (150 mm)	550
Samsung	Galaxy S10+	March 2019	Android 9.0	Super AMOLED	3040x1440	6.4 in (160 mm)	526
Samsung	Galaxy S10 5G	April 2019	Android 9.0	Super AMOLED	3040x1440	6.7 in (170 mm)	502
Sharp	Aquos Zero[125]	January 2019	Android 9.0	OLED	2992x1440	6.2 in (160 mm)	536
Sony	Xperia XZ3	October 2018	Android 9.0	P-OLED	2880x1440	6 in (150 mm)	537

1600 by 3840 (4K UW QHD) [edit]

Main article: Graphics display resolution§3840 × 1600

See also: 21:9§Smartphones and Ultra-wide§Ultra-wide Cinema

Further information: 4K resolution§Other 4K resolutions

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Brand	Model	Release month	Operating system	Display type	Resolution (pixels)	Display size	Pixel density (ppi)
Sony	Xperia 1	April 2019	Android 9.0	OLED	3840x1644	6.5 in (170 mm)	643

2160p by 3840 (4K UHD) [edit]

See also: 16:9

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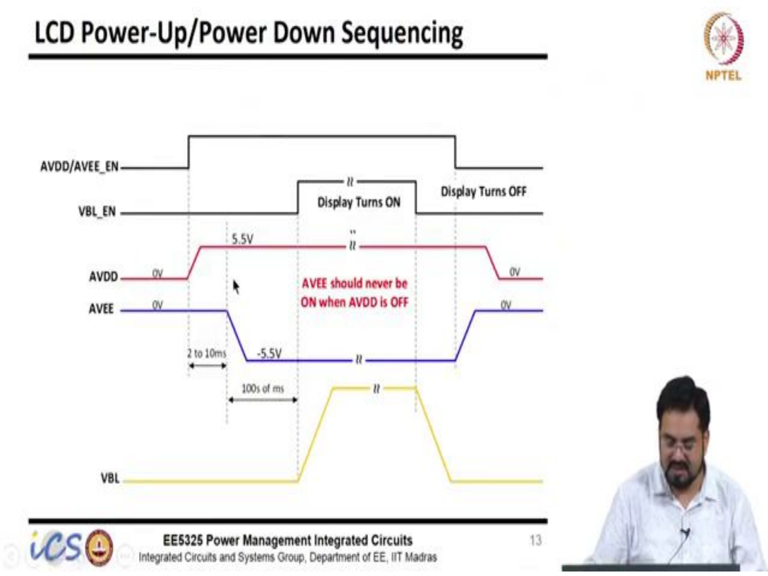
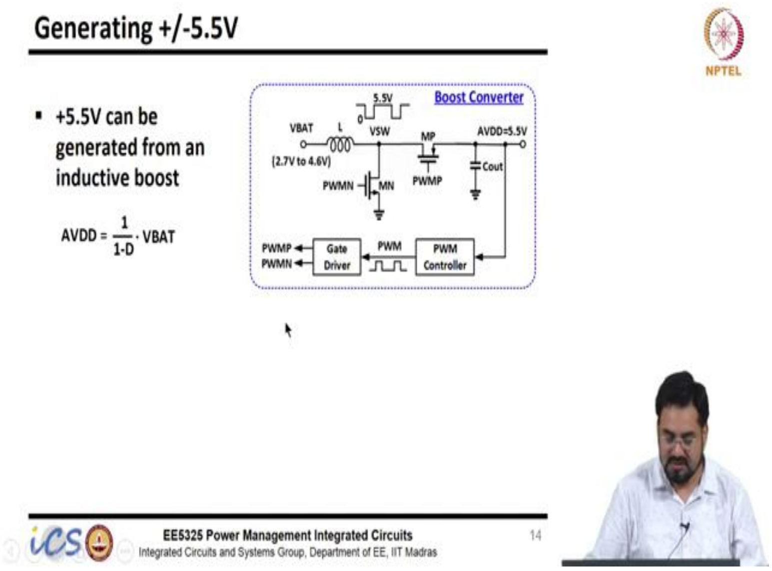
You just move from HD then you have a QHD then you have a UHD. So, it all depends on the size of the display and how many pixels you have and you just multiply the pixels and divide by size and you will get pixel density. So, I mean if you are using let us say this particular display. So, let us say 1080p. So, if you are using this in a 6 inch phone versus a tablet which let us say 8 inches.

Then at 8 inch, the picture quality would not be as good as when you are looking at a 6 inches display because of a smaller display. When you move on to television your pixel size will increase automatically because you have the same number of pixels in the x and y direction. And your power management requirements will change according to the size of the display. So, now, it is quite possible that a bigger display, if you want to maintain the same resolution as a smaller display it may be divided into multiple sub displays and your power management requirement will also change. So, let us say you have let us say two 6 inches displays combined together you divide into two halves and you can put two separate drivers for each in parallel.

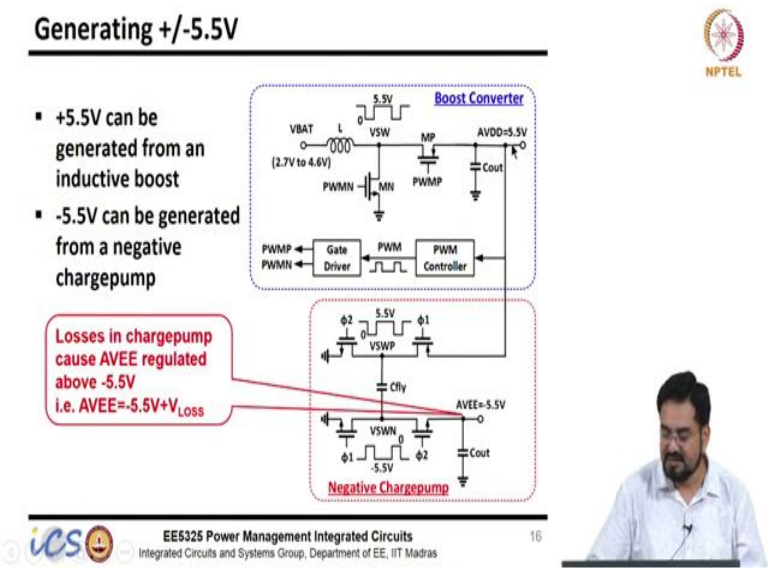
So, what happens is each bigger display will be divided into sub segments and each will have its own backlight and they will have their own drivers. So, if you look at the total number of power regulators, they may increase or the current capability of the regulator will increase if you are using a single regulator. So, the power requirement will change based on the size of the display and resolution both.



So, let us see how we generate these supplies +/- 5.5volt and then the backlight which is higher voltage.

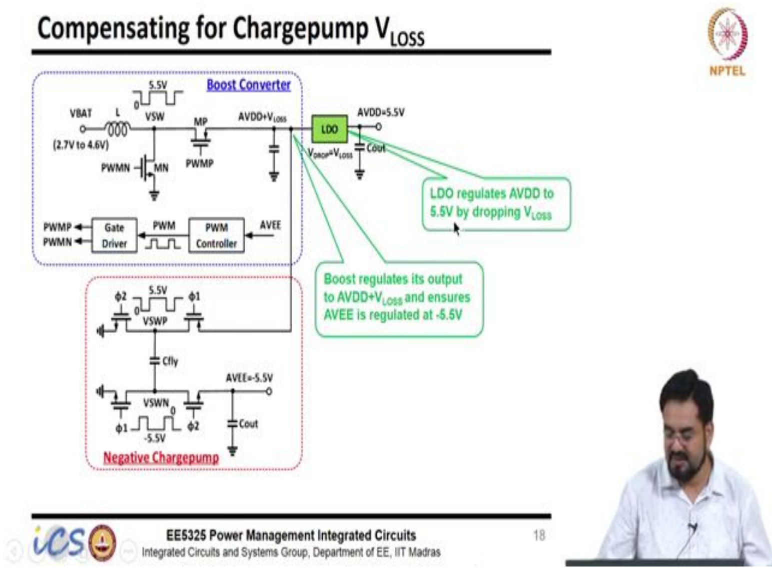


For plus 5 volts, you can simply use a boost converter. So, it is a simple inductive boost regulator and we know the output voltage will be 1 over 1 minus D times into VBAT, where VBAT is the battery voltage which is changing from 2.7 to 4.6 volts. So, based on the voltage control loop will just change the duty cycle and it will keep output regulated at 5.5 volts with variable input supply.



For -5.5 volt, now we have 5.5 volts and we can invert that simply by using an inverting charge pump.

And we also discussed how you generate output voltage equal to minus Vdd and it is just an h bridge and you have a flying capacitor. So, your output will be minus 5.5 volts and this is nothing, but a negative charge pump. So, it is a simple circuit but it has a problem actually. So, since we have switches here and so they will have r_{ds_on} losses as well as switching losses. So, based on the losses, when you apply a 5.5 volt there will be an IR drop across these switches. So, your output will never be exactly 5.5 volts, but below that. So, let us say V_{loss} is the total loss in the voltage we are getting. So, your output will be minus 5.5 volts plus $V_{loss,}$ and let us say V_{loss} is 100 millivolt then instead of -5.5 volts your output will be minus 5.4 volts. So, your output will not be regulated exactly at -5.5 volts. So, we need to fix this.

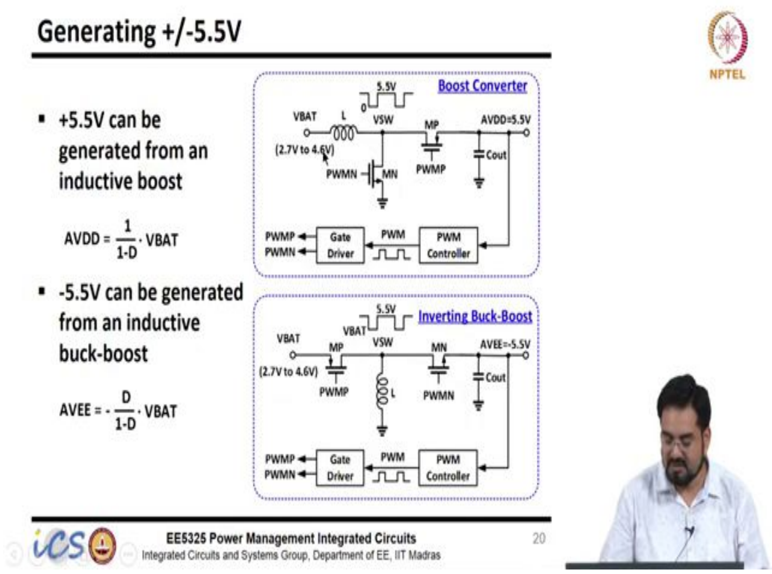


So, in order to get this minus 5.5 volt back, I can regulate this voltage at 5.6 volts so that I can get minus 5.5 volts, and then an extra 100 millivolts I can drop in the LDO. So, your efficiency will be degraded a little bit, but if you have a requirement of exactly the same voltage on both sides then I mean you have to live with that.

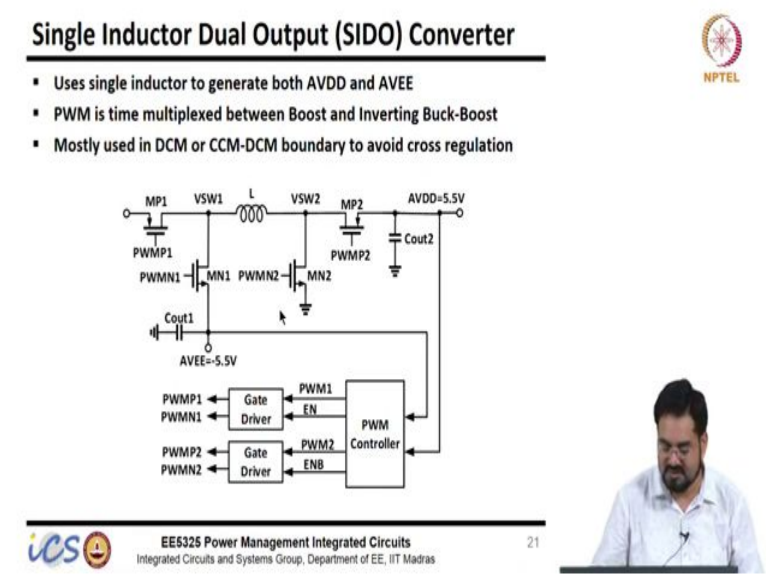
So, now, the feedback will be coming from here because now we are interested in this minus 5.5 volt. So, this will be feedback and this voltage will be regulated at minus 5.5 volts and whatever extra voltage here will be handled by LDO.

Now, this LDO will take an input from here which is more than 5.5 volt and extra voltage will be dropped across this. This feedback to this LDO will be coming directly from AVDD. So, this will be locally regulated from this LDO at 5.5 volts. So, this LDO regulates such

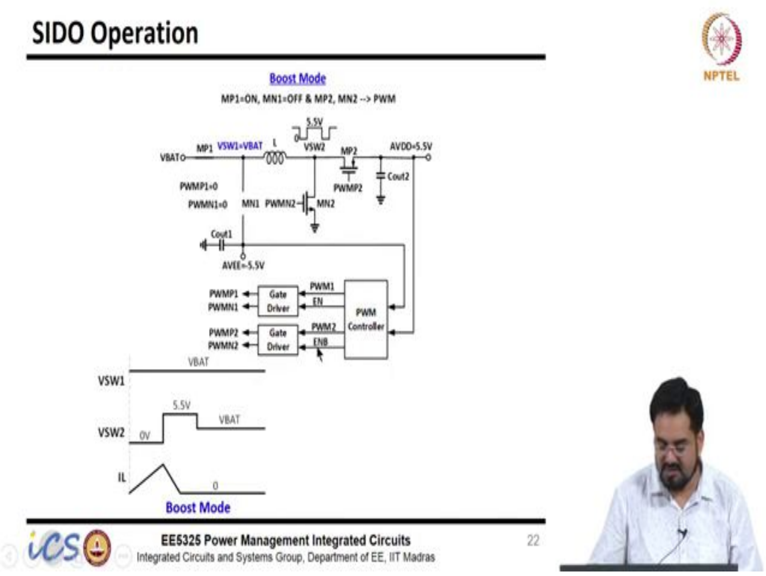
VDD by dropping V_{loss} voltage. So, everything will be taken care of by your control loop and you do not need to know how many losses there are in this.



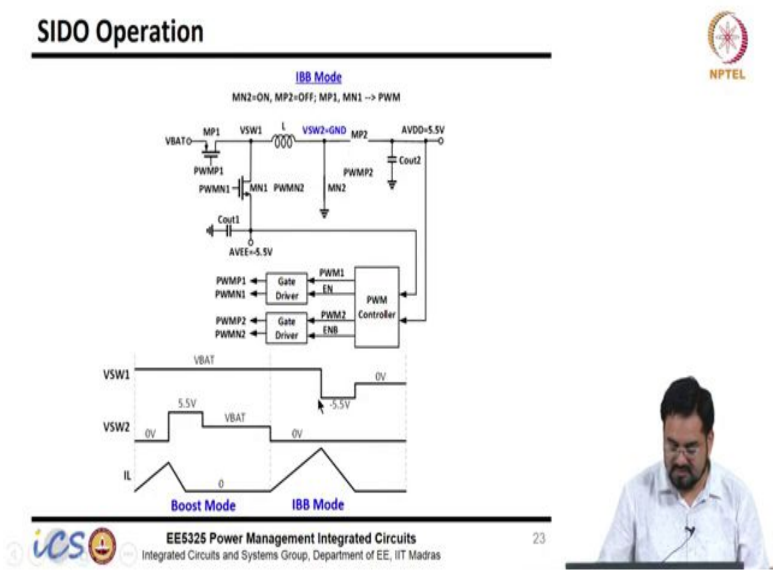
So, another possibility is, we can use an inductive buck-boost to generate a minus voltage. This is a bit expensive because it requires 1 inductor. The output voltage now will be minus D over 1 minus D and your inductor is connected to the ground. So, if you apply a volt second balance, you will know that this is the expression you get from here. So, it is nothing but inverting buck-boost If this is positive then we already know it is a buck boost. So, the only difference is it gets a negative sign here. So, both have their own control loop. So, 5.5 volts will be regulated by boost and minus 5.5 will be regulated by buck boost. So, it is a bit expensive, but in terms of efficiency may be better because it does not require any LDO.



Another possibility could be single inductor multiple outputs. So, now, we know how to do an inductive boost and how to do an inverting buck boost. If we connect this inductor in an H bridge manner which means 4 switches. It is like a time multiplexing just like we saw in the single inductor multiple outputs and we know how to control that. So, it requires an H bridge and we will now have two feedback control one for controlling the duty cycle of your inductive buck boost and another for positive boost converter and this is how it works and we already saw in single inductor multiple outputs.

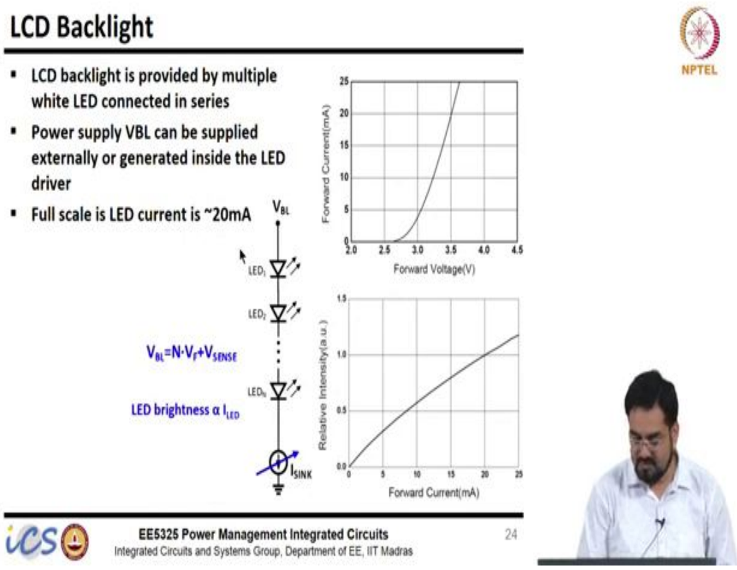


So, you allot half the time to boost and rest next half time to inductive buck boost. So, it is more like multiplexing in time. So, in buck mode, it supplies and one thing is you have to make sure it's operating in DCM mode and it will be in DCM because the current required by these supplies is in order of tens of milliamp or max 50 milliamps.



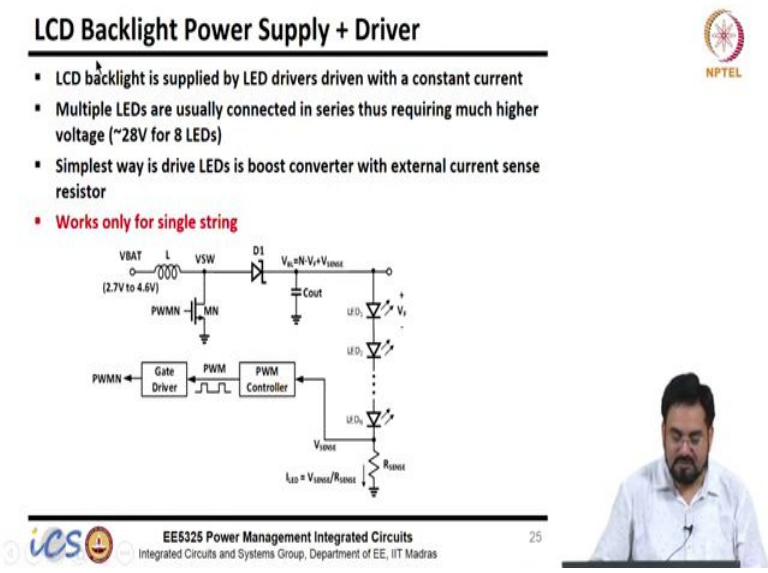
So, there is no issue of cross regulation and all those when your inductor current goes to 0 because it will fully discharge before you activate the next phase or next mode. So, that is how it works, and depending upon the duty cycle the current will change and it will keep the output regulated at plus 5.5 and minus 5.5 volts.

So, if you apply logic you can exactly get the same thing. So, in the boost mode, we want this terminal to be connected to the battery and we want this node to be switching. So, your PWM will be applied on these 2 switches and this switch will be permanently off. So, all the current will be supplied to AVDD and the next mode or next phase when IBB mode is there or inverting buck boost mode is there, what we want we know that the other terminal of the inductor is ground. This switch will be permanently open and now your PWM will be received by this left hand side switch and your output will be here which is minus 5.5 volt.



So, backlight requires LEDs and these LEDs have a certain forward voltage, it is not like a normal PN junction diode which has a 0.7 volt, but these are much higher. So, mostly order of more than 3 volts or so. So, if it is a white LED it may be 3.3 to 3.5 volt and with the forward voltage your forward current also changes and these LEDs require constant current because we know that this current has an exponential behavior with respect to forward voltage.

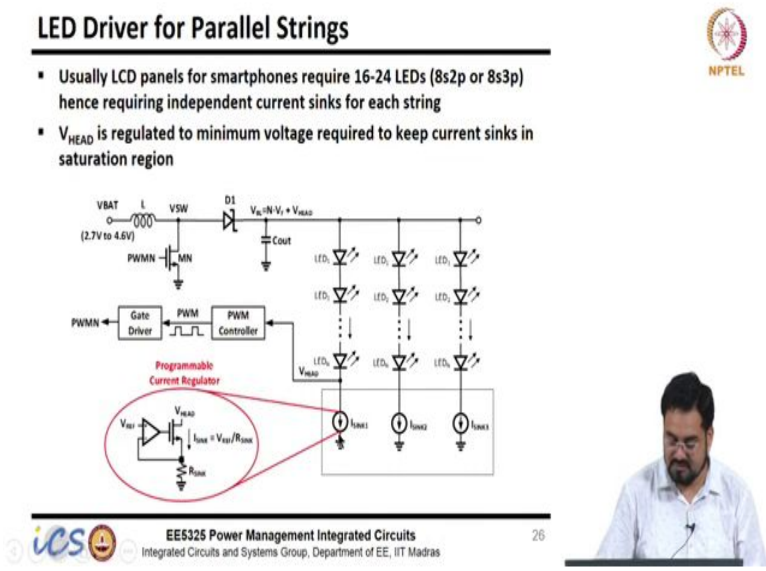
So, if we cannot regulate the voltage as such, if you are regulating the voltage even a small change in the voltage may cause a drastic change in the current. So, it is always preferred to regulate the current and the control loop will take care of whatever voltage is required to get that current. So, most of these LEDs which are used for backlight have a fully scaled current of 20 milliamps or so, and let us say we have a sink current and we have N number of LEDs connected in series So, the total backlight voltage which is required here on the top of this first LED. So, it will be N times forward voltage of each LED plus the V_{sense}, V_{sense} is nothing, but the voltage across this current sink actually. So, LED brightness is proportional to I_{LED}. So, now, you can see here intensity. So, by controlling the current you can control the brightness of your display.



So, the backlight is basically supplied by this boost converter. So, we know that we need to boost this voltage. Let us say that each LED has roughly more than 3 volts. So, 8 LEDs may require roughly 28 to 30 volt,s and in order to get this 28 to 30 volts from battery voltage which is 2.7 to 4.6 volts we need to boost it. It looks like you are boosting more than 5 times here even for the higher maximum voltage. So, when you go to 2.7 volts then that will be even higher.

So, most of the time the process we use is a high voltage process and we mostly get high voltage NMOS, but not PMOS. So, for the high side FET, we put a diode. So, it becomes nonsynchronous. So, it is a non synchronous boost and this is a Schottky diode which is most of the time off chip. The on chip will be only this MOSFET which is MN and you can regulate this current by having an external current sense resistor.

Let us say this resistance is highly accurate because the sense resistor is off chip and you can easily get very accurate results across your temperature and tolerance will also not be that bad. We know that if R_{sense} is fixed and if we regulate this V_{sense} then the current which is flowing through this LED will be nothing but V_{sense} over R_{sense} and that is how you regulate. Now, in the feedback, you can see that it is a simple voltage regulator. So, feedback is voltage and automatically this loop will try to regulate this voltage and there will be a constant current in the LED, but this technique works only for a single string. If we have multiple strings then you do not know which one to feedback here.



In multiple strings instead of using a sense resistor, we use the current source or current sink. You can put this current on the top also then you require a current source but when you are putting it in at the bottom you need a current sink. The main reason we do not want to put it here is that we do not have a high voltage PMOS here and if you are putting it here then you require a PMOS. So, that is why we are putting it at the bottom. So, if you have only an NMOS, then you do not have any choice but put the current sink. If you have a high voltage PMOS then you can even use a high side current instead of a low side current.

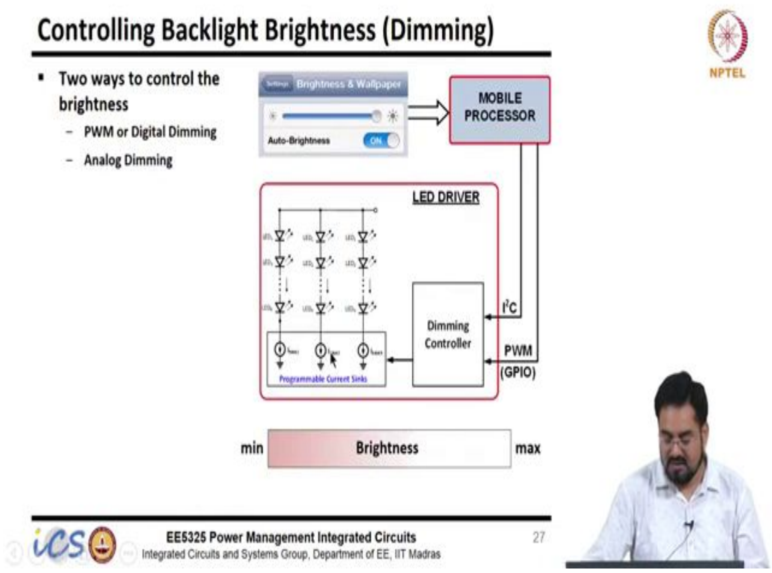
This current regulator is nothing but a linear current regulator. We have on chip R_{SINK} and let us say this is V_{REF}. So, the current flowing here in this MOSFET will be V_{REF} by I_{SINK} and this V_{HEAD} is nothing but this voltage. So, I_{SINK} is nothing but V_{REF} by R_{SINK}. All these have local current regulators and we know that V_{REF} is common and the only different component is this R_{SINK}. So, as long as RSINK remains constant across these different strings then your current will be the same in all the 3 strings, but now you may ask why this V_HEAD feedback is required? We already have feedback here. So, the reason is that the voltage required is very high voltage. So, how do we know what voltage to regulate?

So, one way is that you can use brute force, if you know what V_{HEAD} is required here then you can add all the number of LEDs you require here, and then you know what voltage is required from this formula but that may change. Let us say I have designed a regulator to boost to this particular voltage and somebody changes the number of LEDs in a string and he wants to use the same regulator then obviously it will regulate the current. Let us say there were 8 LEDs and the voltage required here was 28 volt or so. Somebody wants to use 6 LEDs and you are still regulating this at 28 volts and the current will be already regulated by this regulator. So, we have an extra voltage which is nothing but 2 times of V_F and V_F is let us say 3.5 volts. So, the extra 7 volts will be all dropped in this current sink.

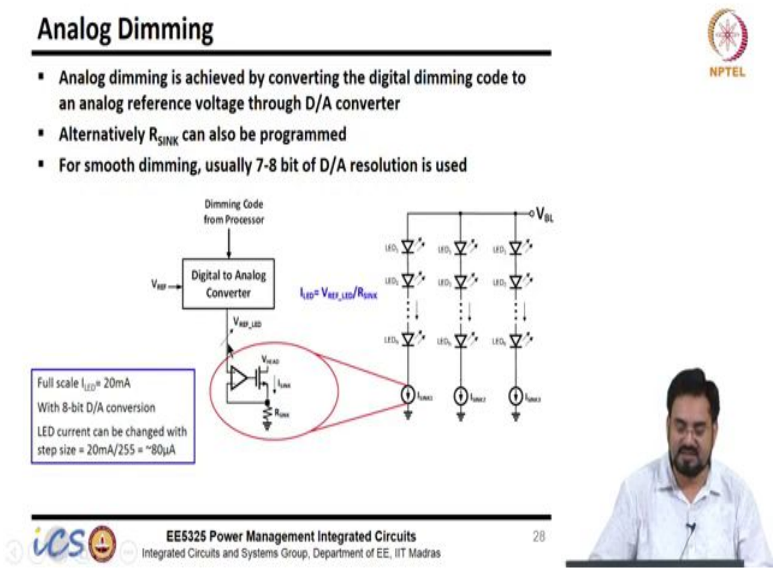
So, this voltage will move up accordingly because in order to keep the current constant, the voltage across these LEDs should be constant. So, the extra voltage will come here and V_{BL} minus V_{HEAD} remains constant depending upon the number of LEDs you require. So, for 6 LEDs, the V_{BL} minus V_{HEAD} will be lower.

So, the extra voltage will be dropped here, and when you are dropping extra voltage here what you are doing? Eventually, you are increasing the dropout voltage and we know that the higher dropout voltage will give me poor efficiency. So, that is why we take the feedback from here and depending upon the minimum voltage which is required to keep this current regulated. So, it will only boost up to that voltage. So, let us say V_{REF} is 100 millivolt and the V_{ds} voltage required by this MOSFET is 400 millivolts. So, I know V_{HEAD} is 500 millivolt which is required in the worst case. I can keep this regulated at 500 millivolts and it will always make sure that this voltage is boosted to a level where this V_{HEAD} will always be stopped at 500 millivolts. I can keep the dropout voltage minimum and achieve higher efficiency.

So, no matter how many LEDs you use it will take care of that but one thing you have to make sure that you have to have the same number of LEDs otherwise you will again run into the same problem because the voltage required here will be based on the maximum number of LEDs. So, this and this voltage is common. So, if you are using a lesser number of LEDs here, again this will have a higher dropout voltage and efficiency will go down.



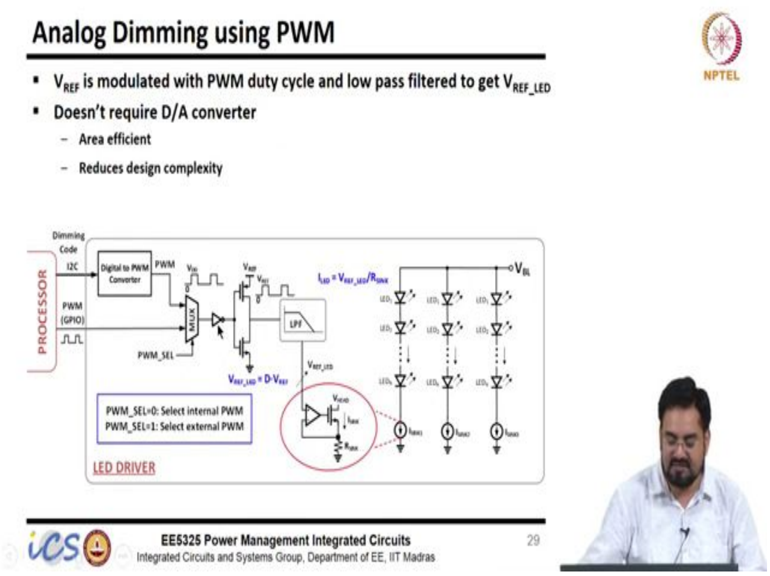
So, now we have these current sinks and they can be programmed. So, that is how you dim your brightness or control your brightness. So, that is what the controlling brightness is called dimming. Changing brightness through the phone does nothing but controls this current and that is how your brightness of the screen is controlled. This current can be controlled in different ways. One way is PWM or digital dimming and the other is analog dimming.



Analog dimming is quite simple, we know we have this sink regulator. All we need to do is change the reference voltage. My current is nothing but this $V_{REF\text{-}LED}$ divided by R_{SINK}. You have a fixed V_{REF} and you can have a digital to analog converter to generate a programmable voltage. So, it has to be digitally programmed because the command I am getting is binary from the processor. So, the input has to be digital, but how you control the output whether digital or analog is a different thing.

When I am controlling V_{REF} which means I am controlling the analog voltage. So, that is why we call it analog dimming. Let us say my full-scale current is 20 milliamps and with 8 bit D to A conversion. So, LED current can be changed with the step size of roughly 80 microamps or so.

Your LSB is 20 milliamp divided by 255. Fully scale LED current is 20 milliamp and we want 8 bit D to A conversion. So, LED current can be changed with step size, what we call LSB is 20 milliamp divided by 2^N minus 1. So, 255 levels we get. So, each bit of each LSB will change this. So, that is the resolution you can achieve in your brightness control.

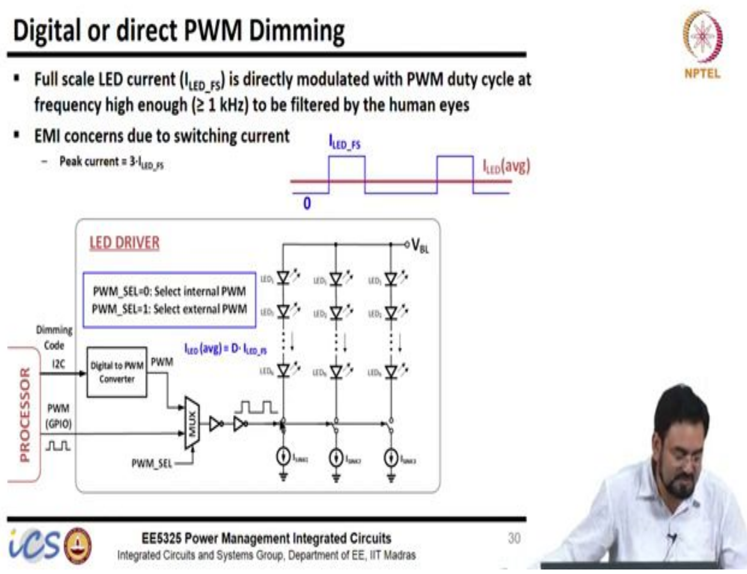


So, analog dimming using PWM is another possibility. Let us say this is your processor and the processor can send a command over I2C. So, this will be sending a digital code and digital code will be programming this voltage directly. Another possibility is instead of sending a command over I2C it may send a command over GPIO (General Purpose IO) and it may be in the form of PWM. So, the duty cycle of this PWM will contain the code. Let us say 0 duty cycle means 0 brightness, 100 percent duty cycle is full brightness. A duty cycle between 0 to 100 percent will give you the level of brightness. So, a 50 percent duty cycle will give you 50 percent brightness. So, it is just proportional to your duty cycle.

This GPIO will have a different level and I know my full scale voltage is V_{REF} here. So, I can level shift this duty cycle to V_{REF}. Now, if I pass it through a low pass filter then the reference voltage which is generated from this will be D times V_{REF}. Just like here, your V_{REF_LED} was depending upon the code here but now it will depend on the duty cycle. V_{REF_LED} will automatically be varying when you vary the duty cycle of this PWM.

You get the PWM from this GPIO and we shift the level of this PWM voltage to V_{REF} because my full scale voltage is V_{REF} and you pass it through a low pass filter. So, if the cutoff of this low pass filter is much lower compared to the switching frequency of PWM, you will get pretty much a DC voltage, just like we get in switching regulators. So, your output voltage of this low pass filter will be proportional to the duty cycle and V_{REF} is constant.

So, by simply varying the duty cycle, we can vary this voltage and my current is V_{REF_LED}/R_{SINK}. The current will still be a continuous current but this voltage will be varying with respect to the duty cycle.

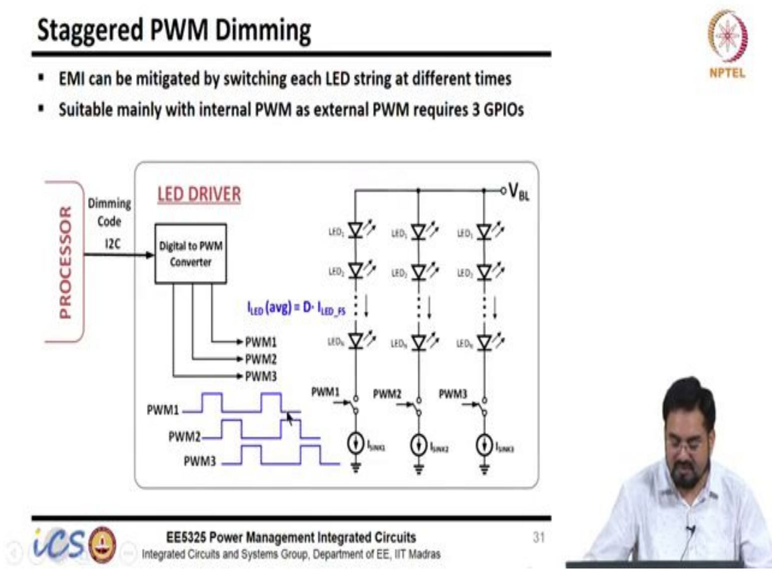


The next one is digital or direct dimming. In the digital dimming instead of programming the voltage, we simply turn on and off the current strings. Let us say this full scale current is 20 milliamps again and depending upon what frequency and duty cycle we are turning on and off. So, it will look continuous to our eyes because our eyes cannot perceive anything beyond 1KHz. It has to be done beyond 1 kiloHertz even though our eyes cannot see anything beyond 100 Hertz but it may vary from person to person and some people may perceive a flicker even 100 or 200 Hertz. So, that is why in order to be safe we just keep it above 1 kiloHertz.

When we switch this current on and off at 1 kiloHertz and at a certain duty cycle it is being done. So, what would happen? It will be averaged out by our eyes. So, our eyes now act as a filter here just like we had a filter here to convert that duty cycle to voltage. So, now, this duty cycle is multiplied by this full scale current and then our eyes will see a continuous brightness. When the duty cycle is varied, it will look like a constant or continuous variation in the current to our eyes. The only thing is that your voltage will be changing a lot.

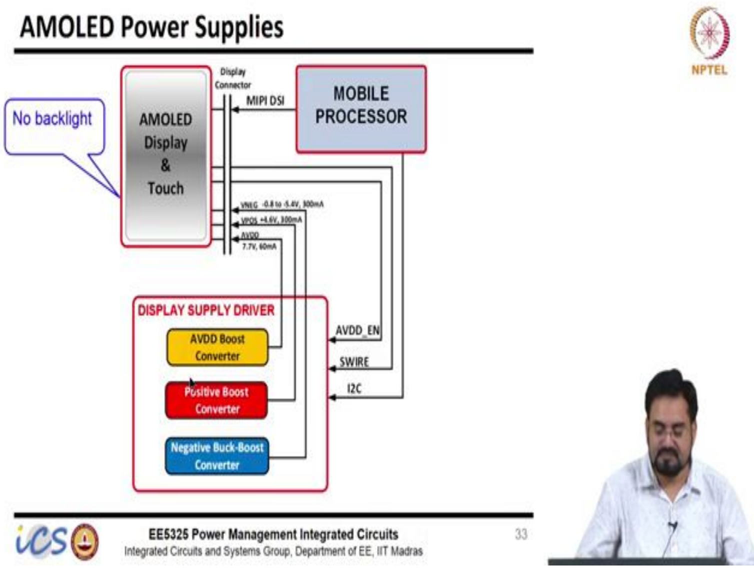
When it is turned on, we know that V_{HEAD} voltage dropout across that, and when you turn off then it may go high. It will be creating more like a switching voltage rather than a continuous voltage. So, there are some EMI concerns with that, but it is usually taken care of by the design and layout. So, just like I said here EMI concerns. Let us say we are turning on and off these 3 currents simultaneously. So, the current seen by the ground will be 3 times of each current. Let us say 20 milliamps in each having full brightness. So, you are injecting 60 milliamps current in the LEDs and this ground and taking out.

These LEDs most of the time are connected through a flex cable, they are on a separate board and are part of your display. This current driver may be sitting on your PMIC which may not be part of your display and most of the time it is outside that. So, now, you can imagine that you are switching 60 milliamp current on and off and these cables have high inductance compared to the short traces which are on your PCB. So, there may be some EMI concerns.



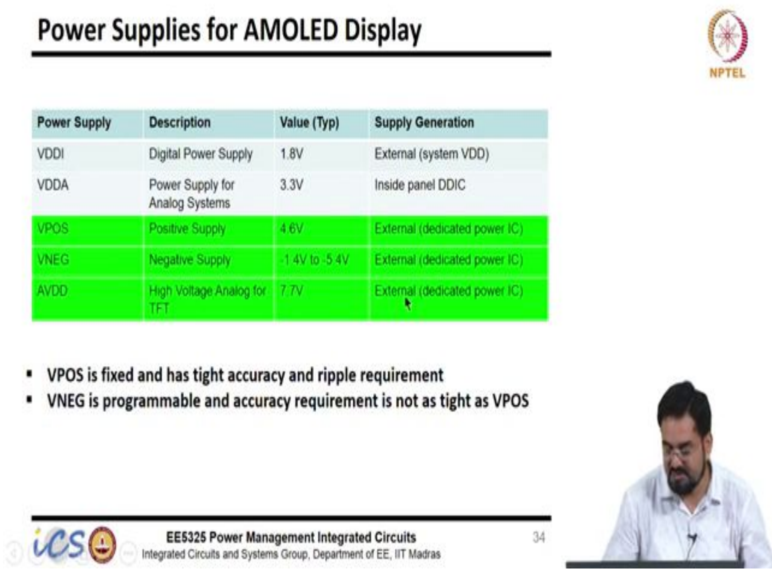
So, what do we actually do? We turn them on and off in a staggered manner. So, instead of simultaneously turning on and off, we shift them in phases. So, we stagger them and now at one time, you will see only 1 LED is turning on next time this LED is turning on, and then this is turning on. So, now you won't be injecting the same amount of current, when these are turning on and off current will be reduced because at a time only one LED is on. So, you will be injecting only 20 milliamps instead of 60 milliamps. If the duty cycle is much higher then at that time you can see all maybe on simultaneously but as long as your duty cycle is lower you will see it would not be a problem in that case.

So, now let us move to this power management for AMOLED displays.

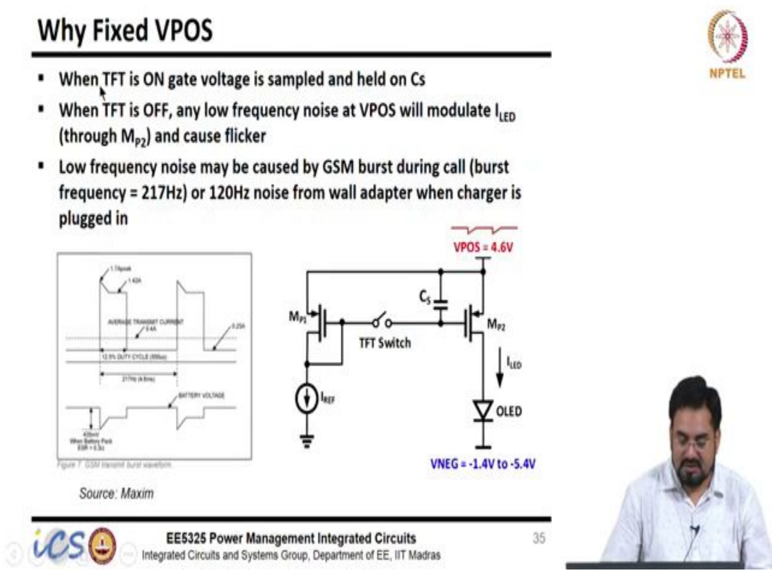


So, AMOLED displays do not require a backlight as we need in LCD and the reason is that it's LED and has its own light. The supply requirement is different for these and what we require again are 3 supplies here just like in LCD, but the voltage levels are different here. We require a negative buck boost or negative supply just like we need in LCD. We require a positive boost also and AVDD is different.

So, the negative voltage required in LCD was fixed at minus 5.5 volts and the positive was fixed at 5.5 volts. Here the negative voltage is varying it may be from -0.8 volt to -5.4 volt and the current requirement is much higher. There we required a maximum of 50 milliamps or so. So, that is the main difference, then the positive voltage is fixed 4.6 volts, but the current requirement remains the same because you can think about these supplies being connected across these LEDs. So, whatever you are sourcing you will be sinking the same. So, that is why the current requirement is the same for both positive and negative. AVDD is again required for some analog and in the driver. So, it requires 7.7 volt. In the case of LCD, we required more than 20 volt or so because it was required for backlight which was supplying those series LEDs. So, again this is the control signal coming from this display to turn on and off. SWIRE is a serial single wire interface which is used to control this voltage.



So, these are the supply requirements. The number of supplies we require is less compared to LCD here and are shown in the above image.



So, why do we require a fixed 4.6 voltage? We know this LED requires constant current. Let us say this is your current source and you are mirroring this current to your LED. So, now, you turn on the switch and this voltage will be sampled by this capacitor and it will be held here. We know this switch is basically running at a very high frequency because it depends on your refresh rate. So, it will be scanning or sampling and then holding this voltage and this switch will turn off. So, when this switch is turned off and let us say any change in this voltage happens then that will be directly reflected into this LED and this current will change because this voltage is already fixed.

But if this switch is turned on then if this is changing and I have a constant current. This voltage will automatically change the gate voltage but that same thing will not happen when you do not have this switch on. So, during off time if any change happens, it may get reflected and change this current here. Let us say that noise is at very low frequency which may fall into your visible frequency range. So, this may appear as a flicker to you that is why we require a very clean supply of 4.6 volts here.