Power Management Integrated Circuits
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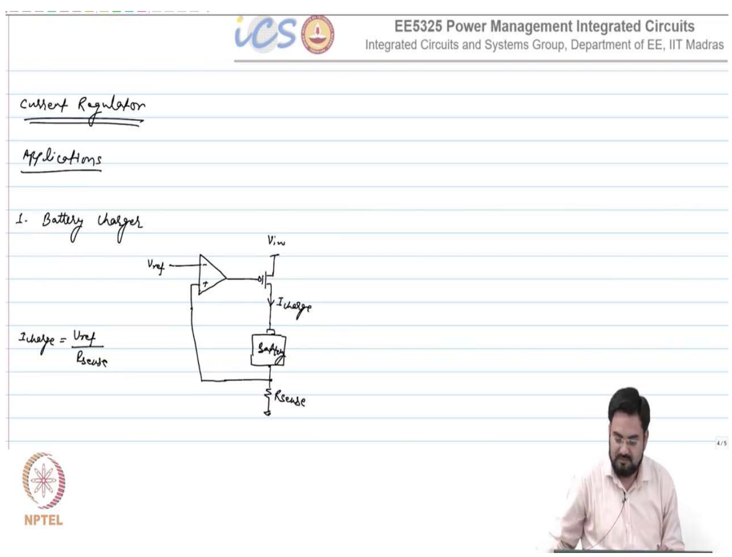
Lecture - 07
Current Regulator Applications, Introduction to Bandgap Voltage References, PTAT and CTAT voltages

Current Regulator applications:

So far, we have been talking about voltage regulators but there are certain applications where you need to regulate the current.

1. Battery Charger: Battery charges with constant current in constant current mode. And current is regulated as shown in below figure.



All we need to do is put a sense resistor and most of the time this is off-chip because we need a very accurate sense resistor. since reference is mostly a voltage reference, we need to convert the current into a constant voltage and compare that. So, now the charging current is given by

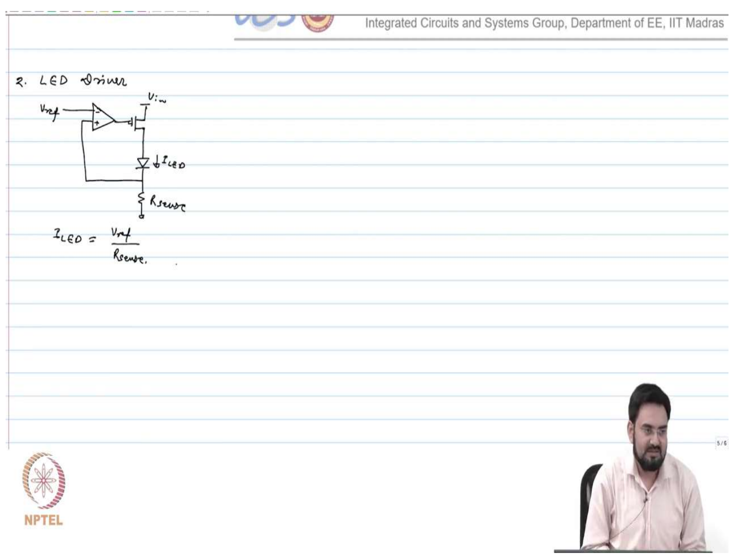
$$I_{charge} = \frac{V_{ref}}{R_{sense}}$$

Depending upon what V_{ref} and R_{sense} we choose, the charging current will be decided. Let's say if we want charging current of 1 A with V_{ref} is 1 V, then we need to put 1 Ω resistor.

But most of the time this R_{sense} is in the order of 10s of milliohm. We do not use such a high value because you will be losing I^2R losses there and you do not want to lose efficiency. So, due to efficiency reasons, most of the time we choose order of 10's of milliohm or at max 100 mΩ so that V_{ref} we can choose 100 mV for 1 A current.

2. LED driver: LEDs require constant current and if you look at the data sheet, they have maximum specified current. If you supply more than that current, these LEDs may heat up and break. That is one thing like you have to limit the maximum current and other thing is the brightness control actually.

The brightness of these LEDs is proportional to the current. So, if you reduce the current you can dim it and if you want to increase the intensity you increase the current. And, most of these dimmable LEDs use current regulators and we simply control the current. These days you would have seen remote control bulbs where you can control the brightness. Those signals will control the current in the LEDs. LED driver circuit diagram is shown in below figure.

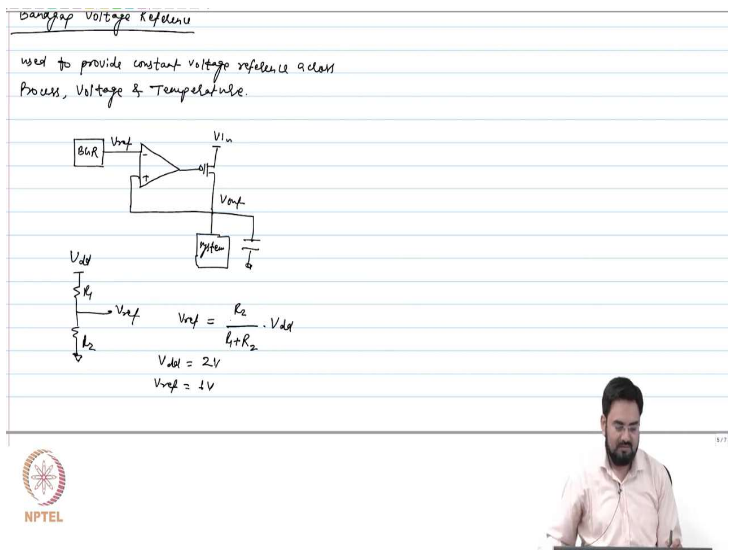


We can either control the V_{ref} or R_{sense}. But most of the time we use V_{ref} because R_{sense} is usually off-chip and difficult to control. But if you have an on-chip R_{sense} then we can build a RDAC but usually these values are of order of ohms. So, you cannot get very good resolution which means you have to have a smallest resistor in order of milliohms which is not easy to build. So, we just control the V_{ref} and get the variable current which will control the intensity of your LED.

Bandgap Voltage Reference:

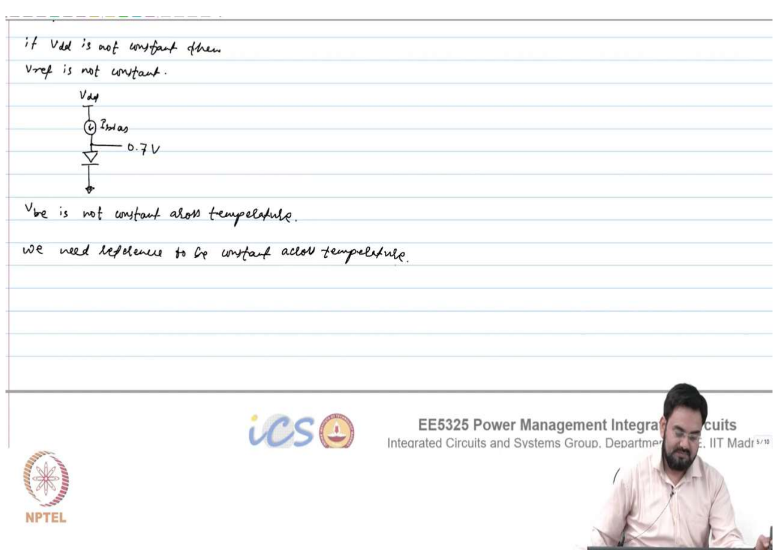
It is used to provide constant voltage reference across process, voltage and temperature.

Consider the linear regulator shown in below figure. We want V_{ref} to be constant across process voltage and temperature because if V_{ref} changes your V_{out} will change and we have some accuracy specification of V_{out}.



To generate V_{ref}, we can use resistor divider as shown in above figure but the problem is if V_{dd} is not constant then V_{ref} is not constant. So, we can't use it.

Is there any other way to generate this constant V_{ref}? We know that when diode is forward biased then voltage across it is 0.7 V and the circuit diagram is shown in below figure.

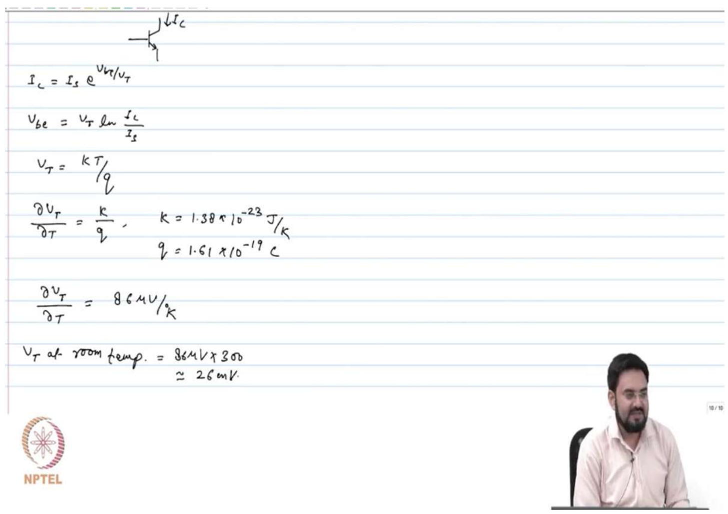


This 0.7 V; voltage across diode may not change with V_{dd} but it is not constant across temperature. So, this won't work.

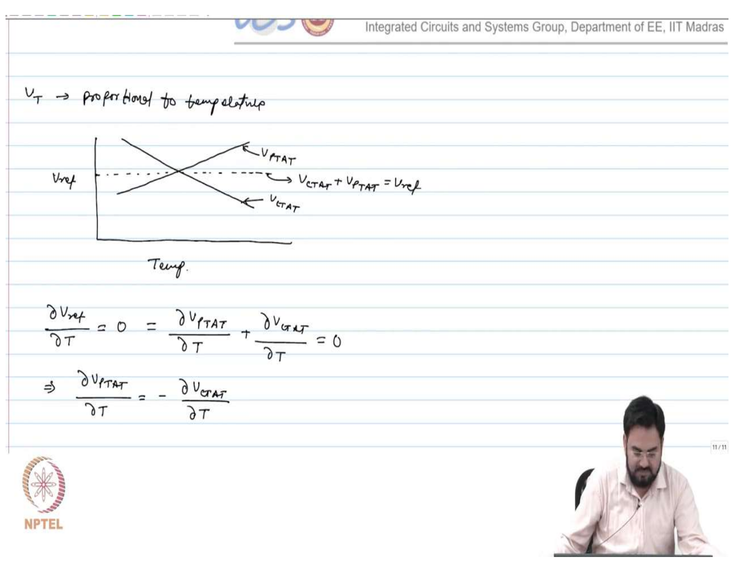
But we will use the same diode concept to build the bandgap reference. Consider the bipolar and we know that collected current (I_c) of bipolar is given by

$$I_c = I_s\, e^{V_{be}/V_T} \text{ where } V_T \text{ is thermal voltage and } V_T = \frac{KT}{q}$$

Change in thermal voltage (V_T) with respect to temperature (T) equals to 86 $\frac{\mu V}{°K}$ and the calculation is shown in below figure.



So, the concept of bandgap is generated from here only.

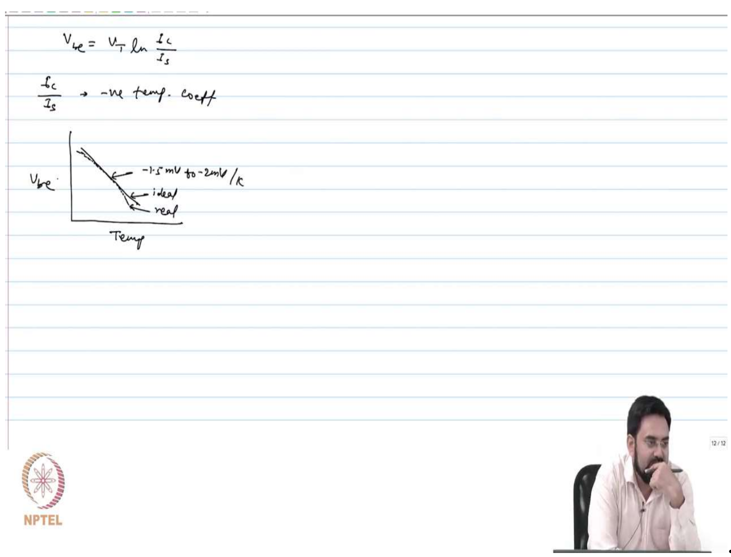


If I have a voltage which is proportional to temperature (V_{PTAT}) and if I have another voltage which is inversely proportional to temperature (V_{CTAT}), then add up the two voltages to get a flat voltage (V_{ref}) which is temperature independent.

We already know how to generate the V_T. V_T is coming from your V_{be}. And we can get V_{be} expression from the current equation as

$$V_{be} = V_T \ln \frac{I_c}{I_s}$$

But it has two more component I_c and I_s. Even though your V_T has a positive temperature coefficient, the overall behavior becomes negative for V_{be} because your I_s has a negative temperature coefficient. So, V_{be} has a negative temperature coefficient and it is -1.5 to -2 $\frac{mV}{°K}$. V_{be} variation w.r.t temperature is shown in below figure.



Since V_{be} has a non-linear term, the variation of V_{be} with respect to temperature won't be linear. It will have some curvature like parabola and that non-linearity comes from V_{be}.

Now we have a voltage V_T which is proportional to temperature and we have a voltage V_{be} which is inversely proportional to temperature. Can we simply add up the two and get the bandgap?

Student: We have to make the slopes equal.

Yeah, slopes are not same. V_{be} has -1.5 $\frac{\text{mV}}{°\text{K}}$ and V_T has 86 $\frac{\mu\text{V}}{°\text{K}}$, which means we need to change the slope of V_T term. How can I do that?

Student: Sir, slope of V_T cannot be changed.

Yeah, but you can add some coefficient. You can design in such a way that we can change the slope.