Analog Electronic Circuits
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Lecture – 39
Introduction to voltage regulators

Welcome back to Analog Electronics. This is lecture 39 and today we are going to start the last module of this course which is Voltage Regulators. So, what is the problem? First of all, let us try to understand what a voltage regulator is, alright. So, the problem is that my analog signal, analog circuit.

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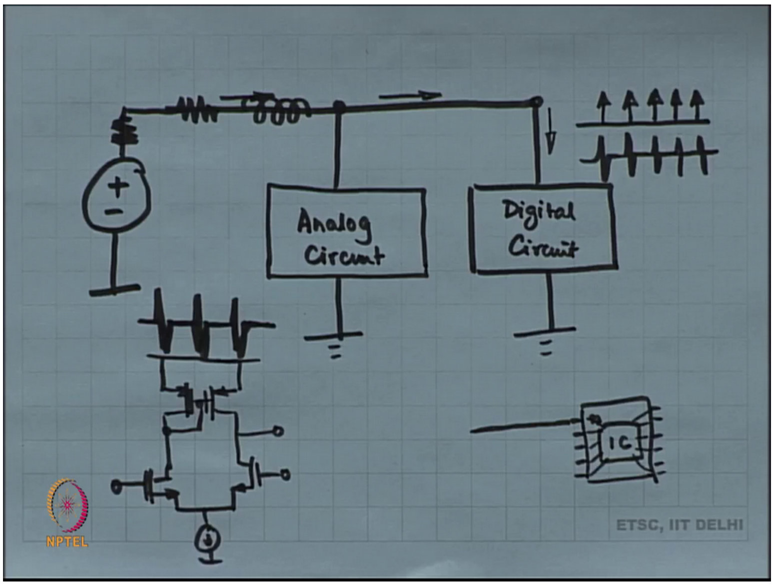

Let us call it ok. So, I have got some analog circuits on my chip. I also might have some digital circuits and these all require power these all require a power supply. So, on one side, they are connected to ground; on the other supply on the other side, I need to connect them to a power source ok.

Now, when I do such a thing invariably, I mean in the in the crudest possible case you might have these two has the same power supply and this wire is going all the way to the battery or the power supply. Now, it is all very nice, this all looks very nice, but the problem is that the battery will have some source resistance, alright. Now, when you are clocking your digital circuit up and down right let us say there are flip flops, there are AND gates, NOR gates, NAND gates right, some signalling is happening when there is a change in the output of these gates or when there is a some activity in the flip flop, then current is going to be drawn at that instant when there is change.

So, at the edges of the clock typically right for example, if it is a d flip flop then the output d is going to become equal to q at the edge of the clock. So, at the edge of the clock this digital circuit is going to draw some current otherwise the digital circuit is going to stay silent, ok. So, if you look at the current profile of the digital circuit, it looks like this right. It is there are impulses current impulses and all of those current impulses are at the edges of the clock.

Now, what is going to happen? This current is going to be drawn. The voltage that you see over here invariably, what is it going to look like? It is going to look like the original battery voltage minus those impulses times this resistance alright and that is going to go to my Analog circuit. And then, the analog circuit, the power supply itself of the analog circuit is behaving in this funny way, right. So, imagine your analog circuit right. Suppose, it some differential amplifier; actually differential amplifier is a very good example. If it is not a differential amplifier, the outcome is going to be very harsh ok.

But suppose this that there is some differential amplifier over here right. The power supply is bouncing like this at the edges of the clock. What is going to happen? It is as if the power supply is a constant plus some signal. So, it as if you have applied a signal over here and through this common gate kind of structure, that signal is going to get amplified at the output alright. So, this is generally very bad news. For an analog circuit, this is all very bad stuff going on, this could have come from the digital circuit, this could have come from any other source, this could have come from the analog circuit itself.

Right, maybe the current in the analog circuit is going up and down like that of a power amplifier right, the current is going up and down like that of a power amplifier right. That is going to get amplified in terms of voltage in some other analog circuit, some differential amplifier cut, the power supply is going up and down and therefore, that will get amplified ok.

So, in general this is all very bad news. You do not want this power supply voltage to move at all alright. Here, I said this is the source resistance of the battery; it is not just the source resistance. You could also have resistance in the wire alright; especially, if the wire is long it is going to have resistance. What is going to be worse is if the wire has inductance and invariably that is what happens, you know you know Murphy's laws right. What does Murphy say? Murphy says that if something can go wrong, it is going to go wrong.

So, what typically happens is that this wire is not just resistive. It is also very inductive. Why is it inductive because it is a long thin wire, ok. Typically, when you make a circuit when you make an integrated circuit, the integrated circuit is going to be packaged inside a package right. You got an IC and then this IC is going to be packaged inside a black plastic packaging which you are going to buy, right. So, that black plastic package is slightly bigger and there are pins on the black plastic package and the actual pins from the IC are bonded to that plastic package through these thin bond wires which are made up of gold ok. They are made of gold because gold is the most malleable element metal right you remember, ductile and malleable element that is gold.

So, typically these wires that connect the actual piece of silicon to the package, they are made up of gold. They are very thin diameters could be as low as 0.025 millimetres ok. That could be the diameter, 25 micrometres could be the diameter of that gold wire, right. So, if you have a thin wire, what is it going to present? It is going to present inductance. So, these wires present inductance. Then, this power supply wire which is inductive already. So, this is already an inductive inductor that goes through a long wire which is again, not very thick right all the way to the power supply that is also inductors right.

So, every where you have inductance and now, this spiky current right, this current which looks like a sequence of impulses is coming through inductance right. If i comes through inductance, what is the drop L times d i by d t. Imagine this is already impulsive right full of impulses, d i by dt is going to look crazy ok, d i by d t is going to look like this right, it is going to look horrible. So, effectively this power supply voltage is not even going to look like this; this is if you are lucky; typically, it is going to look like this which is even worse and L d i by dt is going to go up as the frequency goes up right. The shorter these pulses are d i by dt is going to blow up even more and more, right.

So, the amplitude of this is going to be pretty large even when the current is small right. This current might be of the order of some hundred microamperes alright, but this amplitude is going to be fairly large because what matters is d i by dt not the current itself, alright. So, this is the problem right and whenever there is a potential problem, Murphy has said that that problem is going to crop up in your life ok. So, this is I am identifying this as a potential problem and guess what? This inductance in the power supply wire is everywhere, alright.

So, we have a problem. The problem is that the power supply to the analog circuit is not good, it is not the v d d that you want; it is not a constant voltage. So, this is where we are going to make a voltage regulator right. This is all that I have discussed so far is to motivate to you the requirement of a circuit called a voltage regulator. What does a voltage regulator do?

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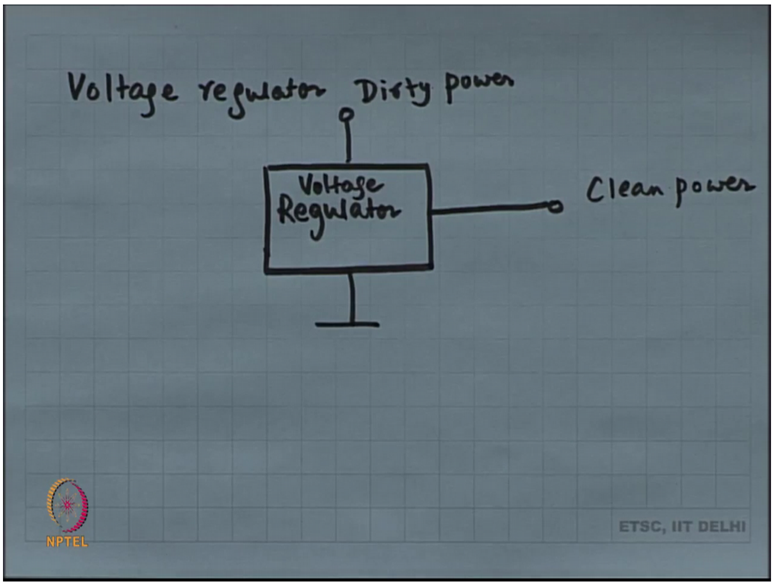

So, nothing much it is a three terminal circuit, one terminal is ground, the other terminal is the dirty power supply and it is output terminal is the clean power supply.

And then, what we are going to do is we are going to give the analog circuit, the differential amplifier is going to draw power from this clean power supply and we have to figure out what is inside, alright. So far so good, I need to make a 3 terminal circuit such that it takes a dirty power supply and converts it into a clean power supply with respect to ground assuming ground is fixed this is the problem attempt. How do we do such a thing? One very straight forward trick is to use an op amp.

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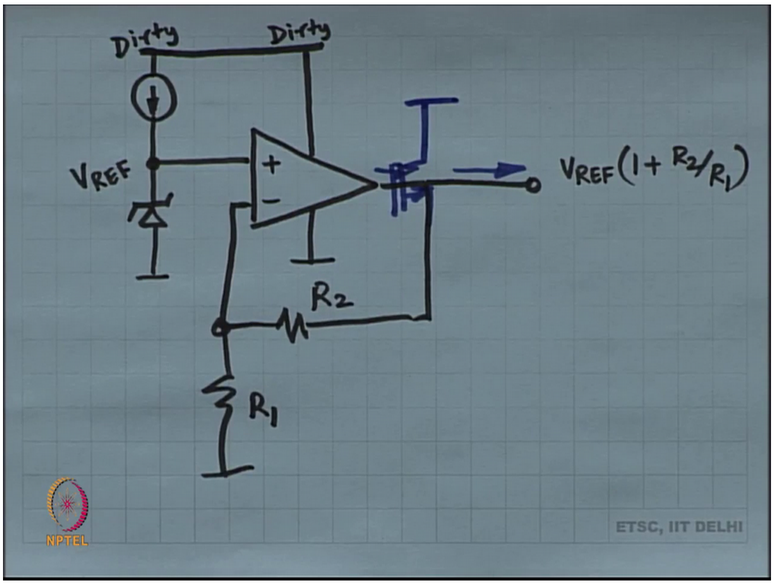

So, imagine an op amp and from somewhere, I give you a constant voltage ok. This is not the source of power, but this is just a constant voltage somehow, somehow let us say I manage to make a constant voltage which is not a source of power it cannot generate power ok. Lot of people make this using Zener diode. Have you heard of a Zener diode? The symbol like this the Zener diode has a fixed breakdown voltage ok. So, if I push current through a zener diode, then the voltage that it creates is a constant voltage. This is the idea, alright lot of people use this Zener diode.

So, I take the zener diode and create a constant voltage, I push a current though a zener diode I bleed a current through a reverse biased zener diode and create a constant voltage and now this is from the dirty supply. The op amp needs power, from the dirty supply I am taking power for the op amp. Now, what we are going to do is we are going to use this and make our non-inverting amplifier.

What happens, what is this output voltage? This output voltage will be one plus R 2 by R one times the original reference voltage and will it be bouncing, no. It would not be bouncing as long as this does not leak out ok. As long as the effect of the dirty power supply does not come into the output right, typically it would not because this is the feedbacks of it right; feedback is going to make sure that this output is related only to V REF and not to the dirty supply at all ok.

So, portion of the dirty power supply will still leak out right and that is I mean for a practical for a practical voltage regulator, a portion of the dirty supply will still manage to leak out, that is called power supply rejection. How much of the dirty power supply is rejected in the actual power clean supply that ratio is called power supply rejection, but otherwise this circuit looks ok, ok. So, some non ideality is there that some dirty power supply might still come out, otherwise this looks ok.

If you want to, there are two things over here; one is loop gain right closed loop gain of the circuit, the other is that the amount of power that you can push. This op amp has to now be able to drive all the power demanded by the actual analog circuit ok. So, all of that current has to come out through the op amp, alright. Generally, that becomes a big bottle neck what people do is instead of doing just this is right this circuit is ok. This circuit works, but it cannot drive a strong load it can drive only as much as the op amp can provide.

The op amp output current is somewhat limited right you have to design the op amp, right. So, that op amp low differential amplifier all of that the output current that is coming out of the op amp typically is not very large. Remember, this is a large output impedance right the op amp output has a large impedance output impedance is quite large. So, you do not want it to drive large amounts of current. Instead, what people do is they put a buffer in between, let us redraw.

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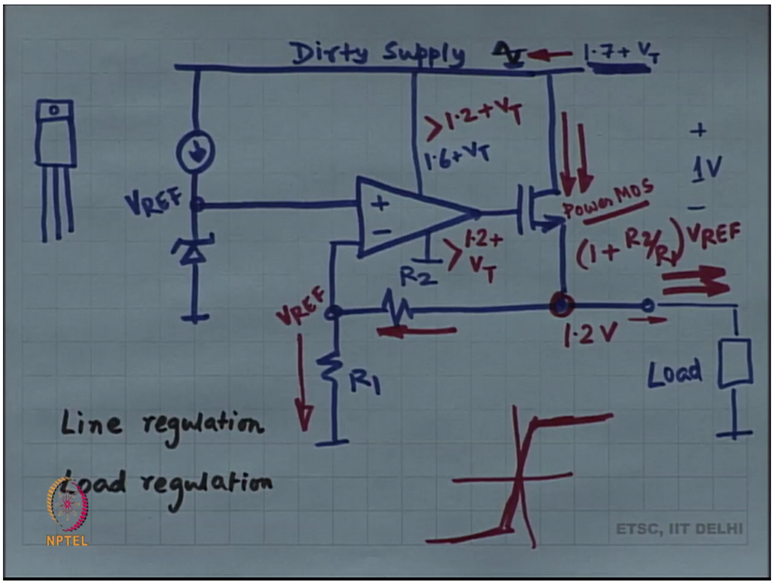

What is this is a common drain circuit? Common drain circuit has a low output impedance ok. If you want to analyse this circuit, what is the output voltage going to be? Is it going to be related to the common drain at all, no. It is not right, if you call this is V REF, then the op amp will make sure that the fed back voltage the voltage at the minus terminal is also V REF if this is V REF the voltage at the minus terminal has also got to be equal to V REF as long as there is negative feedback around the op amp. So, this is equal to V REF which means that this current is V REF by R 1 where is this current coming from, it is coming through this right which means that the output voltage is V REF plus V REF by R 1 times R 2 which happens to be 1 plus R 2 by R 1 times V REF.

So the output voltage has nothing to do with this MOSFET over here. This is just pushing the load current right. You are drawing load current, you want a lot of current whose going to give you the current now, the all of that current is going to come from this particular MOSFET ok. It is not coming from the op amp anymore alright. The op amp is not in charge of pushing current. The op amp is just doing its voltage amplification it is making sure that if this if whatever is the differential input voltage, this is a large amplification factor times the differential input voltage.

So for example, if this goes a little low, then immediately this is going to be if this goes low, then this will go low immediately this is going to go high. If this increases and this decreases immediately, current is going to be pushed ok. So, this is what the op amp does. The op amp is not in charge of supplying power, this large MOSFET over here, this is the power MOSFET ok. You are going to use a power MOSFET over here and that is in charge of pushing power.

Now, sometimes you do not even need a dirty supply right with the supply does not have to be dirty you still need a regulator. For example, if the load itself is varying with time ok, sometimes the load is very large, sometimes the load is very small current large current. If you have, if you draw small current large current from an ordinary power supply, then the internal resistance of that power supply is going to modulate the voltage that you get, here what is going to happen?

If the supply is less, if the requirement is small, then suppose this voltage goes up a little bit then immediately if this voltage goes up right, then immediately this the gate voltage of the power and MOS is going to go down and immediately the current is going to go down ok. If the current over here goes down what pushed, what gets pushed into the load goes down. So, it is stabilizes it brings the voltage down.

If for example, the load starts drawing too much current, suppose I draw extra current from the load then this the output impedance of the circuit right there is some output impedance. So, the voltage over here goes down if the voltage over here goes down, then that gets amplified right. This also goes up if it goes up extra current is pushed over here and it stabilizes the voltage. It pulls it back up fine. So, there are two different actions of the voltage regulator. Action number 1 is called line regulation. If I apply a small signal at the dirty supply, how much of that comes out hopefully nothing comes out ok, but a fraction of it is going to come out and that is called that fraction is called line regulation.

And the other is called load regulation. If I increase or decrease the load current, then ordinarily this voltage is going to get increased or decreased or increased right what is the effect of this feedback, how does it adjust itself, how stable is it ok. So, for example, if the load current varies by 1 percent how much does this voltage vary; does it vary 1 percent, does it vary 0.01 percent ok. So, this called load regulation. So, you have got two different actions; one is called the line regulation, the other is called the load regulation.

How is line regulation taken into account? Suppose, this dirty supply increases a little bit ok. Suppose the supply voltage increases a little bit it does not matter right. This feedback loop still ensures that the voltage over here is just right such that the voltage over here is V REF times R 2 by R 1 plus 1 ok. So, that is line regulation, is that ok. First of all this has isolation, drain to source is isolated, but it is not just that that we are we have over here. It is not just drain to source we also have this feedback and the feedback make sure that this voltage is absolutely steady, alright. So, this is called a voltage regulator, this is the classic voltage regulator circuit that I have in front of you. Absolutely classic voltage regulator circuit this kind of a circuit is used all the time you can buy these ICs of the shelf there are 3 terminal ICs right with the heat sink, they look like this. I do not know if you have seen them right.

There is a heat sink, there is a metallic heat sink on the backside. Why do you need a heat sink all the load current is coming through this power MOSFET right, dirty supply minus clean supply times that load current is the heat in this power MOSFET is the power dissipated by the power MOSFET is dirty supply minus clean supply times the current. So, in the worst case scenario, whatever your load current times dirty supply minus clean supply that is the power given out as heat in this power MOSFET alright.

Now, let us understand a few things. Suppose, I want a clean power supply of 1.2 volt, suppose I want this to be 1.2 volt, what is the minimum value of the dirty supply that I need? What is the lowest value of the dirty supply if the clean supply required is 1.2 volt? How will you figure this out? First of all, if there is any amplitude on the dirty supply right that is going to affect how large this has to be ok, but then there is one more thing involved.

There is the V T of this MOSFET if this is 1.2 volt; however, large this power MOSFET is; however, small this drawn current is the voltage at the gate is at least a V T above 1.2 volt at least at the very least. I am taking the most optimistic situation over here, most optimistic situation is when the power MOSFET is really large such that the amount of current drawn out through the power MOSFET requires absolutely no VGS minus V T which means that V G S of this power MOSFET is equal to V T most optimistic, which means that the voltage at the output of the op amp has to be 1.2 plus a V T.

Now, if the output voltage of the op amp is 1.2 plus a V T what should be the value of the dirty supply? It has to be more right it cannot be less than 1.2 plus V T. It has to be more than 1.2 plus V T maybe you know VGST more or some quantity more there has to be some headroom and this dirty supply has to be above that ok. So, this supply dirty supply certainly has to be more than 1.2 plus V T and that is also a super optimistic situation because if you want this op amp to be having any gain right then the output voltage of the op amp cannot be equal to the supply the output has to be lower than the supply. At the point where the output is equal to the supply at that point the op amp does not have any gain whatsoever, the gain has become 0 right the characteristics of the op amp has become flat.

So, the op amp characteristics remember we have discussed it looks like this. You want to be in the high gain region of the op amp not in this flat region of the op amp where there is no gain ok. So, if your output of the op amp is 1.2 plus V T, your dirty supply certainly has to be somewhat more than 1.2 plus V T. It is not 1.2 plus V T, it cannot be equal ok.

So, for example, if you leave VGS minus V T of 0.2 volts over here and VGS minus V T of 0.2 volts over here then this is probably not 1.2 plus V T, it is 1.6 plus V T ok. I am just now trying to see how optimistic, I was I really was very optimistic alright. Now, let us say you have got an amplitude over here half plus minus 0.1 volt alright. So, the lowest at the lowest point this has to be 1.6 plus V T which means on an average this dirty supply has to be 1.7 plus V T right. I am leaving headroom of 0.1 volt for that amplitude, I am just assuming 0.1 volt of amplitude is there on that dirty supply.

So, now the dirty supply is 1.7 plus V T. The actual supply going to the load is just 1.2 volt. What is the drop over here? It is 0.5 plus V T is the drop across drain and source and suppose V T is another half a volt then; that means, that the drain to source drop is something of the order of 1 volt. So, I have got a 1 volt drop over here. Alright, which means that if my load current maximum load current is 50 milliamperes, then the heat the maximum heat in the MOSFET is going to be 50 milliwatts which means that the form factor of this particular device has to be such that it can dissipate 50 milliwatts as heat without increasing the temperature of the circuit.

When you increase temperature of the circuit, other funny things start happening right, V T starts changing all kinds of things happening right we do not want to go there. We do not want to go into that domain, we want to have some steady state temperature of the circuit right, we do not want to burn right. So, our circuit has to be able to dissipate 1 volt times the maximum load current if that is 50 milliamperes 1 volt times 50 milliamperes, 50 milliwatts the load has to be able this MOSFET has to be able to dissipate that heat safely.

So, that is why you need a heat sink ok, you need a heat sink it is a big metallic flat plate behind the device such that it can throw it out as heat uniformly, nicely without increasing the temperature of the device alright. So far so good, so I was drawing 50 milliamperes 1.2 volt. What is the power delivered to the load? 50 milliamperes times 1.2 volt is the power delivered to the load, 60 milliwatts is the power delivered to the load. What is the power used up over here? 50 milliwatts, 60 delivered, 50 used net is 110 ok. What is the efficiency? Efficiency is power delivered to the load divided by actual power drawn from the supply. So, that is 60 divided by 110 ok, it is less than 60 percent right and this is happening in the power supply ok, this is a disaster.

Right this is out right theft right. I make a battery I give you a battery right and even before you do anything with the power from the battery, you throw out more than half of it as heat right or close to half of it. You just say sorry I want a clean power supply I have to burn half of your battery energy as heat right, this is out right theft right this is a disaster ok. So, unfortunately this is the classical, this is the absolute classic voltage regulator circuit alright. This is the textbook approach. There is one more approach that we can do. So, lot of people do not like this because of course, if the numbers are in favour, suppose I make this larger the numbers will come in favour if the power supply voltage becomes larger.

Suppose instead of 1. 2 volt, you need to deliver 10 volts; 10 volts over here right and add another one volt, 11 volt. So, out of an 11 volt supply you are delivering 10 volts right, then suddenly your efficiency becomes 10 by 11 which is much better than 60 by 110 ok. So, it all depends on how large this value is if this value is large, then you are at an advantage. If this value is low, then unfortunately your efficiency is going to drop like a stone.

Now, in modern technologies, the maximum supplies become low. Why? We have not discussed this at all right the MOSFET becomes smaller and smaller right. You want to pack in more MOSFET s in the same area. You want more functionality on one chip right you and your cell phone to be a camera and Bluetooth and this and that and GPS and audio recorder and so and so and so and so, right and you want to play games on it and you want to watch movies on it right, all in the same handset right.

That basically means that you have to pack in more circuits into the same area, silicon area which means that you need to make the MOSFETs smaller and smaller in size right. When you make the MOSFETs smaller and smaller, you need to also be able to control the channel in the MOSFET to be able to control the channel in the MOSFET when the size of the MOSFET is very small right, the width of the MOSFET is very small, the length of the MOSFET is very small, everything is small right. You want to control the charge in the channel, you have to make the thickness of the gate very small and this is where the disaster happens, right.

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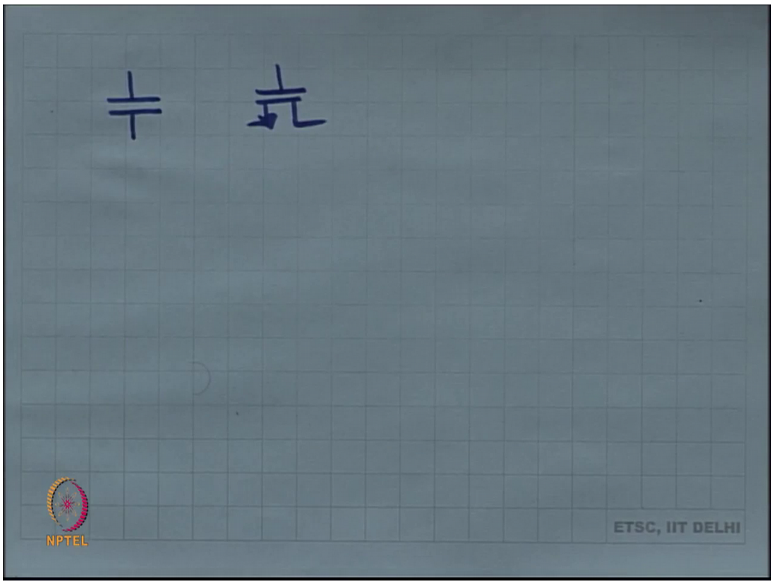

The MOSFET is like a capacitor right. You are making the thickness of this dielectric thinner and thinner and thinner right. In the most modern technologies 28 nanometre, 22 nanometre, Intel is now at 16 nanometres right in these technologies this dielectric this gate dielectric is as thin as a few atoms ok. It is really really thin. Now, if you apply a large voltage over here the dielectric is going to breakdown and by breakdown what it means is that it is going to ionize right, this going to be some welding action, have you done welding. You might have done welding in your workshop right.

You bring the rod very close right and then the air in between the rod and the surface ionizes. Actually you have to touch it and then bring it up little bit, lot of times your rod is going to get stuck over there. So, when you touch it you build up the short circuit current then pull it out a little bit, you get to ionize the air in between right and then there is a arch that develops in between right through the ionized air.

So, the same thing is going to happen over here. You will manage to ionize and then it is going to breakdown and then you know it is going to fuse these two are going to get joined ok. So, when such a thing happens, the MOSFET is no longer usable. This is I am drawing it as a capacitor. It is a MOSFET right, it is some MOSFET is there alright. So, the MOSFET s in finer and finer technologies can tolerate lower and lower and lower voltages.

So, for example, in the latest and I mean this the in your smartest of smartphones right, the maximum voltage that the MOSFET s will tolerate is probably 0.6 volts ok. What will you do? You still have to regulate the voltage. So, it is not even 1.2 that we want we want 0.6, you still have to regulate the voltage that supply is still very dirty right, you still have to do all of this and therefore, the efficiency is going to be even poorer then what we are talking about right. You were unhappy you were complaining of theft when I gave you 50 percent efficiency, it drop it to 0.6 it is going to be even further down 25 percent right.

So, we have a problem. The classical voltage regulator used to work in the classical period right. In the last decade it used to work fine right when voltages were higher when MOSFETs used to be bigger when people would not demand a camera inside a cell phone right. In those days, this classic voltage regulator would work just fine in today's day and age this kind of a voltage regulator is going to give you very poor efficiency. What do we do?

So, the answer actually lies in this MOSFET right. We need to have a power MOSFET over there, but do we have to have it like this, why not flip it around ok?

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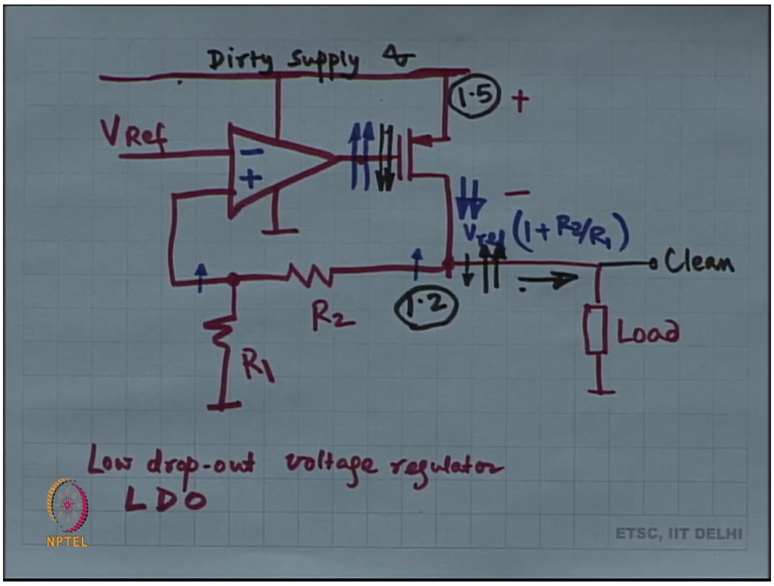

This is your dirty supply. Unfortunately, when you flip it around, this MOSFET starts working like a common source amplifier right from if the input is at this terminal output is at this terminal then it looks like a common source amplifier. If you think of the input over here, then it looks like a common gate amplifier ok. If the input is at the source dirty supply has a small signal, there it looks like a common gate amplifier but the output of the op amp is at the gate there it looks like a common source amplifier.

So, we are going to do exactly the same thing ok. Now, if there is negative feedback, then the op amp will make sure that these two terminals are equal in voltage right. So, the current is V REF by R 1 over here that current is drawn through R 2 and the output voltage is therefore, the same as before V REF into 1 plus R 2 by R 1 right, but this is of course, if there is negative feedback. So, all that we now have to make sure is that there is negative feedback. How do we do that? If I do the same signs as before that is plus on top minus on the bottom then, unfortunately this is an extra inverting amplifier right, common source amplifier, this is going to invert once again you are going to end up with positive feedback ok.

So, instead what we are going to do is we are going to place minus over here and plus over here ok. So, you flip the signs and that should be enough. For example, if this voltage is too high, suppose this voltage is too high right, then this is going to be a fraction of that this is higher than usual. If this is higher than usual, then the amplifier is going to amplify it and make it a lot higher if this is a lot higher, then the PMOS current is going to go down right.

So, the current output of the PMOS is going to decrease which means that this voltage is going to drop ok, that current is getting pushed into the load. On the other hand, if the voltage over here is low, if this is lower than required then what is going to happen? The amplifier is going to amplify and it is going to make it a lot lower; if it is a lot lower, then the PMOS current is going to increase in value it increases in value and then comes into the load and the voltage increases.

So, there is still negative feedback, all I have done is flipped the signs of the op amp, alright. Now, let us do our maths once again our numbers, let us run through the numbers yet again. What do we have? We wanted let us say an output voltage of 1.2 volts ok, that is the output voltage that we wanted. What about this gate voltage, is it important is the value of the gate voltage related to the drain no ok.

For example, the drain of this PMOS can be higher than the gate voltage it does not matter as long as we drain to source to drain is more than source to gate minus V T ok.

So, typical source to gate minus VT VGST is typically 0.2 volts. So, therefore, this source voltage has to be more than 0.2 volts above 1.2 and then you leave some headroom for this dirty supply right, another 0.1 volt. So, this means that this should probably be above at around 1.5 ok, lot lower than earlier, in the earlier case I had it at 1.7 plus a V T; V T I took was 0.5. So, I got this as 2.2.

So in the earlier case, this voltage was 1 volt. In this case, this is just 0.2 alright. So, let us do the same thing. I draw 50 milliamperes over here right, power delivered to the load is 50 milliamperes times 1. 2. So, that 60 milliwatt, power drawn from the source is 50 milliamperes times 1.5 right overall efficiency is 1. 2 by 1.5, that gets you 80 percent, a lot better than what we had; 80 percent means you are now closing in on very high efficiency ok.

So, this kind of a voltage regulator is not the classical one. So, this is called a low drop-out voltage regulator and a lot of people refer to this as an L D O; L D O standing for stands for Low Dropout ok. Low dropout is this this voltage is the dropout ok. So, this headroom that you require this is the dropout voltage. So, in this case the dropout is low. So, this is called a low dropout voltage regulator and this is going to perform much more efficiently than the classical voltage regulator right. The classical voltage regulator is the standard feedback amplifier. This one has an extra inverting amplifier ok. Instead of buffer, common drain buffer you are made a common source amplifier over here that led to of course, flipping in terms of sing, but otherwise everything is the same fine, any questions so far?

Great; can you comment can you think about the difference in the design of suppose you are asked to design this amplifier and you are asked to design this amplifier. Could you comment on any worries or any good things? Well one thing that you can directly observe over here is that if this is a two pole system right if this op amp is going to be two stages it is going to be two poles, but this is just a buffer and hopefully it is not going to create yet another low frequency pole.

However, over here if this is a two pole system, the net structure is actually three poles right. It is as if you have got a three pole amplifier and then you are placing it in feedback alright. Now, when you do that you have to compensate the three pole amplifier and not the two pole or if I mean if you just compensate this two pole or original amplifier. It is not going be good enough, you have to compensate this entire three pole system.

So this is going to be much harder, much harder when you do your compensation of this particular structure it is going to be much harder because there are two poles in this plus one more pole, 3 poles right you can pull this third third stage inside the op amp and you can call that as one gigantic op amp right which has three stages; three common source amplifiers, back to back instead of two, right.

Now, you have to compensate for that 3 stage amplifier. You remember compensating for the 2 stage amplifier itself require so much hard work. Now, if I throw a three stage amplifier at you, it is going to be very very tough ok. So, that is one big problem with this circuit a lot of people avoid that just by making this a one stage amplifier right. They say let us not bother with a two stage amplifier, let us make a one stage amplifier over there and sort it out and then they compensate this over all ok. So, we will discuss these things and more in the next class when we further talk about voltage regulators and start looking at the frequency response.

Thank you.